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Hypersonic Research Facilities Study

Volume III Part 1

Phase II Parametric Studies

Research Requirements and Ground Facility Synthesis

Prepared Under Contract No. NAS2-5458
by
Advanced Engineering
MCDONNELL AIRCRAFT COMPANY
for
OART - ADVANCED CONCEPTS AND MISSIONS DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Moffett Field, California 94035

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FOREWORD

This report summarizes the results of the Hypersonic Research Facilities Study Phase II effort performed during the period from 19 September 1969 through 2 January 1970 under National Aeronauntics and Space Administration Contract NAS2-5458 by McDonnell Aircraft Company, (MCAIR) St. Louis, Missouri, a division of McDonnell Douglas Corporation.

The study was sponsored by the Office of Advanced Research and Technology with Mr. Richard H. Petersen as Study Monitor and Mr. Hubert Drake as alternate Study Monitor.

Mr. Charles J. Pirrello was Manager of the HYFAC project and Mr. Paul A. Czysz was Deputy Manager. The study was conducted within MCAIR Advanced Engineering, which is directed by Mr. R. H. Belt, Vice President, Aircraft Engineering. The HYFAC study team was an element of the Advanced Systems Concepts project managed by Mr. Harold D. Altis.

The basic task of Phase III was to subdivide into research tasks the desirable research objectives for hypersonic flight determined in Phase I, and to refine and evaluate through parametric studies those attractive facilities retained from Phase I.

This is Volume III, Part 1 of the overall HYFAC Report, which is organized as follows:

		NASA CONTRACTOR REPORT NUMBER
Volume I	Summary	CR 114322
Volume II	Phase I Preliminary Studies	
	Part 1 - Research Requirements and Ground Facility Synthesis	CR 114323
	Part 2 - Flight Vehicle Synthesis (Confidential)	CR 114324
Volume III	Phase II Parametric Studies	
	Part 1 - Research Requirements and Ground Facility Synthesis	CR 114325
	Part 2 - Flight Vehicle Synthesis (Confidential)	CR 114326
Volume IV	Phase III - Final Studies	
	Part 1 - Flight Research Facilities (Confidential)	CR 114327
	Part 2 - Ground Research Facilities	CR 114328
	Part 3 - Research Requirements Analysis and Facility Potential	CR 114329
Volume V	Limited Rights Data (Confidential)	CR 114330
Volume VI	Operational System Characteristics (Secret)	CR 114331

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This work was performed by an Aircraft Advanced Engineering study team with Charles J. Pirrello as Study Manager.

The following contributed significantly to the contents of this volume:

P. Czysz	Deputy Study Manager
R. Crook	Flow Facility Design Specialist
W. Cunningham	Non-Flow Facility Design Specialist
J. Klingler	Ground Facility Costs Analyst
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D. Raines	Facility Systems Analyst

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VOLUME III ● PART I

SUMMARY

Airbreathing hypersonic aircraft employing liquid hydrogen fuel have the potential of satisfying a number of mission requirements in the 1980-2000 time period. However, major advances in the technological state of the art are necessary before such aircraft can be considered either feasible or practical. The objective of Contract NAS 2-5458 was to assess the research and development requirements for hypersonic aircraft and based on these requirements, provide the NASA with characteristics of a number of desirable hypersonic research facilities. The study is organized in three phases. Phase I was a preliminary analysis of a broad group of concepts which were reduced to seven flight research facilities and eleven ground research facilities for Phase II study. The purpose of Phase II was to perform parametric studies to refine the facility designs and obtain sensitivity information in the neighborhood of "near optimum" designs, and to select those facilities that appear most attractive in the sense of research potential vs cost for further refinement in Phase III. This part of Volume III presents the results of the research requirements analysis and the synthesis of the ground research facilities. The significant results obtained are:

1. Research in aerodynamics throughout the flight regime, advanced airbreathing propulsion systems and reusable thermal protection systems is valued high.

2. Gasdynamic facilities based on existing equipment performance levels can provide a significant increase in aerodynamic research capability.

3. Near full scale Reynolds number can be achieved in gas dynamic facilities over a significant portion of the flight envelope for the potential operational hypersonic aircraft; including the hypersonic cruise portion. Maintaining near full scale Reynolds numbers at the limits of maximum expected dynamic pressures does incur additional costs.

4. A rationale to establish wind tunnel size versus Reynolds number capability was established based on an analysis of model strength, balance load capability, and model inlet size requirements.

5. An experimental research philosophy was postulated for various engine categories to provide a basis for meaningful engine research facility concepts. This research philosophy determined the size, performance, and costs of the engine research facilities.

6. Research engine facilities based on existing equipment performance levels can provide flight duplicated inlet coniditions up to nearly Mach number six for full scale turbomachinery and ramjet engines. Free jet research associated with flight duplicated conditions for full-scale inlet/engine combinations over a wide range of angles of attack and yaw presents a severe challenge to hardware performance levels, fabrication technology, and acceptable cost levels.

7. For advanced ramjet engines, scramjets and convertible scramjet engines, engine research facilities were based on single engine modules of those characteristic of the potential operational hypersonic aircraft. Smaller complete engines, such as the HRE ramjet or slightly larger engines, could be free jet tested under flight duplicated conditions.

8. Present nozzle cooling limitations for non-impulse, isentropic expansion facilities restrict the completely duplicated flight conditions which can be provided to Mach numbers near ten at the highest dynamic pressures for the potential operational hypersonic aircraft, and near Mach twelve at the lowest dynamic pressures.

9. The enthalpy sources for the advanced ramjet facilities can be used with axisymmetric parallel flow nozzles to provide a significant increment in thermodynamic and structural research capability.

10. Structures research facilities based on existing hardware can provide a significant increment in test article size, up to and including the entire potential operational hypersonic aircraft airframe if necessary. The size and complexity of the candidate structural research facility far exceeds current facilities.

11. The extensive collection of hardware and support systems for the structural research facility can be effectively utilized for smaller scale research in many different related structural technical areas. Existing facilities can be adapted to accomplish the research associated with fluid/structural dynamic interactions associated with large horizontal tankage configurations, normally required for low density cryogenic fuels.

12. Materials research facilities are based on existing hardware, providing a concept of a centralized laboratory available to translate specimen property data into viable structural concepts for potential operational hypersonic aircraft.

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LIST OF SYMBOLS

Symbol	Definition
a	acceleration
A	area
AR	aspect ratio
α	angle of attack, ratio of wing span to vehicle length
β	ratio of mean aerodynamic chord to vehicle length, side slip
b	wing span
C_D	drag coefficient
C_{D_o}	zero lift drag coefficient
C	cross sectional area of wind tunnel test section
$\bar{c}$	mean aerodynamic chord
C_R	wing root chord
C_T	wing tip chord
C_1	balance normal force load capacity divided by balance diameter squared
C_L	lift coefficient
C_{L_α}	lift curve slope
$C_{L_{\alpha_o}}$	lift curve slope at zero lift
C_m	pitching moment
γ	ratio of specific heats, flight path angle
d	diameter, balance diameter
D	drag
δ	deflection
Δ	increment between two values

LIST OF SYMBOLS (Cont)

Symbol	Definition
L/D	lift to drag ratio
m	mass
M	Mach number, bending moment
$\dot{m}$	mass flow
n_z	flight path normal load factor
η_{KE}	inlet kinetic energy efficiency
N.F.	normal force
η	inlet height-to-width ratio
N_2O_4	nitrogen tetroxide
O_2	molecular oxygen
o/f	oxidizer to fuel weight flow ratio
p	pressure
ϕ	fuel equivalence ratio, ratio of actual fuel flow to stoichiometric fuel flow
θ	angle between shock attachment point and cowl lip
q	dynamic pressure
R	specific gas constant
R_E	mean radius of the earth 6,371,100 m
R^*	universal gas constant (8.31432 joules/°K mol)
Re	Reynolds number
ρ	density
σ, F_s	stress
S	area
S/R	dimensionless entropy

LIST OF SYMBOLS

Symbol	Definition
t	time
T	temperature
T_r	recovery temperature
T_w	wall temperature
V	velocity
Vol	volume
$\dot{w}$	weight flow
w	weight
ψ	heading angle, yaw angle
Z	geometric altitude

LIST OF SYMBOLS (Cont)

SUBSCRIPTS

Propulsion Station Designations

0	free stream
c	capture, a fixed reference area on vehicle
cowl	cowl lip
2	engine face
3	engine exit
e	nozzle exit
t	nozzle throat

General

aero	attributable to aerodynamic forces
c	chamber conditions, cruise
cent	attributable to centrifugal forces
D	drag
E	empty
e	engine exit
eff	effective
f	final
F	frontal
i	initial
∞	free stream
G	associated with gravity forces, gross
I	ideal
M	maneuvering

LIST OF SYMBOLS (Cont)

max	maximum
min	minimum
N	net
o	isentropic reservoir conditions, evaluated at zero lift
prop	attributible to propulsion system
p	associated with pressure forces, planform
R	wing root
S	structural
s	vehicle, model stagnation
t	total conditions corresponding to isentropic case
TO	takeoff
TJ	attributable to turbojet propulsion system
SJ	attributable to scramjet propulsion system
t	wing tip
test	associated with test time
wet	wetted
vac	associated with vacuum conditions
x	longitudinal direction
y	lateral direction
z	vertical direction

LIST OF ABBREVIATIONS

Abbreviation	Definition
ARC	Ames Research Center
A	ampere
A-h	Ampere-hour
AB	all body
A/D	analog to digital conversion
Alt	altitude
AM	amplitude modulation
Aero 50	Aerozine 50, a 50/50 mixture of UDMH and Hydrazine
bp	boiling point
Btu	British thermal unit
°C	degrees Celscius (centigrade)
c.g.	center of gravity
c.p.	center of pressure
cm	centimeters
CSJ	convertible scramjet
db	decibel
D/A	digital to analog conversion
diam	diameter
eng	engine
°F	degrees Fahrenheit
FRC	Flight Research Center
ft	feet
fps	feet per second
GE	General Electric Co.

LIST OF ABBREVIATIONS (Cont)

Abbreviation	Definition
hr	hour
Hz	hertz
HF	high frequency
HTO	horizontal takeoff
HYFAC	Hypersonic Research Facilities
ILS	instrument landing system
in.	inch
inst	installed
IRFNA	inhibited red fuming nitric acid
J	joule
JP	jet propulsion fuel
°K	degrees Kelvin (absolute)
kg	kilogram
L	liquid
lb	pounds, force
LO_2	liquid oxygen
LH_2	liquid hydrogen
lbm	pounds, mass
mi	mile
m	meter
max	maximum
min	minimum
MCAIR	McDonnell Aircraft Company
MDAC (EAST)	McDonnell Douglas Astronautics Company (EAST)

LIST OF ABBREVIATIONS (Cont)

Abbreviation	Definition
nmi	nautical mile
N	newtons
No.	number
OWE	operational weight empty
psi	pounds per square inch
PFRT	Preliminary Flight Rating Test
P&WA	Pratt & Whitney Aircraft
°R	degrees Rankine (absolute)
R&D	research and development
RDT&E	research, development, test, and evaluation
RF	radio frequency
RJ	ramjet
RKT	rocket
RP	rocket propellent
s, sec	seconds
SJ	scramjet
smi	statute mile
TF	turbofan
TIT	turbine inlet temperature
TJ	turbojet
TMC	The Marquard Corporation
TRJ	turboramjet
TOGW	takeoff gross weight
UARL	United Aircraft Research Laboratory

LIST OF ABBREVIATIONS (Cont)

Abbreviation	Definition
UDMH	unsymmetrical dimethyl hydrazine
UHF	ultra high frequency
uninst	uninstalled
VTO	vertical takeoff
V	volt
WB	winged body
W/O	without
wt	weight
W	watt

1. INTRODUCTION

This volume of the final report presents the results of Phase II of the Hypersonic Research Facilities (HYFAC) Study. The primary objectives of the HYFAC Study are to assess the research and development requirements for hypersonic aircraft and, based on these requirements, to provide the NASA with descriptions of a number of desirable hypersonic research facilities and estimates of their research capabilities, performance, costs, and development schedules. The research facilities studied include both flight research aircraft and ground test facilities.

To accomplish these objectives, a three-phase analysis program, illustrated in Figure 1-1, was conducted by the McDonnell Aircraft Company. In Phase I, a broad range of flight and ground research facilities were studied. The most attractive of these were retained for refinement in Phase II. The major elements of the Phase II activities were: (1) identification and evaluation of research tasks, (2) parametric trade-off studies of each facility, (3) evaluation of the research value and costs of each facility and selection of the most attractive ones for further refinement during Phase III.

Each of the Research Objectives identified in Phase I was divided into Research Tasks. In so doing, a more specific assessment was made of the types and combinations of facilities (both existing and new) required to accomplish the necessary research on the operational systems identified in Phase I and described in Volume VI.

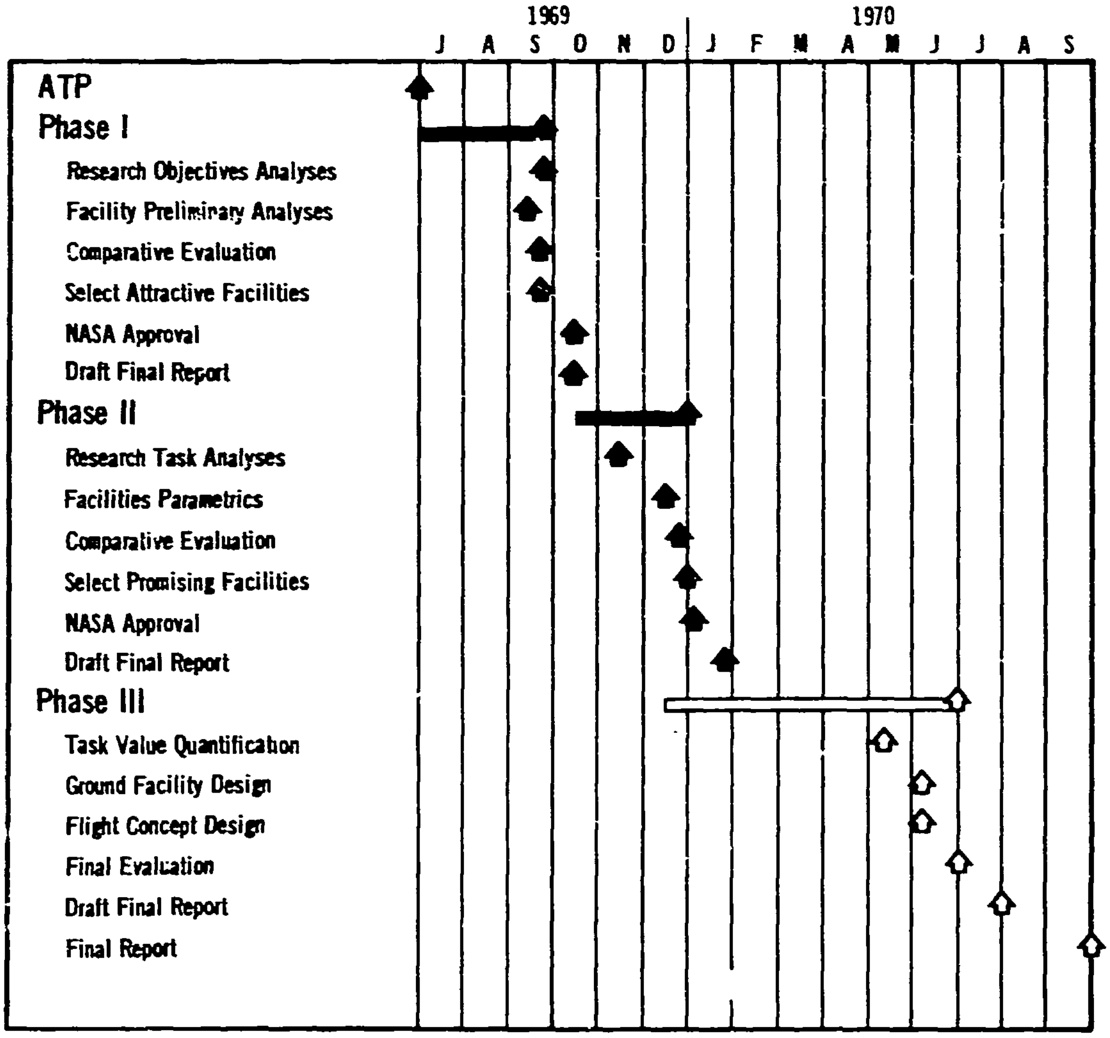
The research contribution of each facility varies with the class of operational system. The capability of each facility to accomplish the research is viewed as its projected ability to provide sufficient confidence in the technology base on which decision makers can initiate an operational system program. In other words, the goal of accomplishing the research is the initiation of a program leading to acquisition, rather than acquisition of the final system itself.

In order to select the best facilities for further refinement in Phase III it was necessary to perform a number of parametric trade-off studies to identify the facilities within each class which were "near-optimum" in consideration of the facility research capability and program cost. Thus for each facility retained from Phase I a corresponding "near-optimum" facility was designed and its cost determined in Phase II.

With the characteristics of each "near-optimum" facility determined, direct comparisons could be made among flight facilities and similarly among ground facilities. These comparisons and subsequent evaluation and screening resulted in selection of the most attractive facilities for further refinement in Phase III.

The results of these parametric trade studies, the comparative evaluations and screening, and the recommended facilities for Phase III refinement are presented in this report.

FIGURE 1-1
PROGRAM MILESTONE SCHEDULE



2. PHASE II ANALYSIS - PARAMETRIC STUDIES

During Phase I a broad group of flight and ground research facilities was studied. The most attractive of these facilities were retained for Phase II parametric study and refinement.

The concepts studied during Phase I and Phase II are illustrated in Figure 2-1 for the Flight Vehicles and Figure 2-2 for the Ground Facilities. In Phase I, 35 flight vehicles and 54 ground facilities were studied. The Phase I screening resulted in 7 flight vehicles and 11 different ground facilities being retained for study in Phase II.

The flight research vehicles retained for Phase II study are summarized in Figure 2-3. They include concepts with maximum speeds of M = 6 through M = 12, using various propulsion system concepts.

The ground research facilities retained for Phase II study are summarized in Figure 2-4. The major emphasis in Phase II was directed toward wind tunnels (GD), engine test facilities (E), structures (S), and materials (M) facilities.

FIGURE 2-1
PHASE II BASIS – FLIGHT VEHICLES

Feature	Phase I Concepts		Phase II Concepts
Mach No.	0.9 2.0 4.5 6 12	Phase I Screening	6 12
Control Mode	Manned Unmanned		Manned Unmanned
Launch Mode	HTO VTO Air Staged		HTO HTO/VTO Air
Accelerator Engine	TJ TRJ RKT Thor Atlas		TJ RKT
Cruise Engine	TJ TRJ RJ CSJ RKT		RJ CSJ SJ RKT
Propellants	Storable Cryogenic		Storable/Cryogenic Cryogenic
Body Shape	Wing Body All Body (Elliptical) All Body (Blended)		Wing Body Blended Wing Body All Body (Elliptical) All Body (Blended)
	35 Vehicles		7 Vehicles

FIGURE 2-2
PHASE II GROUND RESEARCH FACILITIES

	Phase I		Phase II
Gas Dynamic	17	Phase I Screening	3
Engine	11		4
Structural	9		3
Materials	4		1
Simulators	3		0
Fluid Systems	5		0
Subsystems	2		0
Avionics	2		0
Radiation	1		0
	54 Facilities		11 Facilities

FIGURE 2-3
PHASE II FLIGHT RESEARCH VEHICLES

Configuration No.	B 207	B 212	B 232	B 233	B 257	B 260	B 284
Mach Number	6	6	12	12	12	12	12
Engine	RKT/RJ	TJ/RJ	RKT/SJ	RKT	TJ/CSJ	RKT	RKT
Launch Mode	Air	HTO	Air	Air	HTO	HTO/VTO	Air
Body Shape	A B	W B	A B	A B	A B & BWB	A B	A B
Control Mode	Manned	Manned	Manned	Manned	Manned	Manned	Unmanned

FIGURE 2–4
PHASE II GROUND RESEARCH FACILITIES

Configuration Identification	Gas Dynamic			Propulsion			
	GD3	GD20	GD7	E6	E20	E8	E9
Test Time	20 Sec (Minimum)	20 Sec (Minimum)	1 to 4 Sec	Continuous	Continuous	Continuous	Vitiated Air-Continuous; Air – 30 Sec
Mach Range	0.5 to 5.0	Leg 1–0.5 to 5.0 Leg 2–4.5 to 8.5	8 to 13	0 to 5.5 Direct-Connect	Leg 1–0 to 5.5 Direct Connect Leg 2–0 to 5.0 Free Jet	3 to 12 Modified Direct-Connect	3 to 9.5 Modified Direct-Connect
Reynolds No.	1/5 of Flight Re Throughout Range	1/5 Flight Re	1/5 Flight Re	Full Scale	Full Scale	1/3 to 1/6 Scale (One Module)	1/3 to 1/6 Scale (One Module)
Test Article Size	Length = 12.4 ft (3.8 m)	Leg 1 Length = 12.4 ft (3.8 m) Leg 2 Length = 9.3 ft (2.8 m)	Length = 6.8 ft (2.06 m)	Engine Diameter = 90 in. (229 cm)	Engine Diameter = 90 in. (229 cm)	$A_0 = 15$ ft^2 (1.39 m^2) (One Module)	$A_0 = 15$ ft^2 (1.39 m^2) (One Module)
P_0 Range psia (N/cm^2)	17 to 300 (11.7 to 207)	Leg 1 17 to 300 (11.7 to 207) Leg 2 50 to 3200 (34.5 to 2110)	1000 to 18,800 (690 to 12,960)	14.7 to 226 (10.1 to 156)	3 to 200 (2 to 140)	850 to 7000 (586 to 4826)	84 to 3110 (58 to 2144)
T_0 Range	100 to 250^{0}F (38 to 121^{0}C)	Leg 1 100 to 250^{0}F (38 to 121^{0}C) Leg 2 150 to 800^{0}C (66 to 426^{0}C)	1260 to 2500^{0}R (700 to 1389^{0}K)	432 to 3200^{0}R (240 to 1778^{0}K)	432 to 1650^{0}R (240 to 917^{0}K)	3000 to 9500^{0}R (1667 to 5278^{0}K)	1090 to 5100^{0}R (606 to 2833^{0}K)

A_0 = Captured Stream Tube

Configuration Identification	S2 Structural			M20 Materials Technology
	Full Scale	Major Section	Component	
Test Article Size - ft (m)	90 (27.4) High 125 (38.1) Wide 325 (99) Long	39 (11.9) High 70 (21.3) Wide 100 (30.5) Long	20 (6.1) High 20 (6.1) Wide 20 (6.1) Long	Facility contains all necessary equipment to conduct material research, determine material physical and thermal properties, develop manufacturing methods, and to conduct non-destructive evaluation.
Environments Simulated	Mechanical, Thermal Vibration, Acoustic, Altitude, Thermal Acoustic			
Degree of Simulation	All Parameters Simulated to Same Magnitude as Flight Trajectory			
Test Time	Time Variant to Correspond with Flight Trajectory or Static Test Times			

2.1 OBJECTIVES

The objective of Phase II was to continue and refine the facility studies of Phase I. Specific areas of emphasis included: (1) Identification of the necessary research associated with operational hypersonic aircraft, (2) evaluation of methods of accomplishing this research, and (3) analysis of the capability and cost of proposed new ground or flight facilities.

The major Phase II task involved parametric refinement studies of the attractive facilities retained from Phase I. These studies were conducted to determine the performance, research capability, and costs of each facility, as a function of selected parameters, such as Mach number, test time, or size. The specific purpose was to select facilities which were "near-optimum" in the sense of providing maximum research capability per dollar cost. These parametric studies further provided sensitivity information in the neighborhood of the "near-optimum" designs.

2.2 GROUND RULES

General study ground rules applied to all phases of this study are listed below. (Other ground rules which applied to specific segments of the study are presented in the appropriate sections of the report).

(a) All cost estimates are reported in January, 1970 dollars.

(b) The assumed state of the art is commensurate with initiation of facility development during the time period from 1970 to 1975. Wherever feasible, proven technology (or technology expected to be proven by the start date) was utilized. Where such design was not feasible, conservative overdesign practices, requiring minimum improvements in the state of the art, were followed.

(c) Close coordination is assumed between the NASA and the contractors who are building facilities or aircraft, thus minimizing the need for extensive documentation and quality assurance programs.

(d) Aircraft construction is assumed to conform to experimental shop procedures.

(e) The development costs for flight research vehicles include all necessary engine and avionics development costs.

(f) It is assumed that engines need not be developed to the reliability normally required for operational (non-research) use.

(g) The primary flight safety criterion is that no single component malfunction shall cause a catastrophic situation.

(h) Reliable rocket or airbreathing engine performance consistent with that required for JP-fueled, single-engine aircraft is required during take-off and climb to 25,000 ft (7630m).

(i) Where applicable, the vehicle landing characteristics are suitable for unpowered landing by a skilled pilot. Adequate fuel reserves are provided to compensate for uncertainties in engine SFC, for meteorological and operational dispersions in fuel consumption, and for powered emergency operations.

(j) Edwards Air Force Base is considered as the primary operational field for flight research vehicles.

(k) It is assumed that maximum use will be made of existing or planned tracking and communications facilities.

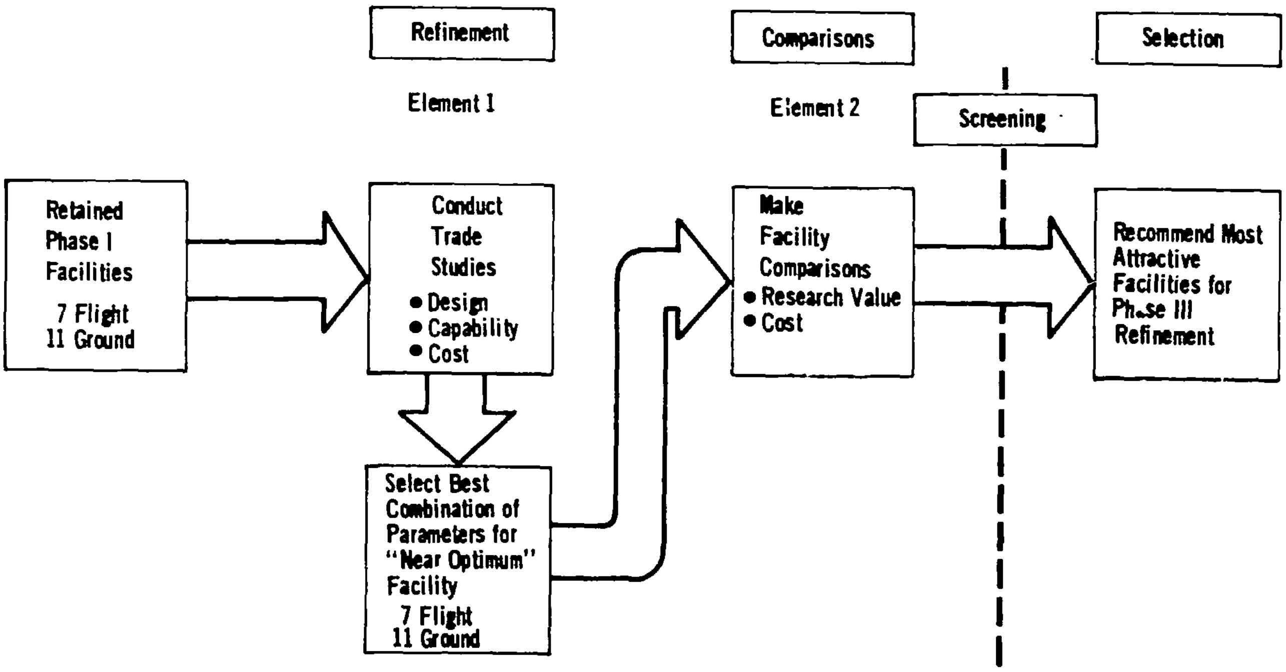
(l) The U.S. Standard Atmosphere - 1962 is used throughout the study.

2.3 APPROACH

The Phase II study approach is illustrated in Figure 2-5. Parametric refinement studies are followed by comparisons, evaluations and screening, with the most attractive facilities being retained for Phase III refinement.

The results of the parametric studies are presented in Section 4 for the flight research vehicles and Section 6 for the ground research facilities. The results of the comparisons and evaluations, along with conclusions and recommended facilities for Phase III refinement, are presented in Section 5 for the flight research vehicles and Section 7 for the ground research facilities.

FIGURE 2-5
PHASE II STUDY PROCESS



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3. HYPERSONIC RESEARCH REQUIREMENTS AND FACILITY RESEARCH VALUES

The fundamental purpose of the research requirements analysis is to establish the intrinsic value of hypersonic research. Toward this end, a comprehensive list of 102 Research Objectives was established in Phase I of this study. A decision theory technique, utilizing inputs from 66 NASA, USAF, and industry technical specialists, was used to establish the relative intrinsic value of these objectives. In Phase II, these Research Objectives were subdivided into 258 distinct Research Tasks to allow more detailed analysis of hypersonic research requirements.

An additional Phase II function was the determination of the capability of the candidate ground facilities and flight vehicles to fulfill the research requirements. The measure of this capability is the facility research value, defined as the relative contribution of the research facility to providing confidence in the technology base. Research values presented in this section relate to study "baseline" facilities. Tradeoff analysis, described in Section 4, resulted in flight vehicle configuration improvements, identified as "near-optimum" systems. Research values for these improved configurations were used to select the best facilities for further refinement during Phase III.

A review of the HYFAC study objectives may be in order at this point. It might be asked what this study can contribute to providing guidance on the hypersonic research facilities which should be procured. Before this question can be answered, however, it must be ascertained what research is required in order to be ready for the future. In this study, research which applies to nine potential operational systems has been defined. The basic criterion used in establishing intrinsic values of the Research Objectives and Research Tasks was that accomplishment of the defined tasks would result in high confidence in a decision to proceed with the development of a particular operational system. This confidence to proceed is believed to be the overwhelming benefit of a disciplined research program. In this day of program terminations due to excessive cost overruns, the cost/risk implications of proceeding directly to an operational system without a well-planned research program should be considered. It is well known that the further technology is extrapolated, the more technological risk is involved in any development program. Studies have shown that development cost escalation is an exponential function of technological risk. Cost overruns often reach 500 percent or more if a program primarily involving innovation is attempted. Technological risks and cost overruns of such magnitude indicate the desirability of building facilities for conducting research prior to the initiation of an acquisition program.

3.1 PHASE II RESEARCH OBJECTIVES

A principal element, and the initial task, in the establishment of research requirements involved identification of valid Research Objectives. The comprehensive list of 102 Research Objectives initially established in Phase I was reduced to a list of 82 objectives, presented in the Hypersonic Research Facilities Phase I Report (Volume II). This reduced list excluded the objectives that involved either (1) design options, particularly optional propulsion systems, or (2) research which overlapped or was redundant with research included within other objectives.

At the beginning of Phase II, the list of Research Objectives was further streamlined by combining a few of the low-valued objectives and eliminating objectives which review revealed to be inappropriate.

The Phase II list of 78 Research Objectives, considered to be the final list for this study, is presented in Figure 3-1. All of the original 102 objectives are included in the list. Those deleted are identified along with the reason for deletion. Applicability of each Research Objective to potential operational systems is also indicated. Principal characteristics of these operational systems are summarized below.

Code	System Type	Mach No.	Propulsion
L_1	Reusable Launch	5 to 7	Turboramjet
L_2	Reusable Launch	8 to 10	Turbojet + Convertible Scramjet
L_3	Reusable Launch	12	Rocket
L_4	Reusable Launch	10	Rocket + Scramjet
C_1	Hypersonic Transport	6	Turboramjet
C_2	Hypersonic Transport	10	Turbojet + Convertible Scramjet
M_1	Advanced Manned Interceptor	4.5	Turboramjet
M_2	Strategic Strike	12	Rocket + Scramjet
M_3	Hypersonic Interceptor	8 to 12	Rocket + Scramjet

Another pertinent element of information concerning Research Objectives is the interrelationship of the objectives. The HYFAC study team identified the major inputs and outputs for each Research Objective and these relationships are presented in Figure 3-2. These inputs and outputs include other objectives, and also factors external to the research requirements analysis, such as inputs from definition of a particular operational vehicle or from flight testing, and outputs impacting directly on design decisions or directly relating to the feasibility of particular design concepts.

FIGURE 3-1
PHASE II RESEARCH OBJECTIVES

	Description	Applicable Operational Systems								
		L_1	L_2	L_3	L_4	C_1	C_2	M_1	M_2	M_3
	CONFIGURATION DEVELOPMENT									
1.	Determine low speed (takeoff and landing) aerodynamic characteristics of hypersonic aircraft.	All								
2.	Determine subsonic and transonic aerodynamic characteristics of hypersonic aircraft.	All								
3.	Determine supersonic and hypersonic aerodynamic characteristics of hypersonic aircraft.	All								
4.	Provide new or update present testing techniques for aerodynamic research facilities so Reynolds number, shock wave, and boundary layer dependent phenomena can be correctly simulated using subscale models.	All								
5.	Define the design criteria and systems requirements for acceptable handling qualities for hypersonic aircraft.	All								
6.	Evaluate design techniques for obtaining favorable aerodynamic interference effects through surface or inlet positioning.	All								
7.	Evaluate design techniques of using the aircraft body for engine exhaust expansion, thereby providing additional lift, and determine the effect of propulsive gas flow interactions, such as rocket exhaust plumes, on the aerodynamic characteristics of hypersonic aircraft.	All								
*8.	Evaluate design techniques to improve low speed, takeoff, and landing characteristics for hypersonic aircraft (i.e., use of variable geometry, auxiliary lift devices, or propulsive lift augmentation) and techniques to reduce transonic drag.	Deleted (overlap) Now a task of objective 1								

* Deleted Objective

FIGURE 3-1 (CONTINUED)
PHASE II RESEARCH OBJECTIVES

	Description	Applicable Operational Systems								
		L_1	L_2	L_3	L_4	C_1	C_2	M_1	M_2	M_3
9.	Investigate the effect on hypersonic aircraft stability and control of variable inlet and nozzle geometry, bypass airflows, propulsion mode changes, and aerothermoelastic effects.	All								
10.	Develop design principles for stage integration which provide reduced drag characteristics and other aerodynamic improvements throughout the speed range for two-stage hypersonic launch vehicles.	✓	✓	✓	✓					
11.	Determine separation techniques for two stage hypersonic vehicles which will provide positive separation and controllability.	✓	✓	✓	✓					
12.	Improve fundamental knowledge of hypersonic boundary layer behavior in the presence of adverse pressure gradients and shock interactions.	All								
* 13.	Investigate unsteady control surface hinge moments due to boundary layer and shock wave interaction.	Deleted (Overlap)				Now a task of objectives 12 & 19				
14.	Develop correlation techniques for the prediction of buffet onset for low aspect ratio configurations, involving longitudinal (body) bending motions as well as wing bending responses.	All								
15.	Evaluate configuration shaping techniques and flight path variation for alleviating sonic boom intensity, and study near and far field noise levels.	All								
16.	Develop correlation methods for the prediction of heat transfer and drag for turbulent boundary layers with pressure gradients and three-dimensional flows for windward flows.	All								

* Deleted objective

FIGURE 3-1 (CONTINUED)
PHASE II RESEARCH OBJECTIVES

	Description	Applicable Operational Systems								
		L_1	L_2	L_3	L_4	C_1	C_2	M_1	M_2	M_3
17.	Determine correlations for the prediction of boundary layer transition.	All								
18.	Investigate the use of strategically located reaction control jets on hypersonic aircraft to reduce the aerodynamic control surface deflection and surface heating.		✓	✓	✓		✓		✓	✓
19.	Determine the effectiveness of various types of control surfaces and their locations for providing sufficient control throughout the entire flight spectrum, and improve methods of predicting aerodynamic heating for deflected control surfaces.	All								
20.	Determine the overall vehicle thermodynamic characteristics in hypersonic flight.	All								
• 21.	Extend the knowledge of aerothermodynamic prediction techniques at hypersonic velocities providing means of relating either analytical or wind tunnel results accurately to real flight conditions.	Deleted (overlap) Now a task of objective 20								
22.	Investigate shaping of aerodynamic surfaces to reduce skin temperatures, and the effects of protuberances and surface irregularities on hypersonic aircraft drag and aerodynamic heating.	All								
23.	Determine the effects of transpirative or ablative processes on skin friction and heat transfer.	✓	✓	✓	✓					
24.	Determine the effects of embedded shock, vortices, separation, and reattachment on skin friction and heat transfer for leeside flows.	All								
25.	Determine the aerodynamic heating effects produced by flow through gaps resulting from adjacent aircraft surfaces, and rapid changes in operational altitude.	All								

• Deleted Objective

FIGURE 3-1 (CONTINUED)
PHASE II RESEARCH OBJECTIVES

	Description	Applicable Operational Systems								
		L_1	L_2	L_3	L_4	C_1	C_2	M_1	M_2	M_3
26.	Determine changes in heat transfer which reduce radiation cooling efficiency due to vehicle geometric interactions (view factors).	All								
27.	Develop methods for predicting heat transfer due to radiation and/or gas impingement from engine exhaust.	All								
	STRUCTURES AND MATERIALS									
28.	Develop efficient reusable thermal protection systems for cryogenic fuels and oxidizer tankage. System considerations should include insulation, vapor barrier, purge techniques, installation and inspection methods, chemical compatibility, temperature cycling, and life time.	✓	✓	✓	✓	✓	✓		✓	✓
*29.	Develop shell theory for non-circular shells with a view to practical fuselage and tank structures to more precisely predict stress levels associated with combined mechanical-thermal loads and their impact on useful life.	Deleted (overlap) Now a task of Objective 30								
30.	Evolve more efficient concepts for fuselage and tank structures for both circular and non-circular applications.	All								
• 31.	Develop heat shield technology for reusable heat shield systems. System considerations should include heat shield flutter, sonic and mechanical fatigue, erosion, and chemical reactions with air stream and attaching structure.	Deleted (overlap) Now a task of Objectives 28 & 43								
32.	Develop efficient reusable leading edge concepts and identify promising concepts for specific materials in relation to the flight regime.	All								

* Deleted Objective

FIGURE 3-1 (CONTINUED)
PHASE II RESEARCH OBJECTIVES

	Description	Applicable Operational Systems								
		L_1	L_2	L_3	L_4	C_1	C_2	M_1	M_2	M_3
33.	Develop control surface technology, including thermal protection requirements, methods of attachment, sealing, methods of actuation, and thermal cycling.	All								
34.	Develop long life regeneratively cooled structural concepts for application in high heat flux areas such as leading edges and propulsion systems.	All								
35.	Provide a structure which maintains aerodynamic smoothness under actual operational conditions and use.	All								
36.	Define the effects of combined mechanical loading and thermal stress cycling under actual environmental conditions on the life of the structural components.	All								
• 37.	Determine the effects of separation forces on the structural dynamic characteristics of the vehicles.	Deleted (overlap)				Now a task of Objectives 11 & 85				
38.	Determine the effects of fuel slosh on the dynamics and inertia loads of low aspect ratio hypersonic aircraft with large volume fuel tankage.	✓	✓	✓	✓	✓	✓		✓	✓
39.	Determine the parameters of correlation for the analysis of the effects of near field noise on minimum gauge structures, composite structures, and non-metallics.	All								
40.	Develop non-destructive test and inspection methods for sandwich structure, composite materials, diffusion bonded materials, and coatings.	All								
41.	Develop a capability to accurately estimate component and structural mass fractions for all types of hypersonic aircraft designs.	All								
42.	Verify the integrity of the structural and thermal-structural systems through full-scale component testing.	All								

* Deleted Objective

FIGURE 3-1 (CONTINUED)
PHASE II RESEARCH OBJECTIVES

	Description	Applicable Operational Systems								
		L_1	L_2	L_3	L_4	C_1	C_2	M_1	M_2	M_3
43.	Develop reusable thermal protection systems for the primary structure.	All								
44.	Define the mechanical and physical properties of advanced materials that have potential application in hypersonic aircraft. Prime candidates are: metal matrix composites, high temperature titaniums, superalloys, and refractories.	All								
45.	Improve fabrication techniques for advanced materials and complex structures. These include: welding, diffusion bonding, and brazing of metals; composite forming; fabrication of sandwich structure; and fabrication of non-metallics.	All								
46.	Develop high temperature bearings, lubricants, closure seals, tires, windshields, and radomes.	All								
*47.	Develop protective coatings for metals and non-metals to provide resistance to corrosion, erosion, oxidation and wear and to enhance emittance and radar absorption, for long term exposures to the hypersonic environment.	Deleted (overlap) Now a task of Objectives 28 & 43								
	PROPULSION									
48.	Develop inlet configurations of either fixed- or variable-geometry that yield high total pressure recovery, low weight and drag, good stability, and minimum distortion over the range of desired flight conditions and engine operating modes, and enable the engine to achieve the desired specific impulse and thrust, through improved techniques for predicting cowl, spill, additive, bleed and bypass drag characteristics and improved inlet off-design performance.	✓	✓		✓	✓	✓	✓	✓	✓

* Deleted Objective

FIGURE 3-1 (CONTINUED)
PHASE II RESEARCH OBJECTIVES

	Description	Applicable Operational Systems								
		L_1	L_2	L_3	L_4	C_1	C_2	M_1	M_2	M_3
• 49.	Evaluate effects of inlet installation within the vehicle pressure field on inlet performance and on inlet drag. The effect of boundary layer ingestion on inlet performance must be determined and techniques to control and remove boundary layer must be developed.	Deleted (overlap) Now a task of Objective 48								
•50.	Evaluate variable capture area inlet designs required for operation across the range of desired flight conditions of speed and attitude (angle of attack).	Deleted (overlap) Now a task of Objective 48								
•51.	Evaluate real gas effects on inlet and nozzle performance.	Deleted (overlap)				Now a task of Objective 48 & 65				
52.	Develop engine design concepts amenable to cooling by various techniques (regeneration, ablation, radiation, transpiration).	✓	✓		✓	✓	✓	✓	✓	✓
• 53	Develop engine component technology (burners, turbines, heat exchangers, controls) suitable for cryogenic fuels.	Deleted (overlap)				Now a task of Objectives 57, 59, 60 & 61				
•54.	Develop advanced engine components having light weight with perhaps shortened lifetime.	Deleted (overlap)				Now a task of Objectives 57, 59, 60 & 61				
55.	Investigate methods for reducing engine noise during takeoff and landing.					✓	✓			
•56.	Study combustion problems of ramjets when operated for thrust augmentation at transonic or low supersonic flight speeds.	Deleted (overlap)				Now a task of Objectives 57 & 59				
57.	Develop and integrate engine components into a complete large-scale turboramjet system. Demonstrate compatibility and overall performance throughout an applicable flight envelope.	✓				✓		✓		

• Deleted Objective

FIGURE 3-1 (CONTINUED)
PHASE II RESEARCH OBJECTIVES

Description	Applicable Operational Systems								
	L_1	L_2	L_3	L_4	C_1	C_2	M_1	M_2	M_3
58. Perform sufficient cycle analysis, component testing, and mission analysis to select the best multi-mode cycle and size engine for application to a specific hypersonic mission aircraft.	All								
59. Develop and integrate engine components into a complete large-scale ramjet system. Demonstrate compatibility and overall performance throughout an applicable flight envelope.	✓				✓		✓		
60. Develop and integrate engine components into a complete subscale convertible scramjet module. Demonstrate compatibility and overall performance throughout an applicable flight envelope.		✓				✓			
61. Develop and integrate engine components into a complete subscale scramjet module. Demonstrate compatibility and overall performance throughout an applicable flight envelope.				✓				✓	✓
62. Demonstrate rocket-powered engine operation in a horizontal takeoff aircraft.			✓	✓				✓	✓
63. Develop inlet controls for hypersonic aircraft which are simple, reliable, accurate, and have rapid response.	✓	✓		✓	✓	✓	✓	✓	✓
64. Evaluate suitability of auxiliary turbojets for landing of hypersonic vehicles.			✓	✓				✓	✓
65. Determine nozzle configurations to produce high net thrust while maintaining efficient integration with the airframe.	✓	✓		✓	✓	✓	✓	✓	✓

FIGURE 3-1 (CONTINUED)
PHASE II RESEARCH OBJECTIVES

	Description	Applicable Operational Systems								
		L_1	L_2	L_3	L_4	C_1	C_2	M_1	M_2	M_3
* 66.	Evaluate variable nozzle geometry requirements for operation across a wide speed range, and mechanical concepts to produce it.	Deleted (overlap)				Now a task of Objective 65				
67.	Determine inlet/engine compatibility criteria (both steady-state and time-varying) of high-total-pressure-recovery, wide Mach range inlets.	✓	✓		✓	✓	✓	✓	✓	✓
	SUBSYSTEMS									
68.	Develop operational systems and procedures for the thermal conditioning, storage, and safe handling of cryogenic propellants which are compatible with typical airfield requirements.	✓	✓	✓	✓	✓	✓		✓	✓
69.	Develop analytical correlation techniques through empirical evaluation to permit the determination of the fluid dynamic and thermodynamic characteristics of cryogenic propellants in large horizontal tankage in a vibrating, sloshing, pressurized environment.	✓	✓	✓	✓	✓	✓		✓	✓
70.	Develop regenerative cryogenic heat exchangers, thermodynamic correlations, and control systems for structural and engine cooling which are compatible with representative vehicle heat loads and material temperature limits.	✓	✓		✓	✓	✓		✓	✓
71.	Improve fuel performance of new or existing hydrocarbon fuels through increase in (1) thermal stability and/or utilization of vaporizing and endothermic fuels, (2) fuel density and energy content.	✓	✓			✓	✓	✓		

* Deleted Objective

FIGURE 3-1 (CONTINUED)
PHASE II RESEARCH OBJECTIVES

	Description	Applicable Operational Systems								
		L_1	L_2	L_3	L_4	C_1	C_2	M_1	M_2	M_3
72.	Determine fuel system design requirements imposed by the use of thermally stable and endothermic fuels in high temperature aircraft environment, including such areas as contamination limits, inert pressurization, and ground support systems.	✓	✓			✓	✓	✓		
73.	Advance the technology of cryogenic fuel system components in the areas of reduced weight and increased reliability. Particular areas requiring advancement include liquid hydrogen static and dynamic sealing and rotating machinery operating in cryogenic environment.	✓	✓	✓	✓	✓	✓		✓	✓
74.	Determine rapid cryogenic servicing techniques necessary to achieve required reaction and turnaround times for military and commercial vehicles.					✓	✓		✓	✓
75.	Develop viable aircraft fuel tankage concepts (integral and non-integral tanks, sub-cooled and saturated fuel), and develop cryogenically fueled integrated aircraft fuel system operation and control techniques to account for propellant utilization, management, and pressurization requirements during both ground and flight environments.	✓	✓	✓	✓	✓	✓		✓	✓
* 76.	Determine capability of flush recessed antennas required for hypersonic flight to supply patterns compatible with communication, navigation, and electronic warfare functions.	Deleted (overlap)				Now a task of Objective 77				
77.	Determine flush or recessed antenna design techniques necessary to allow operation in the elevated hypersonic temperature environment.	All								
78.	Investigate stability augmentation systems capable of control in the hypersonic region, and recovery from pilot-induced oscillations.	All								

* Deleted Objective

FIGURE 3-1 (CONTINUED)
PHASE II RESEARCH OBJECTIVES

	Description	Applicable Operational Systems								
		L_1	L_2	L_3	L_4	C_1	C_2	M_1	M_2	M_3
79.	Determine air data measurement techniques applicable to the hypersonic environment such as fixed orifice pressure measurements and laser densitometers.	All								
80.	Develop actuation techniques and hardware to provide control surface motion over the range of environment encountered in the hypersonic flight regime. This includes development of high temperature hydraulic and pneumatic drive systems and components.	All								
• 81.	Develop high temperature actuator systems for engine inlet and nozzle adjustment.	Deleted (overlap)				Now a task of Objectives 57, 59, 60, 61 & 63				
82.	Develop auxiliary power units for rocket, scram, and ramjet powered aircraft including necessary emergency power equipment in case of primary unit failure.	All								
83.	Develop environmental control system utilizing liquid cryogens as the heat sink, based on allowable internal wall temperatures for crew and passenger comfort and effectiveness.	✓	✓	✓	✓	✓	✓		✓	✓
84.	Develop environmental control systems for Mach 4 to 6 hydrocarbon fueled vehicles, based on allowable internal wall temperatures for crew and passenger comfort and effectiveness.							✓		
85.	Develop launch techniques for AAM and ASM weapons in hypersonic flight.							✓	✓	✓
*86.	Investigate methods of heat shielding missile launchers, doors, and internal structure in hypersonic environment.	Deleted (overlap)				Now a task of Objective 85				

* Deleted Objective

FIGURE 3-1 (CONTINUED)
PHASE II RESEARCH OBJECTIVES

	Description	Applicable Operational Systems								
		L_1	L_2	L_3	L_4	C_1	C_2	M_1	M_2	M_3
	OPERATION									
87.	Evaluate various methods of terminal approach, landing, ground operations, and takeoff aircraft, and determine the design penalty associated with operational requirements.	All								
88.	Study hazards inherent in the use of cryogenic fuels, on ground and in flight, during both normal and abnormal operation.	Deleted (overlap)				Now a task of Objective 94				
89.	Investigate man-machine compatibility as related to the control and navigation of a hypersonic vehicle at both high and low Mach numbers.	All								
*90.	Establish optimum landing techniques for a hypersonic vehicle.	Deleted (overlap)				Now a task of Objective 87				
*91.	Develop effective communication techniques for safe flight planning.	Deleted (Low Value)								
*92.	Investigate various ascent trajectories to assess the tolerable axial and normal "g" loads.	Deleted (Low Value)								
93.	Investigate effects of vehicle dynamics on crew performance capability and passenger comfort in hypersonic flight.	All								
94.	Develop abort and crew escape systems and procedures for hypersonic aircraft.	All								
* 95	Determine the effects of bank angle, yaw, angle of attack, flow field benefit, turbulence, and variations in atmospheric conditions on boost, cruise, and descent performance for hypersonic aircraft.	Deleted (overlap) Now a task of Objectives 1, 2, & 3								

* Deleted Objective

FIGURE 3-1 (CONTINUED)
PHASE II RESEARCH OBJECTIVES

	Description	Applicable Operational Systems								
		L_1	L_2	L_3	L_4	C_1	C_2	M_1	M_2	M_3
96.	Define and demonstrate the capability to stay within specified operational margins to not exceed aircraft placards (i.e., duct pressure, temperature, stability, dynamic pressure, and load factor limits).	All								
97.	Develop leak detection methods for cryogenic propellant tanks.	All								
* 98.	Investigate concepts for providing an atmosphere of motion and security for passengers in a windowless aircraft.	Deleted (Low Value)								
99.	Investigate short takeoff techniques using forced rotation, including gimballed rocket and canard techniques.			✓	✓				✓	✓
100.	Develop practical ground hold methods for cryogenic systems leading to quick response times and high operational readiness.								✓	✓
101.	Develop specifications for adequate Air Traffic Control procedures and ground based navigation systems.	Deleted (Low Value)								
102.	Develop inspection and repair techniques for hypersonic vehicle structures.	All								

Deleted Objective

(U) FIGURE 3-2
INTERRELATIONSHIP OF RESEARCH OBJECTIVES

Relationships Other Than Research Objectives:
VD = Input from Definition of Vehicle Geom., Prop., Type, Mission, etc.
D = Output Influences Design Decision
F = Output Directly Impacts Feasibility of Concept or Entire Vehicle
FT = Requires Data from Flight Test

Needs Inputs from R.O.#	Research Objective		Feeds Output to R.O. #
2,3,4	1	Low Speed Aero. Char. T/O & Landing	D,F,5,14,65,65,78,80,87,96, 99
3,4	2	Subsonic/Transonic Aero. Characteristics	1,5,14,65,78,80,96
VD,4,6,7,9,10,11,12,16,17 18,19,22	3	Hypersonic Aerodynamic Characteristics	D,1,2,5,14,15,20,30,48,65 78,80,89,96
	4	Dev. New Test Technology for Re, B.L. Research	1,2,3,4,12,17,20,24
1,2,3,18,19,69,93	5	Design Criteria & System Req. for Acceptable Handling	D,78,80,87,89,96,99
	6	Aero. Interference, Inlets/Surface	3,20,26,48
	7	Propulsion Lift	3,20,48,99
48	9	Inlet/Nozzle Effects on Aero.	3,14,48,65
	10	Design Prin. for Stage Integration	3,11
10	11	Separation Techniques	3,20,78
4	12	Hypersonic B.L. Behavior	3,18,19,20,22,27,35,39,48
FT,1,2,3,9	14	Corr. Tech. - Buffet Onset	D,78,96
FT,3	15	Sonic Boom & Noise	D,F,39,87,96
FT,4,22	16	Corr. for H/T & Fric. Drag Turbulent B.L.	D,3,20

FIGURE 3-2 (CONTINUED)
INTERRELATIONSHIP OF RESEARCH OBJECTIVES

Needs Inputs from R.O.#	Research Objective	Feeds Output to R.O.#
4,22	17 Corr. Prediction of Hyp. B.L. Transition	D,3,20,35,39,48
12,19	18 Use of Reaction Cont. Jets	3,5,20,33,78
12	19 Control Surface Effects & Location	3,5,18,20,25,33,78,80,99
3,4,6,7,11,12,16,17,18, 19, 22,23,24,25,26,27	20 Overall Thermal Char. in Hypersonic Flight	D,23,28,30,32,33,34,35,42, 43,44,46,69,70,75,77,83,84, 85,96
12	22 Shading to Reduce Skin Temp., Roughness Effects on Drag and Heating	3,16,17,20,23,30,35,48
20,22	23 Eff. of Transpirative or Ablative Processes on Skin Frict. & H/T	D,20,23,52
4	24 Shock, Vortices, Separation, Reattach on Lee Side Frict. & H/T	D,20
19,23	25 Aero. Heating by Flow Thru Gaps	D,20,33
5,6	26 Eff. of Geom. Inter. on H/T	D,20,27,32,34,59,60,61
12,26	27 Meth. Pred. H/T due to Radiation Gas Impingement	D,20,48,65
20,44,45	28 Dev. Reusable Tankage Thermal Prot. Sys. (Cryogenic Fuels)	D,F,41,42,69,75,97
3,20,22,40,43,44,45	30 Concepts for Fus. & Tank Struc.	D,41,42,43,75,
20,26,39,40,44.45	32 Reusable L.E. Technology	D,34,35,41,42,96

FIGURE 3-2 (CONTINUED)
INTERRELATIONSHIP OF RESEARCH OBJECTIVES

Needs Inputs from R.O.#	Research Objective	Feeds Output to R.O.#
18,19,20,25,39,40,43,44,45,80	33 Control Surface Technology	D,35,41,42,96
4,20,26,32,39,40,44,45,70	34 Regen. Cooled L.E., etc.	D,41,42,52,59,60,61,96
12,17,20,22,32,33,40,43,44,45	35 Structure which provides Smooth Surface	D,42
28,30,32,33,34,40,44,45	36 Eff. of Combined Mech. Loading, Thermal Stress, Temp. Var. on Structure Life	D,42,96
69	38 Det. Effects of Slosh	D,42,96
Eng. Test, 12,15,17	39 Corr. of Eff. of Near Field Noise on Structures	32,33,34,43
45	40 Non-Dest. Test & Insp. Methods	30,32,33,34,35,36,70,102
28,30,32,33,34	41 Structural Mass Fraction Estimation	D
20,28,30,32,33,34,35,36,38,43,45,69	42 Component Testing	D,F
VD,20,30,39	43 Reusable Thermal Prot. for Prim. Struc.	30,35,42,83,84,85,96
20	44 Mechanical & Physical Prop. of Advanced Materials	28-36,45,46,70
44	45 Fabrication Techniques for Advanced Mat'l & Structures	28-36,40,42,46,70
20,44,45,77	46 Develop Hi Temp Bearings, Lubs, Seals, Tires, Windshields, Radomes	D,F,33,63,77,80,96
VD,3,6,7,9,12,17,22,27	48 Develop Inlet Config.	9,57,59,60,61,63,67,96

FIGURE 3-2 (CONTINUED)
INTERRELATIONSHIP OF RESEARCH OBJECTIVES

Needs Inputs from R.O.#	Research Objective	Feeds Output to R.O.#
23,34,70	52 Engine Cooling Concepts	57,59,60,61
59,60,61,64	55 Reduce Engine Noise T/O & Land	57,62,87
48,52,55,63,65,67,71,72	57 Dev. Integ. Components Turboram Sys.	D,F,58,67,84
VD,57,59,60,61,72,75	58 Cycle & Mission Anal. Multi-Mode Cycle	D,F
26,34,48,52,63,65,67,70, 73,75	59 Dev. & Integ. Ramjet Systems	D,F,55,58,67,70
26,34,48,52,63,65,67,70, 73,75	60 Dev. & Integ. Sub-scale CSJ Mod.	D,F,55,58,67,70
26,34,48,52,63,65,67,70, 73,75	61 Dev. & Integ. Sub-scale SJ Mod.	D,F,55,58,67,70
FT,55	62 Demonstrate Rocket Horizontal T/O Aircraft	F,96,99
46,48,67	63 Dev. Inlet Controls	D,F,57,59,60,61,89,96
1	64 Auxiliary Turbojets	D,F,55,87
1,2,3,9,27	65 Nozzle Configuration/ Airframe Integration	D,57,59,60,61
48,57,59,60,61	67 Determine Inlet/Engine Compatability Criteria	D,F,57,60,61,63
	68 Subcooling & Logistics	F,87
20,28	69 Slosh, Tankage Fluid Thermo-dynamics	5,38,42,75
20,40,44,45,59,60,61	70 Regen. H/E, Control Sys.	34,52,59,60,61,75
	71 Hydrocarbon Fuel Improvements	57,72

FIGURE 3-2 (CONTINUED)
INTERRELATIONSHIP OF RESEARCH OBJECTIVES

Needs Inputs from R.O.#	Research Objective	Needs Output to R.O.#
71	72 Hydrocarbon Fuel Systems	57,58
	73 Cryo Fuel Sys. Components	59,60,61,75,83
VD	74 Rapid Servicing Cryo Vehicles	75,87,100
20,28,30,69,70,73,74	75 Dev. Cryo Tanks & Systems	58,59,60,61,97
VD,20,46	77 Antenna Design Tech.	D,46
1,2,3,5,11,14,18,19,79, 82,89	78 Stability Augment. & PIO	D,80,87,96
VD	79 Air Data Measurement	D,78,96
1,2,3,5,19,46,78	80 Control Surface Actuation	D,33,96
VD	82 APU [RKT, SJ, RJ]	D,87
VD,20,43,73	83 Cyrogenic ECS	D,F
VD,20,43,57	84 Hydrocarbon ECS	D
VD,20,43	85 Weapon Launch Methods	D,F
1,5,15,55,64,68,74,78,82, 94,99,100	87 Approach, Land, Ground Hand. Meth.	F,78,96
VD,3,5,63	89 Man-Machine Compatibility Control & Nav.	D,78,96
VD	93 Vehicle Dyn.-Crew Perf. Pass. Comfort	5,96
VD,FT	94 Abort, Escape Sys. & Procedures	F,87
1,2,3,5,14,15,20,32,33,34, 36,38,43,46,48,62,63,78, 79,80,87,89	96 Det. Capability to Stay Within Oper. Margins	D,F

FIGURE 3-2 (CONTINUED) INTERRELATIONSHIP OF RESEARCH OBJECTIVES

Needs Inputs from R.O.#	Research Objective	Feeds output to R.O.#
28,75	97 Leak Detection Meth. (Cryo)	D
FT,1,5,7,19,62	99 Short T/O Tech-Forced Rotation Using Rkts., Canard	D,87
74	100 Ground Hold Methods	D,87
40	102 Inspect & Repair Tech.	D

3.2 RESEARCH OBJECTIVE INTRINSIC VALUES

The intrinsic values of the Research Objectives, defined as the relative fundamental value of each objective as it relates to a potential operational system, are presented in Figures 3-3 through 3-11. The value of each objective varies from one operational system to another, because a different combination of objectives corresponds to each system. The decision theory process used to determine the intrinsic values, utilizing inputs from 66 NASA, USAF, and industry specialists, was described in the Phase I report (Volume II). Revision of the list of Research Objectives at the beginning of Phase II resulted in slight changes in most of the values. The values were updated by re-processing the basic inputs from the 66 specialists to account for the revised combination of objectives applicable to each operational system. The intrinsic values presented in the following nine figures are considered to be the final values for the study.

One must be careful to avoid placing undue significance on the actual values determined for each of these objectives. The purpose of this evaluation is to determine a placement of the entire set of objectives applying to a particular potential operational system along a predetermined scale of values. The intrinsic value of an objective so determined only has meaning when considered in relation to those of the other objectives in the list. The intent of the process was to identify research areas [illegible] which there are significant differences in importance. Such areas are indicated by large numeric variances in research value.

3.3 IDENTIFICATION OF RESEARCH TASKS

The principal Phase II task under the heading of Research Requirements was definition of the pertinent Research Tasks under each Research Objective. These tasks are intended to define the specific research effort required to fulfill the objective. Primary ground rules for the delineation of Research Tasks included:

(a) The sum of the tasks under Research Objective essentially comprises all research effort defined by that objective.

(b) Each Research Task is intended to be comparable in technical scope (within objectives as well as across the board for all objectives), representing a judgement of the level of research required to satisfy the particular Research Objective. This goal for uniformity in the content of the various tasks was achieved only in a fairly rough sense.

The Research Tasks were defined by MCAIR technology specialists in aerodynamics, thermodynamics, structures and materials, propulsion, subsystems, and operations. All tasks were coordinated by study supervision to assure consistency of expression and, hopefully, clarity of intent. The 258 Research Tasks are presented in Figure 3-12 in [illegible] which directly establishes their relevance to the 78 Research Objecti[illegible]

[illegible] were delineated with the nine potential operational systems in m[illegible] be noted that this does not preclude application of most [illegible] many other systems, such as space transportation syst[illegible] systems, and various missile systems.

FIGURE 3-3
RESEARCH OBJECTIVE INTRINSIC VALUE

OPERATIONAL SYSTEM NO. 1 - (L1)

WEIGHTED AVERAGE FOR ALL EVALUATION CRITERIA

TECHNOLOGICAL AREA	REL. WT.	NO. EVALUATORS
A. AERODYNAMICS	.184	23
B. THERMODYNAMICS	.165	19
C. STRUCTURES & MATERIAL	.193	22
D. PROPULSION	.209	32
E. SUBSYSTEMS	.126	18
F. OPERATION	.123	22

EVALUATION CRITERION	REL. WT.
A. TECHNOLOGY ADVANCEMENT	.607
B. COST & SCHEDULE	.393

RANK	CODE	OBJECTIVE	INTRINSIC VALUE
1	28	REUS THML PROT STMS - CRYO FUELS/OXIDR TNKG	73.5
2	43	REUSABLE THML PROTECT STMS - PRIMARY STRUCTURE	72.6
3	34	LONG-LIFE REGEN-COOLED STRUCTURAL CONCEPTS	70.9
4	3	SUPERSONIC & HYPERSONIC AERO CHARACTERISTICS	70.5
5	57	TURBORAMJET SYSTEMS - DEVELOP & DEMONSTRATE	68.9
6	59	RAMJET SYSTEMS - DEVELOP & DEMONSTRATE	67.4
7	48	INLET CONFIGURATIONS WITH DESIRABLE CHARS	66.0
8	67	INLET/ENGINE COMPATIBILITY CRITERIA	65.4
9	4	TEST TECHNS FOR RE NO, SHOCK WAVE & BNDY LR PHEN	65.0
10	44	MECH/PHYS PROPERTIES OF ADVANCED MATERIALS	64.8
11	58	BEST MULTIMODE CYCLE & ENGINE SIZE	64.4
12	45	FAB TECHNS - ADV MATERIALS/COMPLEX STRUCTURES	64.0
13	42	FULL SCALE COMP TEST OF STRCT/THMSTRCT SYSTEMS	62.5
14	33	CONTROL SURFACE TECHNOLOGY	61.6
15	36	EFF OF COMB-MECH LONG, THML STRS CYC, TEMP VAR	61.5
16	9	PARAMATERS AFFECTING STABILITY & CONTROL	60.9
17	12	HYPERSONIC BOUNDARY LAYER BEHAVIOR	59.9
18	40	TEST & INSP METHODS FOR ADVANCED STRUCTURES	59.0
19	65	NOZZLE CONFIGURATIONS	58.7
20	37	REUSABLE LEADING EDGE CONCEPTS	58.4
21	52	ENGINE DESIGN CNCPTS FOR VARIOUS COOLING TECHNS	58.3
22	30	FUSELAGE/TANK STRUCTS - MORE EFFICIENT CONCEPTS	57.8
23	7	ENG EXST EXP FOR ADD LIFT/PROP GAS FLO INT EFCTS	57.5
24	19	CNTL SURFACE EFFECT/HEAT EFFECTS WHEN DEFLECTED	56.9
25	16	HEAT TRANS & DRAG FOR TURBULENT BOUNDARY LAYERS	56.6
26	2	SUBSONIC & TRANSONIC AERO CHARACTERISTICS	56.6
27	5	OPTIMUM & ACCEPTABLE HANDLING QUALITIES	56.6
28	24	EMBEDDED SHOCK, VORTEX, SEPAR & REATCH EFFECTS	56.5
29	1	LOW SPEED (T/O & LANDING) AERO CHARACTERISTICS	56.0
30	26	HEAT EFFECTS - FLOW FIELD/VEH GEOM INTERACTIONS	55.3
31	20	HYPERSONIC AEROTHERMO PARAMS IN 3-DIM FLOW	54.8
32	6	SURFACE/INLET POSITION - FAVOR AERO INTERFERENCE	54.7
33	46	HIGH TEMPERATURE EQUIPMENT	53.4
34	22	SURFACE SHAPING & PROTUB EFFECTS ON DRAG & HEAT	52.6
35	11	SEPARATION TECHNS FOR POSITIVE SEPAR & CONTROL	52.6
36	63	EFFECTIVE INLET CONTROLS	52.5
37	17	PREDICT TECHNS FOR BNDY LAYER TRANSITION	51.9
38	41	ESTIM OF COMPONENT/STRUCTURAL MASS FRACTIONS	51.4
39	10	STAGE INTEGRATION FOR AERO IMPROVEMENTS	47.9
40	70	REGEN CRYO HEAT EXCHRS/THRMO CURLS/COOL CNT STMS	46.1
41	25	HEATING EFFECTS FROM FLOW THRU GAPS	45.9
42	[illegible]	FUEL TANK CONCEPTS/FUEL SYS OPER & CNTL TECHNS	45.8
43	[illegible]	MAN-MACHINE COMPATIBILITY - CONTROL/NAVIGATION	42.7
44	27	PREDICT TECHNS FOR HEAT TRANSFER - ENG EXHAUST	41.9
45	73	CRYO SYSTEM COMPONENTS - RCD WT/INCR RELIABILITY	41.9
46	39	NEAR FIELD NOISE EFFECTS	41.3
47	80	ACTUATION TECHNS & HDWR FOR CNTL SURFACE MOTION	41.0
48	15	TECHNS FOR ALLEVIATING SONIC BOOM INTENSITY	40.4
49	68	THML C D, STORAGE & SAFE HNDLG OF CRYO FUELS	[illegible]
50	78	STABILITY AUGMENT SYSTEMS/RECOVERY FROM PIO'S	39.5
51	23	TRANSPI./ABLAT EFCTS - SKIN FRICT/HEAT TRANSFER	39.5
52	94	ABORT, FUEL DUMP, ESCAPE & EMERG EGRESS TECHNS	39.4
53	14	PREDICT TECHNS FOR BUFFET ONSET OF LOW AR A/C	39.2
54	83	ENVIRON CNTL SYSTEM - LIQUID CRYO AS HEAT SINK	38.7
55	[illegible]	TERMINAL APPROACH & LANDING METHODS	37.9
56	102	INSPECTION & REPAIR TECHNS FOR HYPER VEH STRCTS	37.5
57	38	FUEL SLOSH EFFECTS ON DYNAMICS/INERTIA LOADS	37.4
58	69	FLUID DYN/THERMODYN CHARS OF CRYO FUELS	36.9
59	72	FUEL SYSTEM DESIGN REQUIREMENTS	36.6
60	35	STRUCTURE MAINTAINING AERODYNAMIC SMOOTHNESS	36.5
61	97	LEAK DETECTION METHODS FOR CRYO FUEL TANKS	36.4
62	96	CAPABILITY TO STAY WITHIN SPECIF OPER MARGINS	35.1
63	71	IMPROVEMENT OF HYDROCARBON FUEL PERFORMANCE	33.4
64	02	AUXILIARY POWER UNITS	32.8
65	79	AIR DATA MEASUREMENT TECHNIQUES	29.9
66	93	EFCTS OF VEH DYN/CENTRIF EFCTS ON CREW/PSSNGRS	29.3
67	77	FLUSH OR RECESSED ANTENNA DESIGN TECHNIQUES	28.5

FIGURE 3-4
RESEARCH OBJECTIVE INTRINSIC VALUE

OPERATIONAL SYSTEM NO. 2 - (L2)

WEIGHTED AVERAGE FOR ALL EVALUATION CRITERIA

TECHNOLOGICAL AREA	REL. WT.	NO. EVALUATORS
A. AERODYNAMICS	.184	23
B. THERMODYNAMICS	.165	19
C. STRUCTURES & MATERIAL	.193	22
D. PROPULSION	.209	32
E. SUBSYSTEMS	.126	18
F. OPERATION	.123	22

EVALUATION CRITERION	REL. WT.
A. TECHNOLOGY ADVANCEMENT	.607
B. COST & SCHEDULE	.393

RANK	CODE	OBJECTIVE	INTRINSIC VALUE
1	28	REUS THML PROT STMS - CRYO FUELS/OXIDR TNKG	73.5
2	43	REUSABLE THML PROTECT STMS - PRIMARY STRUCTURE	72.6
3	60	CONVERTIBLE SCRAMJET SYSTEMS - DEVELOP & DEMON	72.4
4	3	SUPERSONIC & HYPERSONIC AERO CHARACTERISTICS	70.9
5	34	LONG-LIFE REGEN-COOLED STRUCTURAL CONCEPTS	70.4
6	48	INLET CONFIGURATIONS WITH DESIRABLE CHARS	66.6
7	4	TEST TECHNS FOR RE NO, SHOCK WAVE & BNDY LR PHEN	66.1
8	67	INLET/ENGINE COMPATIBILITY CRITERIA	65.6
9	58	BEST MULTIMODE CYCLE & ENGINE SIZE	65.1
10	44	MECH/PHYS PROPERTIES OF ADVANCED MATERIALS	64.8
11	45	FAB TECHNS - ADV MATERIALS/COMPLEX STRUCTURES	64.0
12	42	FULL SCALE COMP TEST OF STRCT/THMSTRCT SYSTEMS	62.5
13	9	PARAMATERS AFFECTING STABILITY & CONTROL	62.0
14	33	CONTROL SURFACE TECHNOLOGY	61.6
15	36	EFF OF COMB MECH LONG, THML STRS CYC, TEMP VAR	61.5
16	12	HYPERSONIC BOUNDARY LAYER BEHAVIOR	61.4
17	[illegible]	TEST & INSP METHODS FOR ADVANCED STRUCTURES	59.0
18	[illegible]	ENG EXST EXP FOR ADD LIFT/PROP GAS FLO INT EFCTS	58.9
19	52	ENGINE DESIGN CNCPTS FOR VARIOUS COOLING TECHNS	58.8
20	19	CNTL SURFACE EFFECT/HEAT EFFECTS WHEN DEFLECTED	58.4
21	32	REUSABLE LEADING EDGE CONCEPTS	58.4
22	65	NOZZLE CONFIGURATIONS	58.1
23	5	OPTIMUM & ACCEPTABLE HANDLING QUALITIES	58.1
24	1	LOW SPEED (T/O & LANDING) AERO CHARACTERISTICS	58.1
25	2	SUBSONIC & TRANSONIC AERO CHARACTERISTICS	58.0
26	16	HEAT TRANS & DRAG FOR TURBULENT BOUNDARY LAYERS	57.8
27	30	FUSELAGE/TANK STRUCTS - MORE EFFICIENT CONCEPTS	57.8
28	24	EMBEDDED SHOCK, VORTEX, SEPAR & REATCH EFFECTS	56.5
29	6	SURFACE/INLET POSITION - FAVOR AERO INTERFERENCE	56.2
30	26	HEAT EFFECTS - FLOW FIELD/VEH GEOM INTERACTIONS	55.3
31	20	HYPERSONIC AEROTHERMO PARAMS IN 3-DIM FLOW	54.8
32	11	SEPARATION TECHNS FOR POSITIVE SEPAR & CONTROL	53.5
33	46	HIGH TEMPERATURE EQUIPMENT	53.4
34	17	PREDICT TECHNS FOR BNDY LAYER TRANSITION	53.2
35	22	SURFACE SHAPING & [illegible] EFFECTS ON DRAG & HEAT	52.6
36	63	EFFECTIVE INLET CONTROLS	52.3
37	41	ESTIM OF COMPONENT/STRUCTURAL MASS FRACTIONS	51.4
38	10	STAGE INTEGRATION FOR AERO IMPROVEMENTS	48.9
39	70	REGEN CRYO HEAT EXCHRS/THRMO CORLS/COOL CNT STMS	46.1
40	25	HEATING EFFECTS FROM FLOW THRU GAPS	45.9
41	75	FUEL TANK CONCEPTS/FUEL SYS OPER & CNTL TECHNS	45.8
42	89	MAN-MACHINE COMPATIBILITY - CONTROL/NAVIGATION	42.7
43	27	PREDICT TECHNS FOR HEAT TRANSFER - ENG EXHAUST	41.9
44	73	CRYO SYSTEM COMPONENTS - RED WT/INCR RELIABILITY	41.9
45	15	TECHNS FOR ALLEVIATING SONIC BOOM INTENSITY	41.6
46	39	NEAR FIELD NOISE EFFECTS	41.3
47	80	ACTUATION TECHNS & HDWR FOR CNTL SURFACE MOTION	41.0
48	14	PREDICT TECHNS FOR BUFFET ONSET OF LOW AR A/C	40.9
49	68	THML COND, STORAGE & SAFE HNDLG OF CRYO FUELS	40.3
50	78	STABILITY AUGMENT SYSTEMS/RECOVERY FROM PIO'S	39.5
51	23	TRANSPIR/ABLAT EFCTS - SKIN FRICT/HEAT TRANSFER	39.5
52	94	ABORT, FUEL DUMP, ESCAPE & EMERG EGRESS TECHNS	39.4
53	83	ENVIRON CNTL SYSTEM - LIQUID CRYO AS HEAT SINK	38.7
54	87	TERMINAL APPROACH & LANDING METHODS	37.9
55	102	INSPECTION & REPAIR TECHNS FOR HYPER VEH STRCTS	37.5
56	38	FUEL SLOSH EFFECTS ON DYNAMICS/INERTIA LOADS	37.4
57	69	FLUID DYN/THERMODYN CHARS OF CRYO FUELS	36.9
58	72	FUEL SYSTEM DESIGN REQUIREMENTS	36.6
59	35	STRUCTURE MAINTAINING AERODYNAMIC SMOOTHNESS	36.5
60	97	LEAK DETECTION METHODS FOR CRYO FUEL TANKS	36.4
61	96	CAPABILITY TO STAY WITHIN SPECIF OPER MARGINS	35.1
62	18	EFFECTS OF REACTION CONTROL JETS	34.4
63	71	IMPROVEMENT OF HYDROCARBON FUEL PERFORMANCE	33.4
64	82	AUXILIARY POWER UNITS	32.8
65	79	AIR DATA MEASUREMENT TECHNIQUES	29.9
66	93	EFCTS OF VEH DYN/CENTRIF EFCTS ON CREW/PSSNGRS	29.3
67	77	FLUSH OR RECESSED ANTENNA DESIGN TECHNIQUES	28.5

FIGURE 3-5
RESEARCH OBJECTIVE INTRINSIC VALUE

OPERATIONAL SYSTEM NO. 3 - (L3)

WEIGHTED AVERAGE FOR ALL EVALUATION CRITERIA

TECHNOLOGICAL AREA	REL. WT.	NO. EVALUATORS
A. AERODYNAMICS	.184	23
B. THERMODYNAMICS	.165	19
C. STRUCTURES & MATERIAL	.193	22
D. PROPULSION	.209	32
E. SUBSYSTEMS	.126	18
F. OPERATION	.123	22

EVALUATION CRITERION	REL. WT.
A. TECHNOLOGY ADVANCEMENT	.607
B. COST & SCHEDULE	.393

RANK	CODE	OBJECTIVE	INTRINSIC VALUE
1	58	BEST MULTIMODE CYCLE & ENGINE SIZE	84.5
2	28	REUS THML PROT STRS - CRYO FUELS/OXIDR TNKG	73.5
3	43	REUSABLE THML PROTECT STMS - PRIMARY STRUCTURE	72.6
4	3	SUPERSONIC & HYPERSONIC AERO CHARACTERISTICS	70.9
5	34	LONG-LIFE REGEN-COOLED STRUCTURAL CONCEPTS	70.9
6	4	TEST TECHNS FOR RE NO, SHOCK WAVE & BNDY LR PHEN	66.1
7	44	MECH/PHYS PROPERTIES OF ADVANCED MATERIALS	64.8
8	45	FAB TECHNS - ADV MATERIALS/COMPLEX STRUCTURES	64.0
9	42	FULL SCALE COMP TEST OF STRCT/THMSTRCT SYSTEMS	62.5
10	9	PARAMATERS AFFECTING STABILITY & CONTROL	62.0
11	33	CONTROL SURFACE TECHNOLOGY	61.6
12	36	EFF OF COMB MECH LONG, THML STRS CYC, TEMP VAR	61.5
13	12	HYPERSONIC BOUNDARY LAYER BEHAVIOR	61.4
14	40	TEST & INSP METHODS FOR ADVANCED STRUCTURES	59.0
15	7	ENG EXST EXP FOR ADD LIFT/PROP GAS FLO INT EFCTS	58.9
16	19	CNTL SURFACE EFFECT/HEAT EFFECTS WHEN DEFLECTED	58.4
17	32	REUSABLE LEADING EDGE CONCEPTS	58.4
18	5	OPTIMUM & ACCEPTABLE HANDLING QUALITIES	58.1
19	1	LOW SPEED (T/O & LANDING) AERO CHARACTERISTICS	58.1
20	2	SUBSONIC & TRANSONIC AERO CHARACTERISTICS	58.0
21	16	HEAT TRANS & DRAG FOR TURBULENT BOUNDARY LAYERS	57.8
22	30	FUSELAGE/TANK STRUCTS - MORE EFFICIENT CONCEPTS	57.8
23	24	EMBEDDED SHOCK, VORTEX, SEPAR & REATCH EFFECTS	56.5
24	6	SURFACE/INLET POSITION - FAVOR AERO INTEFERENCE	56.2
25	26	HEAT EFFECTS - FLOW FIELD/VEH GEOM INTERACTIONS	55.3
26	20	HYPERSONIC AEROTHERMO PARAMS IN 3-DIM FLOW	54.8
27	62	RKT-PWD ENGINE OPERATION IN HORIZ T/O A/C	54.1
28	11	SEPARATION TECHNS FOR POSITIVE SEPAR & CONTROL	53.5
29	46	HIGH TEMPERATURE EQUIPMENT	53.4
30	17	PREDICT TECHNS FOR BNDY LAYER TRANSITION	53.2
31	22	SURFACE SHAPING & PRCTUB EFFECTS ON DRAG & HEAT	52.6
32	41	ESTIM OF COMPONENT/STRUCTURAL MASS FRACTIONS	51.4
33	64	AUXILIARY TURBOJETS FOR LANDING HYPERSONIC VEHS	49.5
34	10	STAGE INTEGRATION FOR AERO IMPROVEMENTS	48.9
35	75	FUEL TANK CONCEPTS/FUEL SYS OPER & CNTL TECHNS	46.5
36	25	HEATING EFFECTS FROM FLOW THRU GAPS	45.9
37	89	MAN-MACHINE COMPATIBILITY - CONTROL/NAVIGATION	43.3
38	73	CRYO SYSTEM COMPONENTS - RED WT/INCR RELIABILITY	42.0
39	27	PREDICT TECHNS FOR HEAT TRANSFER ENG EXHAUST	41.9
40	15	TECHNS FOR ALLEVIATING SONIC BOOM INTENSITY	41.6
41	80	ACTUATION TECHNS & HDWR FOR CNTL SURFACE MOTION	41.5
42	39	NEAR FIELD NOISE EFFECTS	41.3
43	14	PREDICT TECHNS FOR BUFFET ONSET OF LOW AR A/C	40.9
44	78	STABILITY AUGMENT SYSTEMS/RECOVERY FROM PIO'S	40.8
45	68	THML COND, STORAGE & SAFE HNDLG OF CRYO FUELS	40.3
46	94	ABORT, FUEL DUMP, ESCAPE & EMERG EGRESS TECHNS	40.0
47	23	TRANSPIR/ABLAT EFCTS - SKIN FRICT/HEAT TRANSFER	39.5
48	83	ENVIRON CNTL SYSTEM - LIQUID CRYO AS HEAT SINK	39.1
49	87	TERMINAL APPROACH & LANDING METHODS	39.0
50	102	INSPECTION & REPAIR TECHNS FOR HYPER VEH STRCTS	38.3
51	97	LEAK DETECTION METHODS FOR CRYO FUEL TANKS	37.5
52	38	FUEL SLUSH EFFECTS ON DYNAMICS/INERTIA LOADS	37.4
53	69	FLUID DYN/THERMODYN CHARS OF CRYO FUELS	37.2
54	35	STRUCTURE MAINTAINING AERODYNAMIC SMOOTHNESS	36.5
55	96	CAPABILITY TO STAY WITHIN SPECIF OPER MARGINS	35.9
56	18	EFFECTS OF REACTION CONTROL JETS	34.4
57	82	AUXILIARY POWER UNITS	32.6
58	99	SHORT TAKEOFF TECHNIQUES	30.6
59	93	EFCTS OF VEH DYN/CENTRIF EFCTS ON CREW/PSSNGRS	30.5
60	79	AIR DATA MEASUREMENT TECHNIQUES	30.5
61	77	FLUSH OR RECESSED ANTENNA DESIGN TECHNIQUES	27.7

FIGURE 3-6
RESEARCH OBJECTIVE INTRINSIC VALUE

OPERATIONAL SYSTEM NO. 4 - (L4)

WEIGHTED AVERAGE FOR ALL EVALUATION CRITERIA

TECHNOLOGICAL AREA	REL. WT.	NO. EVALUATORS
A. AERODYNAMICS	.184	23
B. THERMODYNAMICS	.165	19
C. STRUCTURES & MATERIAL	.193	22
D. PROPULSION	.209	32
E. SUBSYSTEMS	.126	18
F. OPERATION	.123	22

EVALUATION CRITERION	REL. WT.
A. TECHNOLOGY ADVANCEMENT	.607
B. COST & SCHEDULE	.393

RANK	CODE	OBJECTIVE	INTRINSIC VALUE
1	48	INLET CONFIGURATIONS WITH DESIRABLE CHARS	73.7
2	28	REUS THML PROT STMS - CRYO FUELS/OXIDR TNKG	73.5
3	67	INLET/ENGINE COMPATIBILITY CRITERIA	73.1
4	61	SCRAMJET SYSTEMS - DEVELOP & DEMONSTRATE	73.0
5	43	REUSABLE THML PROTECT STMS - PRIMARY STRUCTURE	72.6
6	3	SUPERSONIC & HYPERSONIC AERO CHARACTERISTICS	70.9
7	34	LONG-LIFE REGEN-COOLED STRUCTURAL CONCEPTS	70.9
8	58	BEST MULTIMODE CYCLE & ENGINE SIZE	70.0
9	52	ENGINE DESIGN CNCPTS FOR VARIOUS COOLING TECHNS	67.7
10	65	NOZZLE CONFIGURATIONS	66.9
11	4	TEST TECHNS FOR RE NO, SHOCK WAVE & BNDY LR PHEN	66.1
12	44	MECH/PHYS PROPERTIES OF ADVANCED MATERIALS	64.8
13	45	FAB TECHNS - ADV MATERIALS/COMPLEX STRUCTURES	64.0
14	42	FULL SCALE COMP TEST OF STRCT/THMSTRCT SYSTEMS	62.5
15	9	PARAMATERS AFFECTING STABILITY & CONTROL	62.0
16	33	CONTROL SURFACE TECHNOLOGY	61.6
17	63	EFFECTIVE INLET CONTROLS	61.6
18	36	EFF OF COMB MECH LDNG, THML STRS CYC, TEMP VAR	61.5
19	12	HYPERSONIC BOUNDARY LAYER BEHAVIOR	61.4
20	40	TEST & INSP METHODS FOR ADVANCED STRUCTURES	59.0
21	7	ENG EXST EXP FOR ADD LIFT/PROP GAS FLO INT EFCTS	58.9
22	19	CNTL SURFACE EFFECT/HEAT EFFECTS WHEN DEFLECTED	58.4
23	32	REUSABLE LEADING EDGE CONCEPTS	58.4
24	5	OPTIMUM & ACCEPTABLE HANDLING QUALITIES	58.1
25	1	LOW SPEED (T/O & LANDING) AERO CHARACTERISTICS	58.1
26	2	SUBSONIC & TRANSONIC AERO CHARACTERISTICS	58.0
27	16	HEAT TRANS & DRAG FOR TURBULENT BOUNDARY LAYERS	57.8
28	30	FUSELAGE/TANK STRUCTS - MORE EFFICIENT CONCEPTS	57.8
29	24	EMBEDDED SHOCK, VORTEX, SEPAR & REATCH EFFECTS	56.5
30	6	SURFACE/INLET POSITION - FAVOR AERO INTEFERENCE	56.2
31	26	HEAT EFFECTS - FLOW FIELD/VEH GEOM INTERACTIONS	55.3
32	20	HYPERSONIC AEROTHERMO PARAMS IN 3-DIM FLOW	54.8
33	11	SEPARATION TECHNS FOR POSITIVE SEPAR & CONTROL	53.5
34	46	HIGH TEMPERATURE EQUIPMENT	53.4
35	17	PREDICT TECHNS FOR BNDY LAYER TRANSITION	53.2
36	22	SURFACE SHAPING & PROTUB EFFECTS ON DRAG & HEAT	52.6
37	41	ESTIM OF COMPONENT/STRUCTURAL MASS FRACTIONS	51.4
38	10	STAGE INTEGRATION FOR AERO IMPROVEMENTS	48.9
39	70	REGEN CRYO HEAT EXCHRS/THRMO CORLS/COOL CNT STMS	[illegible]
40	25	HEATING EFFECTS FROM FLOW THRU GAPS	45.9
41	75	FUEL TANK CONCEPTS/FUEL SYS OPER & CNTL TECHNS	45.3
42	89	MAN-MACHINE COMPATIBILITY - CONTROL/NAVIGATION	43.3
43	27	PREDICT TECHNS FOR HEAT TRANSFER - ENG EXHAUST	41.9
44	62	RKT-PWD ENGINE OPERATION IN HORIZ T/O A/C	41.8
45	15	TECHNS FOR ALLEVIATING SONIC BOOM INTENSITY	[illegible]
46	39	NEAR FIELD NOISE EFFECTS	41.3
47	73	CRYO SYSTEM COMPONENTS - RCD WT/INCR RELIABILITY	41.2
48	14	PREDICT TECHNS FOR BUFFET ONSET OF LOW AR A/C	40.9
49	80	ACTUATION TECHNS & HDWR FOR CNTL SURFACE MOTION	40.5
50	94	ABORT, FUEL DUMP, ESCAPE & EMERG EGRESS TECHNS	40.3
51	68	THML COND, STORAGE & SAFE HNDLG OF CRYO FUELS	39.6
52	23	TRANSPIR/ABLAT EFCTS - SKIN FRICT/HEAT TRANSFER	39.5
53	78	STABILITY AUGMENT SYSTEMS/RECOVERY FROM PIO'S	39.3
54	87	TERMINAL APPROACH & LANDING METHODS	39.0
55	102	INSPECTION & REPAIR TECHNS FOR HYPER VEH STRCTS	38.3
56	83	ENVIRON CNTL SYSTEM - LIQUID CRYO AS HEAT SINK	38.1
57	97	LEAK DETECTION METHODS FOR CRYO FUEL TANKS	37.5
58	38	FUEL SLOSH EFFECTS ON DYNAMICS/INERTIA LOADS	37.4
59	64	AUXILIARY TURBOJETS FOR LANDING HYPERSONIC VEHS	36.6
60	69	FLUID DYN/THERMODYN CHARS OF CRYO FUELS	36.5
61	35	STRUCTURE MAINTAINING AERODYNAMIC SMOOTHNESS	36.5
62	96	CAPABILITY TO STAY WITHIN SPECIF OPER MARGINS	35.9
63	18	EFFECTS OF REACTION CONTROL JETS	34.4
64	82	AUXILIARY POWER UNITS	31.9
65	99	SHORT TAKEOFF TECHNIQUES	30.6
66	93	EFCTS OF VEH DYN/CENTRIF EFCTS ON CREW/PSSNGRS	30.5
67	79	AIR DATA MEASUREMENT TECHNIQUES	30.0
68	77	FLUSH OR RECESSED ANTENNA DESIGN TECHNIQUES	27.5

FIGURE 3-7
RESEARCH OBJECTIVE INTRINSIC VALUE

OPERATIONAL SYSTEM NO. 5 - (C1)

WEIGHTED AVERAGE FOR ALL EVALUATION CRITERIA

TECHNOLOGICAL AREA	REL. WT.	NO. EVALUATORS
A. AERODYNAMICS	.184	23
B. THERMODYNAMICS	.165	19
C. STRUCTURES & MATERIAL	.193	22
D. PROPULSION	.209	32
E. SUBSYSTEMS	.126	18
F. OPERATION	.123	22

EVALUATION CRITERION	REL. WT.
A. TECHNOLOGY ADVANCEMENT	.607
B. COST & SCHEDULE	.393

RANK	CODE	OBJECTIVE	INTRINSIC VALUE
1	57	TURBORAMJET SYSTEMS - DEVELOP & DEMONSTRATE	73.6
2	28	REUS THML PROT STMS - CRYO FUELS/OXIDR TNKG	73.5
3	43	REUSABLE THML PROTECT STMS - PRIMARY STRUCTURE	72.6
4	34	LONG-LIFE REGEN-COOLED STRUCTURAL CONCEPTS	70.9
5	3	SUPERSONIC & HYPERSONIC AERO CHARACTERISTICS	70.6
6	59	RAMJET SYSTEMS - DEVELOP & DEMONSTRATE	70.2
7	48	INLET CONFIGURATIONS WITH DESIRABLE CHARS	69.4
8	67	INLET/ENGINE COMPATIBILITY CRITERIA	68.9
9	58	BEST MULTIMODE CYCLE & ENGINE SIZE	68.5
10	4	TEST TECHNS FOR RE NO, SHOCK WAVE & BNDY LR PHEN	64.9
11	44	MECH/PHYS PROPERTIES OF ADVANCED MATERIALS	64.[illegible]
12	65	NOZZLE CONFIGURATIONS	64.1
13	45	FAB TECHNS - ADV MATERIALS/COMPLEX STRUCTURES	64.0
14	42	FULL SCALE COMP TEST OF STRCT/THMSTRCT SYSTEMS	62.5
15	52	ENGINE DESIGN CNCPTS FOR VARIOUS COOLING TECHNS	61.8
16	33	CONTROL SURFACE TECHNOLOGY	61.6
17	36	EFF OF COMB MECH LDNG, THML STRS CYC, TEMP VAR	61.5
18	9	PARAMATERS AFFECTING STABILITY & CONTROL	60.7
19	40	TEST & INSP METHODS FOR ADVANCED STRUCTURES	59.0
20	12	HYPERSONIC BOUNDARY LAYER BEHAVIOR	59.0
21	32	REUSABLE LEADING EDGE CONCEPTS	58.4
22	63	EFFECTIVE INLET CONTROLS	57.9
23	30	FUSELAGE/TANK STRUCTS - MORE EFFICIENT CONCEPTS	57.8
24	7	ENG EXST EXP FOR ADD LIFT/PROP GAS FLO INT EFCTS	56.4
25	19	CNTL SURFACE EFFECT/HEAT EFFECTS WHEN DEFLECTED	56.1
26	5	OPTIMUM & ACCEPTABLE HANDLING QUALITIES	56.0
27	2	SUBSONIC & TRANSONIC AERO CHARACTERISTICS	56.0
28	1	LOW SPEED (T/O & LANDING) AERO CHARACTERISTICS	55.9
29	16	HEAT TRANS & DRAG FOR TURBULENT BOUNDARY LAYERS	55.5
30	24	EMBEDDED SHOCK, VORTEX, SEPAR & SWITCH EFFECTS	54.9
31	26	HEAT EFFECTS - FLOW FIELD/VEH GEOM INTERACTIONS	54.6
32	6	SURFACE/INLET POSITION - FAVOR AERO INTERFRENCE	53.8
33	20	HYPERSONIC AEROTHERMO PARAMS IN 3-DIM FLOW	53.5
34	[illegible]	HIGH TEMPERATURE EQUIPMENT	53.4
35	4[illegible]	ESTIM OF COMPONENT/STRUCTURAL MASS FRACTIONS	51.4
36	22	SURFACE SHAPING & PROTUB EFFECTS ON DRAG & HEAT	50.8
37	17	PREDICT TECHNS FOR BNDY LAYER TRANSITION	50.5
38	70	REGEN CRYO HEAT EXCHRS/THRMO CURLS/COOL CNT STMS	46.4
39	75	FUEL TANK CONCEPTS/FUEL SYS OPER & CNTL TECHNS	46.4
40	25	HEATING EFFECTS FROM FLOW THRU GAPS	43.0
41	89	MAN-MACHINE COMPATIBILITY - CONTROL/NAVIGATION	42.7
42	73	CRYO SYSTEM COMPONENTS - RED WT/INCR RELIABILITY	42.4
43	80	ACTUATION TECHNS & POWR FOR CNTL SURFACE MOTION	41.4
44	39	NEAR FIELD NOISE EFFECTS	41.3
45	68	THML COND, STORAGE & SAFE HNDLG OF CRYO FUELS	40.8
46	27	PREDICT TECHNS FOR HEAT TRANSFER - ENG EXHAUST	40.2
47	78	STABILITY AUGMENT SYSTEMS/RECOVERY FROM PIO'S	39.[illegible]
48	15	TECHNS FOR ALLEVIATING SONIC BOOM INTENSITY	39.6
49	94	ABORT, FUEL DUMP, ESCAPE & EMERG EGRESS TECHNS	39.4
50	83	ENVIRON CNTL SYSTEM - LIQUID CRYO AS HEAT SINK	39.1
51	87	TERMINAL APPROACH & LANDING METHODS	37.9
52	14	PREDICT TECHNS FOR BUFFET ONSET OF LOW AR A/C	37.7
53	102	INSPECTION & REPAIR TECHNS FOR HYPER VEH STRCTS	37.5
54	69	FLUID DYN/THERMODYN CHARS OF CRYO FUELS	37.4
55	38	FUEL SLUSH EFFECTS ON DYNAMICS/INERTIA LOADS	37.4
56	72	FUEL SYSTEM DESIGN REQUIREMENTS	37.0
57	35	STRUCTURE MAINTAINING AERODYNAMIC SMOOTHNESS	36.5
58	37	LEAK DETECTION METHODS FOR CRYO FUEL TANKS	35.4
59	96	CAPABILITY TO STAY WITHIN SPECIF OPER MARGINS	35.1
60	71	IMPROVEMENT OF HYDROCARBON FUEL PERFORMANCE	33.7
61	82	AUXILIARY POWER UNITS	33.3
62	74	RAPID CRYOGENIC SERVICING TECHNIQUES	32.[illegible]
63	55	ENGINE NOISE REDUCTION DURING T/O & LANDING	30.5
64	79	AIR DATA MEASUREMENT TECHNIQUES	30.3
65	93	EFCTS OF VEH DYN/CENTRIF EFCTS ON CREW/PSSNGRS	29.3
66	77	FLUSH OR RECESSED ANTENNA DESIGN TECHNIQUES	29.0

FIGURE 3-8
RESEARCH OBJECTIVE INTRINSIC VALUE

OPERATIONAL SYSTEM NO. 6 - (C2)

WEIGHTED AVERAGE FOR ALL EVALUATION CRITERIA

TECHNOLOGICAL AREA	REL. WT.	NO. EVALUATORS
A. AERODYNAMICS	.184	23
B. THERMODYNAMICS	.165	19
C. STRUCTURES & MATERIAL	.193	22
D. PROPULSION	.209	32
E. SUBSYSTEMS	.126	18
F. OPERATION	.123	22

EVALUATION CRITERION	REL. WT.
A. TECHNOLOGY ADVANCEMENT	.607
B. COST & SCHEDULE	.393

RANK	CODE	OBJECTIVE	INTRINSIC VALUE
1	60	CONVERTIBLE SCRAMJET SYSTEMS - DEVELOP & DEMON	76.0
2	28	REUS THML PROT STMS - CRYO FUELS/OXIDR TNKG	73.5
3	43	REUSABLE THML PROTECT STMS - PRIMARY STRUCTURE	72.6
4	3	SUPERSONIC & HYPERSONIC AERO CHARACTERISTICS	71.1
5	34	LONG-LIFE REGEN-COOLED STRUCTURAL CONCEPTS	70.9
6	48	INLET CONFIGURATIONS WITH DESIRABLE CHARS	70.3
7	67	INLET/ENGINE COMPATIBILITY CRITERIA	69.5
8	58	BEST MULTIMODE CYCLE & ENGINE SIZE	65.1
9	4	TEST TECHNS FOR RE NO, SHOCK WAVE & BNDY LR PHEN	65.1
10	44	MECH/PHYS PROPERTIES OF ADVANCED MATERIALS	64.8
11	65	NOZZLE CONFIGURATIONS	64.4
12	45	FAB TECHNS - ADV MATERIALS/COMPLEX STRUCTURES	64.0
13	52	ENGINE DESIGN CNCPTS FOR VARIOUS COOLING TECHNS	62.7
14	42	FULL SCALE COMP TEST OF STRCT/THMSTRCT SYSTEMS	62.5
15	9	PARAMATERS AFFECTING STABILITY & CONTROL	62.0
16	33	CONTROL SURFACE TECHNOLOGY	61.6
17	36	EFF OF COMB MECH LONG, THML STRS CYC, TEMP VAR	61.3
18	12	HYPERSONIC BOUNDARY LAYER BEHAVIOR	60.8
19	40	TEST & INSP METHODS FOR ADVANCED STRUCTURES	59.0
20	63	EFFECTIVE INLET CONTROLS	58.5
21	37	REUSABLE LEADING EDGE CONCEPTS	58.4
22	1	LOW SPEED (T/O & LANDING) AERO CHARACTERISTICS	58.3
23	7	ENG EXST EXP FOR ADD LIFT/PROP GAS FLO INT EFCTS	58.1
24	19	CNTL SURFACE EFFECT/HEAT EFFECTS WHEN DEFLECTED	57.8
25	5	OPTIMUM & ACCEPTABLE HANDLING QUALITIES	57.8
26	30	FUSELAGE/TANK STRUCTS - MORE EFFICIENT CONCEPTS	57.8
27	2	SUBSONIC & TRANSONIC AERO CHARACTERISTICS	57.6
28	16	HEAT TRANS & DRAG FOR TURBULENT BOUNDARY LAYERS	57.0
29	6	SURFACE/INLET POSITION - FAVOR AERO INTERFERENCE	55.5
30	24	EMBEDDED SHOCK, VORTEX, SEPAR & REATCH EFFECTS	54.9
31	26	HEAT EFFECTS - FLOW FIELD/VEH GEOM INTERACTIONS	54.6
32	20	HYPERSONIC AEROTHERMO PARAMS IN 3-DIM FLOW	53.5
33	46	HIGH TEMPERATURE EQUIPMENT	53.4
34	17	PREDICT TECHNS FOR BNDY LAYER TRANSITION	52.1
35	41	ESTIM OF COMPONENT/STRUCTURAL MASS FRACTIONS	51.4
36	22	SURFACE SHAPING & PROTUB EFFECTS ON DRAG & HEAT	50.8
37	70	REGEN CRYO HEAT EXCHRS/THRMO COILS/COOL CNT STMS	46.4
38	75	FUEL TANK CONCEPTS/FUEL SYS OPER & CNTL TECHNS	46.4
39	25	HEATING EFFECTS FROM FLOW THRU GAPS	43.0
40	89	MAN-MACHINE COMPATIBILITY - CONTROL/NAVIGATION	42.7
41	73	CRYO SYSTEM COMPONENTS - RED WT/INCR RELIABILITY	42.6
42	80	ACTUATION TECHNS & HDWR FOR CNTL SURFACE MOTION	41.4
43	39	NEAR FIELD NOISE EFFECTS	41.3
44	15	TECHNS FOR ALLEVIATING SONIC BOOM INTENSITY	41.0
45	68	THML COND, STORAGE & SAFE HNDLG OF CRYO FUELS	40.8
46	27	PREDICT TECHNS FOR HEAT TRANSFER - ENG EXHAUST	40.2
47	78	STABILITY AUGMENT SYSTEMS/RECOVERY FROM PIO'S	39.9
48	14	PREDICT TECHNS FOR BUFFET ONSET OF LOW AR A/C	39.9
49	94	ABORT, FUEL DUMP, ESCAPE & EMERG EGRESS TECHNS	39.4
50	83	F [illegible] CNTL SYSTEM - LIQUID CRYO AS HEAT SINK	39.1
51	8[illegible]	[illegible] APPROACH & LANDING METHODS	37.[illegible]
52	102	INSPECTION & REPAIR TECHNS FOR HYPER VEH STRCTS	37.5
53	69	FLUID DYN/THERMODYN CHARS OF CRYO FUELS	37.4
54	38	FUEL SLOSH EFFECTS ON DYNAMICS/INERTIA LOADS	37.4
55	72	FUEL SYSTEM DESIGN REQUIREMENTS	37.0
56	35	STRUCTURE MAINTAINING AERODYNAMIC SMOOTHNESS	36.5
57	97	LEAK DETECTION METHODS FOR CRYO FUEL TANKS	36.4
58	96	CAPABILITY TO STAY WITHIN SPECIF OPER MARGINS	35.1
59	71	IMPROVEMENT OF HYDROCARBON FUEL PERFORMANCE	33.7
60	82	AUXILIARY POWER UNITS	33.3
61	18	EFFECTS OF REACTION CONTROL JETS	32.9
62	74	RAPID CRYOGENIC SERVICING TECHNIQUES	32.0
63	55	ENGINE NOISE REDUCTION DURING T/O & LANDING	31.1
64	79	AIR DATA MEASUREMENT TECHNIQUES	30.3
65	93	EFCTS OF VEH DYN/CENTRIF EFCTS ON CREW/PSSNGRS	29.3
66	77	FLUSH OR RECESSED ANTENNA DESIGN TECHNIQUES	29.0

FIGURE 3-9
RESEARCH OBJECTIVE INTRINSIC VALUE

OPERATIONAL SYSTEM NO. 7 - (M1)

WEIGHTED AVERAGE FOR ALL EVALUATION CRITERIA

TECHNOLOGICAL AREA	REL. WT.	NO. EVALUATORS
A. AERODYNAMICS	.184	23
B. THERMODYNAMICS	.165	19
C. STRUCTURES & MATERIAL	.193	22
D. PROPULSION	.209	32
E. SUBSYSTEMS	.126	18
F. OPERATION	.123	22

EVALUATION CRITERION	REL. WT.
A. TECHNOLOGY ADVANCEMENT	.607
B. COST & SCHEDULE	.393

RANK	CODE	OBJECTIVE	INTRINSIC VALUE
1	43	REUSABLE THML PROTECT STMS - PRIMARY STRUCTURE	72.9
2	3	SUPERSONIC & HYPERSONIC AERO CHARACTERISTICS	70.6
3	34	LONG-LIFE REGEN-COOLED STRUCTURAL CONCEPTS	69.3
4	57	TURBORAMJET SYSTEMS - DEVELOP & DEMONSTRATE	68.8
5	59	RAMJET SYSTEMS - DEVELOP & DEMONSTRATE	67.4
6	48	INLET CONFIGURATIONS WITH DESIRABLE CHARS	66.0
7	67	INLET/ENGINE COMPATIBILITY CRITERIA	65.4
8	4	TEST TECHNS FOR RE NO, SHOCK WAVE & BNDY LR PHEN	64.9
9	44	MECH/PHYS PROPERTIES OF ADVANCED MATERIALS	64.6
10	58	BEST MULTIMODE CYCLE & ENGINE SIZE	64.4
11	45	FAB TECHNS - ADV MATERIALS/COMPLEX STRUCTURES	63.4
12	42	FULL SCALE COMP TEST OF STRCT/THMSTRCT SYSTEMS	62.3
13	33	CONTROL SURFACE TECHNOLOGY	61.3
14	36	EFF OF COMB MECH LONG, THML STRS CYC, TEMP VAR	60.9
15	9	PARAMATERS AFFECTING STABILITY & CONTROL	60.7
16	12	HYPERSONIC BOUNDARY LAYER BEHAVIOR	59.0
17	65	NOZZLE CONFIGURATIONS	58.7
18	40	TEST & INSP METHODS FOR ADVANCED STRUCTURES	58.5
19	32	REUSABLE LEADING EDGE CONCEPTS	58.3
20	52	ENGINE DESIGN CNCPTS FOR VARIOUS COOLING TECHNS	58.3
21	30	FUSELAGE/TANK STRUCTS - MORE EFFICIENT CONCEPTS	58.2
22	7	ENG EXST EXP FOR ADD LIFT/PROP GAS FLO INT EFCTS	56.4
23	19	CNTL SURFACE EFFECT/HEAT EFFECTS WHEN DEFLECTED	56.1
24	5	OPTIMUM & ACCEPTABLE HANDLING QUALITIES	56.0
25	2	SUBSONIC & TRANSONIC AERO CHARACTERISTICS	56.0
26	1	LOW SPEED (T/O & LANDING) AERO CHARACTERISTICS	55.9
27	16	HEAT TRANS & DRAG FOR TURBULENT BOUNDARY LAYERS	55.5
28	24	EMBEDDED SHOCK, VORTEX, SEPAR & REATCH EFFECTS	54.9
29	26	HEAT EFFECTS - FLOW FIELD/VEH GEOM INTERACTIONS	54.3
30	6	SURFACE/INLET POSITION - FAVOR AERO INTEFERENCE	53.8
31	20	HYPERSONIC AEROTHERMO PARAMS IN 3-DIM FLOW	53.5
32	46	HIGH TEMPERATURE EQUIPMENT	53.0
33	63	EFFECTIVE INLET CONTROLS	52.5
34	41	ESTIM OF COMPONENT/STRUCTURAL MASS FRACTIONS	51.5
35	22	SURFACE SHAPING & PROTUB EFFECTS ON DRAG & HEAT	50.8
36	17	PREDICT TECHNS FOR BNDY LAYER TRANSITION	50.5
37	80	ACTUATION TECHNS & POWR FOR CNTL SURFACE MOTION	44.4
38	25	HEATING EFFECTS FROM FLOW THRU GAPS	43.0
39	89	MAN-MACHINE COMPATIBILITY - CONTROL/NAVIGATION	42.7
40	78	STABILITY AUGMENT SYSTEMS/RECOVERY FROM PIO'S	42.6
41	85	LAUNCH TECHNS FOR AAM & ASM WEAPONS	41.7
42	84	ENVIRON CNTL SYSTEM - M4-6 HYDROCARBON VEHICLE	40.7
43	39	NEAR FIELD NOISE EFFECTS	40.4
44	27	PREDICT TECHNS FOR HEAT TRANSFER - ENG EXHAUST	40.2
45	15	TECHNS FOR ALLEVIATING SONIC BOOM INTENSITY	39.6
46	94	ABORT, FUEL DUMP, ESCAPE & EMERG EGRESS TECHNS	39.4
47	72	FUEL SYSTEM DESIGN REQUIREMENTS	38.5
48	87	TERMINAL APPROACH & LANDING METHODS	37.9
49	14	PREDICT TECHNS FOR BUFFET ONSET OF LOW AR A/C	37.7
50	102	INSPECTION & REPAIR TECHNS FOR HYPER VEH STRCTS	37.5
51	97	LEAK DETECTION METHODS FOR CRYO FUEL TANKS	36.4
52	35	STRUCTURE MAINTAINING AERODYNAMIC SMOOTHNESS	36.0
53	71	IMPROVEMENT OF HYDROCARBON FUEL PERFORMANCE	35.7
5	96	CAPABILITY TO STAY WITHIN SPECIF OPER MARGINS	35.1
55	82	AUXILIARY POWER UNITS	35.0
56	79	AIR DATA MEASUREMENT TECHNIQUES	31.2
57	77	FLUSH OR RECESSED ANTENNA DESIGN TECHNIQUES	30.4
58	93	EFCTS OF VEH DYN/CENTRIF EFCTS ON CREW/PSSNGRS	29.3

2

FIGURE 3-10
RESEARCH OBJECTIVE INTRINSIC VALUE

OPERATIONAL SYSTEM NO. 8 - (M2)

WEIGHTED AVERAGE FOR ALL EVALUATION CRITERIA

TECHNOLOGICAL AREA	REL. WT.	NO. EVALUATORS
A. AERODYNAMICS	.184	23
B. THERMODYNAMICS	.165	19
C. STRUCTURES & MATERIAL	.193	22
D. PROPULSION	.209	32
E. SUBSYSTEMS	.126	18
F. OPERATION	.123	22

EVALUATION CRITERION	REL. WT.
A. TECHNOLOGY ADVANCEMENT	.607
B. COST & SCHEDULE	.393

RANK	CODE	OBJECTIVE	INTRINSIC VALUE
1	48	INLET CONFIGURATIONS WITH DESIRABLE CHARS	74.7
2	28	REUS THML PROT STMS - CRYO FUELS/OXIDR TNKG	73.5
3	67	INLET/ENGINE COMPATIBILITY CRITERIA	73.1
4	61	SCRAMJET SYSTEMS - DEVELOP & DEMONSTRATE	73.0
5	43	REUSABLE THML PROTECT STMS - PRIMARY STRUCTURE	72.6
6	3	SUPERSONIC & HYPERSONIC AERO CHARACTERISTICS	71.1
7	34	LONG-LIFE REGEN-COOLED STRUCTURAL CONCEPTS	70.9
8	58	BEST MULTIMODE CYCLE & ENGINE SIZE	70.0
9	52	ENGINE DESIGN CNCPTS FOR VARIOUS COOLING TECHNS	67.7
10	65	NOZZLE CONFIGURATIONS	66.9
11	4	TEST TECHNS FOR RE NO, SHOCK WAVE & BNDY LR PHEN	66.1
12	44	MECH/PHYS PROPERTIES OF ADVANCED MATERIALS	64.8
13	45	FAB TECHNS - ADV MATERIALS/COMPLEX STRUCTURES	64.0
14	42	FULL SCALE COMP TEST OF STRCT/THMSTRCT SYSTEMS	62.5
15	9	PARAMATERS AFFECTING STABILITY & CONTROL	62.0
16	33	CONTROL SURFACE TECHNOLOGY	61.6
17	63	EFFECTIVE INLET CONTROLS	61.6
18	36	EFF OF COMB MECH LONG, THML STRS CYC, TEMP VAR	61.5
19	12	HYPERSONIC BOUNDARY LAYER BEHAVIOR	60.8
20	40	TEST & INSP METHODS FOR ADVANCED STRUCTURES	59.0
21	32	REUSABLE LEADING EDGE CONCEPTS	58.4
22	1	LOW SPEED (T/O & LANDING) AERO CHARACTERISTICS	58.3
23	7	ENG EXST EXP FOR ADD LIFT/PROP GAS FLO INT EFCTS	58.1
24	19	CNTL SURFACE EFFECT/HEAT EFFECTS WHEN DEFLECTED	57.9
25	5	OPTIMUM & ACCEPTABLE HANDLING QUALITIES	57.9
26	30	FUSELAGE/TANK STRUCTS - MORE EFFICIENT CONCEPTS	57.8
27	2	SUBSONIC & TRANSONIC AERO CHARACTERISTICS	57.6
28	16	HEAT TRANS & DRAG FOR TURBULENT BOUNDARY LAYERS	57.0
29	6	SURFACE/INLET POSITION - FAVOR AERO INTERFERENCE	55.5
30	24	EMBEDDED SHOCK, VORTEX, SEPAR & REATCH EFFECTS	54.9
31	26	HEAT EFFECTS - FLOW FIELD/VEH GEOM INTERACTIONS	54.6
32	20	HYPERSONIC AEROTHERMO PARAMS IN 3-DIM FLOW	53.5
33	46	HIGH TEMPERATURE EQUIPMENT	53.4
34	17	PREDICT TECHNS FOR BNDY LAYER TRANSITION	52.1
35	41	ESTIM OF COMPONENT/STRUCTURAL MASS FRACTIONS	51.4
36	22	SURFACE SHAPING & PROTUB EFFECTS ON DRAG & HEAT	50.8
37	70	REGEN CRYO HEAT EXCHRS/THRMO CORLS/COOL CNT STMS	46.2
38	75	FUEL TANK CONCEPTS/FUEL SYS OPER & CNTL TECHNS	46.0
39	89	MAN-MACHINE COMPATIBILITY - CONTROL/NAVIGATION	43.7
40	25	HEATING EFFECTS FROM FLOW THRU GAPS	43.0
41	62	RKT-PWD ENGINE OPERATION IN HORIZ T/O A/C	41.6
42	73	CRYO SYSTEM COMPONENTS - RCD WT/INCR RELIABILITY	41.5
43	39	NEAR FIELD NOISE EFFECTS	41.3
44	15	TECHNS FOR ALLEVIATING SONIC BOOM INTENSITY	41.0
45	94	ABORT, FUEL DUMP, ESCAPE & EMERG EGRESS TECHNS	40.9
46	80	ACTUATION TECHNS & HDWR FOR CNTL SURFACE MOTION	40.8
47	27	PREDICT TECHNS FOR HEAT TRANSFER - ENG EXHAUST	40.2
48	68	THML COND, STORAGE & SAFE HNDLG OF CRYO FUELS	39.9
49	14	PREDICT TECHNS FOR BUFFET ONSET OF LOW AR A/C	39.9
50	87	TERMINAL APPROACH & LANDING METHODS	39.6
51	78	STABILITY AUGMENT SYSTEMS/RECOVERY FROM PIO'S	39.6
52	85	LAUNCH TECHNS FOR AAM & ASM WEAPONS	39.1
53	102	INSPECTION & REPAIR TECHNS FOR HYPER VEH STRCTS	39.1
54	83	ENVIRON CNTL SYSTEM - LIQUID CRYO AS HEAT SINK	38.2
55	97	LEAK DETECTION METHODS FOR CRYO FUEL TANKS	37.9
56	38	FUEL SLUSH EFFECTS ON DYNAMICS/INERTIA LOADS	37.4
57	69	FLUID DYN/THERMODYN CHARS OF CRYO FUELS	37.0
58	64	AUXILIARY TURBOJETS FOR LANDING HYPERSONIC VEHS	36.6
59	35	STRUCTURE MAINTAINING AERODYNAMIC SMOOTHNESS	36.5
60	96	CAPABILITY TO STAY WITHIN SPECIF OPER MARGINS	36.4
61	18	EFFECTS OF REACTION CONTROL JETS	32.9
62	82	AUXILIARY POWER UNITS	32.6
63	100	PRACTICAL GROUND HOLD METHODS FOR CRYO SYSTEMS	32.4
64	99	SHORT TAKEOFF TECHNIQUES	31.3
65	74	RAPID CRYOGENIC SERVICING TECHNIQUES	31.3
66	93	EFCTS OF VEH DYN/CENTRIF EFCTS ON CREW/PSSNGRS	30.8
67	79	AIR DATA MEASUREMENT TECHNIQUES	30.6
68	77	FLUSH OR RECESSED ANTENNA DESIGN TECHNIQUES	28.6

FIGURE 3-11
RESEARCH OBJECTIVE INTRINSIC VALUE

OPERATIONAL SYSTEM NO. 9 - (M3)

WEIGHTED AVERAGE FOR ALL EVALUATION CRITERIA

TECHNOLOGICAL AREA	REL. WT.	NO. EVALUATORS
A. AERODYNAMICS	.184	23
B. THERMODYNAMICS	.165	19
C. STRUCTURES & MATERIAL	.193	22
D. PROPULSION	.209	32
E. SUBSYSTEMS	.126	18
F. OPERATION	.123	22

EVALUATION CRITERION	REL. WT.
A. TECHNOLOGY ADVANCEMENT	.607
B. COST & SCHEDULE	.393

RANK	CODE	OBJECTIVE	INTRINSIC VALUE
1	48	INLET CONFIGURATIONS WITH DESIRABLE CHARS	73.7
2	28	REUS THML PROT STMS - CRYO FUELS/OXIDR TNKG	73.5
3	67	INLET/ENGINE COMPATIBILITY CRITERIA	73.1
4	61	SCRAMJET SYSTEMS - DEVELOP & DEMONSTRATE	73.0
5	43	REUSABLE THML PROTECT STMS - PRIMARY STRUCTURE	72.6
6	3	SUPERSONIC & HYPERSONIC AERO CHARACTERISTICS	71.1
7	34	LONG-LIFE REGEN-COOLED STRUCTURAL CONCEPTS	70.9
8	58	BEST MULTIMODE CYCLE & ENGINE SIZE	70.0
9	52	ENGINE DESIGN CNCPTS FOR VARIOUS COOLING TECHNS	67.7
10	65	NOZZLE CONFIGURATIONS	66.9
11	4	TEST TECHNS FOR RE NO, SHOCK WAVE & BNDY LR PHEN	66.1
12	44	MECH/PHYS PROPERTIES OF ADVANCED MATERIALS	64.8
13	45	FAB TECHNS - ADV MATERIALS/COMPLEX STRUCTURES	64.0
14	42	FULL SCALE COMP TEST OF STRCT/THMSTRCT SYSTEMS	62.5
15	9	PARAMATERS AFFECTING STABILITY & CONTROL	62.0
16	33	CONTROL SURFACE TECHNOLOGY	61.6
17	63	EFFECTIVE INLET CONTROLS	61.6
18	36	EFF OF COMB MECH LONG, THML STRS CYC, TEMP VAR	61.5
19	12	HYPERSONIC BOUNDARY LAYER BEHAVIOR	60.6
20	40	TEST & INSP METHODS FOR ADVANCED STRUCTURES	59.0
21	32	REUSABLE LEADING EDGE CONCEPTS	58.4
22	1	LOW SPEED (T/O & LANDING) AERO CHARACTERISTICS	58.3
23	7	ENG EXST EXP FOR ADD LIFT/PROP GAS FLO INT EFCTS	58.1
24	19	CNTL SURFACE EFFECT/HEAT EFFECTS WHEN DEFLECTED	57.9
25	5	OPTIMUM & ACCEPTABLE HANDLING QUALITIES	57.8
26	30	FUSELAGE/TANK STRUCTS - MORE EFFICIENT CONCEPTS	57.8
27	2	SUBSONIC & TRANSONIC AERO CHARACTERISTICS	57.6
28	16	HEAT TRANS & DRAG FOR TURBULENT BOUNDARY LAYERS	57.0
29	6	SURFACE/INLET POSITION - FAVOR AERO INTERFERENCE	55.5
30	24	EMBEDDED SHOCK, VORTEX, SEPAR & REATCH EFFECTS	54.9
31	26	HEAT EFFECTS - FLOW FIELD/VEH GEOM INTERACTIONS	54.6
32	20	HYPERSONIC AEROTHERMO PARAMS IN 3-DIM FLOW	53.5
33	46	HIGH TEMPERATURE EQUIPMENT	53.4
34	17	PREDICT TECHNS FOR BNDY LAYER TRANSITION	52.1
35	41	ESTIM OF COMPONENT/STRUCTURAL MASS FRACTIONS	51.4
36	22	SURFACE SHAPING & PROTUB EFFECTS ON DRAG & HEAT	50.8
37	70	REGEN CRYO HEAT EXCHRS/THRMO CORLS/COOL LNT STM	46.2
38	75	FUEL TANK CONCEPTS/FUEL SYS OPER & CNTL TECHNS	46.0
39	89	MAN-MACHINE COMPATIBILITY - CONTROL/NAVIGATION	43.7
40	25	HEATING EFFECTS FROM FLOW THRU GAPS	43.0
41	62	RKT-PWD ENGINE OPERATION IN HORIZ T/O A/C	41.8
42	73	CRYO SYSTEM COMPONENTS - RCD WT/INCR RELIABILITY	41.5
43	39	NEAR FIELD NOISE EFFECTS	41.3
44	15	TECHNS FOR ALLEVIATING SONIC BOOM INTENSITY	41.0
45	94	ABORT, FUEL DUMP, ESCAPE & EMERG EGRESS TECHNS	40.9
46	80	ACTUATION TECHNS & HDWR FOR CNTL SURFACE MOTION	40.8
47	27	PREDICT TECHNS FOR HEAT TRANSFER - ENG EXHAUST	40.2
48	68	THML COND, STORAGE & SAFE HNDLG OF CRYO FUELS	39.9
49	14	PREDICT TECHNS FOR BUFFET ONSET OF LOW AR A/C	39.9
50	87	TERMINAL APPROACH & LANDING METHODS	39.6
51	78	STABILITY AUGMENT SYSTEMS/RECOVERY FROM PIO'S	39.6
52	85	LAUNCH TECHNS FOR AAM & ASM WEAPONS	39.1
53	102	INSPECTION & REPAIR TECHNS FOR HYPER VEH STRCTS	39.1
54	83	ENVIRON CNTL SYSTEM - LIQUID CRYO AS HEAT SINK	38.2
55	97	LEAK DETECTION METHODS FOR CRYO FUEL TANKS	37.9
56	38	FUEL SLOSH EFFECTS ON DYNAMICS/INERTIA LOADS	37.4
57	69	FLUID DYN/THERMODYN CHARS OF CRYO FUELS	37.0
58	64	AUXILIARY TURBOJETS FOR LANDING HYPERSONIC VEHS	36.6
59	35	STRUCTURE MAINTAINING AERODYNAMIC SMOOTHNESS	36.5
60	96	CAPABILITY TO STAY WITHIN SPECIF OPER MARGINS	36.[illegible]
61	18	EFFECTS OF REACTION CONTROL JETS	32.9
62	82	AUXILIARY POWER UNITS	32.6
63	100	PRACTICAL GROUND HOLD METHODS FOR CRYO SYSTEMS	32.4
64	99	SHORT TAKEOFF TECHNIQUES	31.3
65	74	RAPID CRYOGENIC SERVICING TECHNIQUES	31.3
66	93	EFCTS OF VEH DYN/CENTRIF EFCTS ON CREW/PSSNGRS	30.8
67	79	AIR DATA MEASUREMENT TECHNIQUES	30.[illegible]
68	77	FLUSH OR RECESSED ANTENNA DESIGN TECHNIQUES	28.6

The principal reason for defining the Research Tasks is to allow a precise evaluation of the research capabilities of the candidate ground facilities and flight vehicles. A detailed description of this evaluation is presented in Section 3.5.

3.4 RESEARCH TASK INTRINSIC VALUES

Phase II effort in the research requirements area involved delineating several Research Tasks under each Research Objective, previously described in Section 3.3, and establisheing the relative research value of these tasks, discussed in this section. A decision theory approach was utilized in Phase I to establish intrinsic values for each Research Objective. These intrinsic values are presented in Section 3.2. Intrinsic values were determined for each Research Task during Phase II. Research Task intrinsic values, similar to the Research Objective intrinsic values, determine the ranking of the tasks by research contribution. Intrinsic values for the Research Tasks are determined as described below. The process used insures that the intrinsic value relationship among objectives is carried over to the tasks included under the objectives.

3.4.1 RESEARCH TASK EVALUATION METHODOLOGY - Two fundamental elements are involved in establishing Research Task intrinsic values. First, an importance value is determined for each task, indicating the relative importance of a task in fulfilling its Research Objective. Secondly, these task importance values are multiplied by the Research Objective intrinsic values to obtain intrinsic values for the Research Tasks.

Importance values between 0 and 1 are assigned to the Research Tasks, indicating the relative importance of the tasks to one another in contributing toward the fulfillment of their objectives. These importance values take into account: (1) the importance of a given task relative to the other tasks listed under its Research Objective and (2) the extent to which the tasks under one objective, taken collectively, contribute to its fulfillment, in relation to the extent the tasks under other objectives contribute to the fulfillment of those objectives.

The second element in the Research Task evaluation process, the computing of the task intrinsic values, is accomplished by multiplying the Research Task importance values for each task by the objective intrinsic values for the Research Objective under which the task is listed. In this way the value of the objective to which the task contributes is incorporated in the task intrinsic value.

FIGURE 3-12
PHASE II RESEARCH TASKS

AERODYNAMICS

RO 1 - Determine low speed (takeoff and landing) aerodynamic characteristics of hypersonic aircraft.

RT 1.1 - Investigate methods of providing low speed stability and control for hypersonic configurations.

RT 1.2 - Investigate various methods of improving takeoff and landing characteristics such as variable geometry, auxiliary lift devices, and propulsive lift augmentation.

RT 1.3 - Investigate maximum usable angle of attack, power off and on, as limited by control power, buffet, wing drop, ground clearance, or pilot visibility.

RT 1.4 - Investigate trim capability at worst c.g. location on basic aerodynamic characteristics and on the control power available from the trimmed condition.

RT 1.5 - Evaluate relative importance of ground effect for typical hypersonic configurations, specifically the impact on auxiliary devices.

RT 1.6 - Investigate handling qualities via computerized simulation.

RO 2 - Determine subsonic and transonic aerodynamic characteristics of hypersonic aircraft.

RT 2.1 - Investigate methods of providing stability and control for hypersonic configurations in the high subsonic/transonic flight mode.

RT 2.2 - Conduct research into transonic drag rise associated with configuration related phenomena such as installed thrust minus drag, shock wave/boundary layer interaction, and shaping for high subsonic efficiency.

RT 2.3 - Investigate subsonic and transonic maximum usable angle of attack as limited by buffet onset, thrust margin, maximum lift, and longitudinal control power.

RT 2.4 - Investigate study subsonic and transonic flying qualities as a final measure of the adequacy of the design solutions.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RO 3 - Determine supersonic and hypersonic aerodynamic characteristics of hypersonic aircraft.

RT 3.1 - Investigate aerodynamic methods of providing stability and control for hypersonic configurations in the supersonic and hypersonic flight regime.

RT 3.2 - Investigate the effect of boundary layer transition, separation, and interaction with shock waves on attaining desired lift and drag and wave drag reduction for improved L/D.

RT 3.3 - Investigate the effect of engine exhaust plumes on lift, drag, and longitudinal stability at supersonic and hypersonic Mach numbers.

RO 4 - Provide new or update present testing techniques for aerodynamic research facilities so Reynolds number, shock wave, and boundary layer dependent phenomena can be correctly simulated using subscale models.

RT 4.1 - Investigate techniques to better approximate the free flight recovery temperature to skin temperature ratios for ground tests.

RT 4.2 - Develop techniques to allow determining more representative free flight aerodynamic data from conventional wind tunnels. Minimize extrapolation range and improve soundness of technical base.

RT 4.3 - Investigate relationship between boundary layer thickness and shock location on the local flow structure.

RO 5 - Define the design criteria and systems requirements for acceptable handling qualities for hypersonic aircraft.

RT 5.1 - Define fundamental parameters and levels of acceptance of flying qualities in longitudinal and lateral directional mode.

RT 5.2 - Investigate control systems response characteristics required to provide acceptable flying qualities for a hypersonic aircraft.

RT 5.3 - Investigate the interaction between control capability, structural flexibility, controls system dynamics, and pilot response as related to pilot induced oscillations.

RO 6 - Evaluate design techniques for obtaining favorable aerodynamic interference effects through surface or inlet positioning.

RT 6.1 - Investigate the flight trajectory/mission profile to identify those regions where reductions in installation losses provide meaningful overall performance increments.

RT 6.2 - Investigate inlet and control surface positioning to obtain most favorable interference.

RT 6.3 - Determine the magnitude of the force and moment decrement associated with geometric changes.

FIGURE 3-12 (CONTINUED) PHASE II RESEARCH TASKS

RT 6.4 - Evaluate trim changes and associated penalties which accompany off-design operation.

RO 7 - Evaluate design techniques of using the aircraft body for engine exhaust expansion, thereby providing lift. Determine the effect of propulsive gas flow interactions.

RT 7.1 - Determine simulation requirements (flow field and exhaust flow) for meaningful data return from ground tests of subscale models.

RT 7.2 - Investigate effects of afterbody contours (with engine operation) on aerodynamic characteristics over the flight Mach number range.

RO 9 - Investigate the effects of variable inlet and nozzle geometry, bypass airflow, propulsion mode changes, and aerothermoelastic effects on hypersonic aircraft stability and aerodynamic forces.

RT 9.1 - Delineate the relevance and specific requirements associated with individual propulsion systems concepts over their operating range.

RT 9.2 - Investigate methods of extending current aeroelastic test techniques.

RT 9.3 - Investigate implications of a flexible aircraft structure on the ability to maintain stability and desired aerodynamic force distribution.

RO 10 - Develop design principles for stage integration which provide reduced drag characteristics and other aerodynamic improvements throughout the speed range for two-stage hypersonic launch vehicles.

RT 10.1 - Evaluate launch mode stage integration concepts including configuration, performance, and structural design requirements.

RT 10.2 - Investigate the aerothermodynamic effects and the impact of the design concepts on flight vehicle performance.

RO 11 - Determine separation techniques for two-staged hypersonic vehicles which will provide positive separation and control of individual stages.

RT 11.1 - Identify attractive separation/vehicle concepts.

RT 11.2 - Define individual vehicle performance, control characteristics, and the effects of local flow field interactions during separation with and without exhaust gas simulation until the stages are free of mutual interference.

RT 11.3 - Investigate active, augmented, and passive control techniques initiated from the second stage control system during separation.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RT 11.4 - Evaluate the effect of the pressure fields created during separation on the structural dynamic characteristics of both stages. This task includes research into compatible measurement and analysis methods to obtain quantitative data.

RO 12 - Improve fundamental knowledge of hypersonic boundary layer behavior in the presence of adverse pressure gradients and shock interactions.

RT 12.1 - Investigate the effect of recovery temperature to surface temperature ratio on shock-induced flow separation tolerance at hypersonic Mach numbers.

RT 12.2 - Investigate the effect of shock strength and Reynolds number in the presence of varying pressure gradients on shock-induced flow separation tolerance which considers surface inclination, surface continuity, surface mass transfer, and boundary layer growth (laminar and turbulent).

RT 12.3 - Investigate unsteady control surface hinge moments due to boundary layer and shock wave interaction.

RO 14 - Develop correlation techniques for the prediction of buffet onset for low aspect ratio configurations, involving longitudinal (body) bending motions as well as wing bending responses.

RT 14.1 - Develop new techniques to reliably scale buffet intensity determined from wind tunnel models.

RT 14.2 Correlate buffet onset with geometric parameters such as aspect ratio, leading edge sweepback, and slenderness ratio.

RT 14.3 - Evaluate the effect of a non-steady flow field condition on buffet onset.

RT 14.4 - Correlate wind tunnel obtained buffet onset and intensity with a flight vehicle representative of an operational hypersonic vehicle.

RO 15 - Evaluate configuration shaping techniques and flight path variation for alleviating sonic boom intensity, and study near and far field noise levels.

RT 15.1 - Investigate sonic boom signature characteristics and near and far field noise frequency/intensity spectrum which constitute an irritation.

RT 15.2 - Investigate the feasibility of configuration shaping to materially affect the perceived sonic boom intensity.

RT 15.3 - Evaluate changes in perceived sonic boom intensity and noise levels as produced by variation in flight path.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RO 16 - Develop correlation methods for the prediction of heat transfer and friction drag for turbulent boundary layers with pressure gradients and three-dimensional flows for windward flows.

RT 16.1 - Perform experimental research on turbulent boundary layers in a realistic windward flow field. This task provides for correlation with analytical techniques, definition of laminar sublayer extent, and verification of applicability of Reynolds Analogy.

RT 16.2 - Conduct research at equivalent flight conditions to obtain verification of correlation techniques.

RO 17 - Determine correlations for the prediction of hypersonic boundary layer transition.

RT 17.1 - Investigate the mechanics of boundary layer transition as influenced by Reynolds number, Mach number, flow gradients, and noise.

RT 17.2 - Investigate the mechanisms of boundary layer transition which are affected by surface inclination, surface roughness, and angle of attack.

RO 18 - Investigate the use of strategically located reaction control jets on hypersonic aircraft to reduce the aerodynamic control surface deflection and surface heating.

RT 18.1 - Investigate and evaluate the effects of deflection angle on local control surface temperatures as a function of reaction jet thrust/time history and jet location.

RT 18.2 - Investigate reductions in control deflection (i.e., surface temperature) as a function of reaction jet thrust/time history and jet location.

RT 18.3 - Evaluate the relative payoff of reaction control weight as compared to reductions in control surface weight (thermal protection). This task includes considerations of flow field interaction (pressure, heat transfer) and reduction of jet efficiency as a function of external flow.

RO 19 - Determine the effectiveness of various types of control surfaces and their locations for providing sufficient control throughout the entire flight spectrum, and improve methods of predicting aerodynamic heating for deflected control surfaces.

RT 19.1 - Investigate effectiveness of various control concepts such as wing tip, trailing edge devices, all movable surfaces, and canards throughout the flight regime.

RT 19.2 - Investigate local control surface temperature as a function of deflection angle.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

THERMODYNAMICS

RO 20 - Determine the overall vehicle thermodynamic characteristics in hypersonic flight.

RT 20.1 - Investigate the heat transfer distribution for configuration concepts based on aerodynamic refinement of vehicle shape/contour, vehicle flight attitude, control surfaces/reaction jets, and multiple vehicle proximity.

RT 20.2 - Study and substantiate the analytical modeling of generalized and localized flow fields to provide corrections and extrapolation of model results in terms of full-scale values.

RO 22 - Investigate shaping of aerodynamic surfaces to reduce skin temperatures, and the effects of protuberances and surface irregularities on hypersonic aircraft drag and aerodynamic heating.

RT 22.1 - Evaluate methods of achieving significant reductions in skin temperature or increased surface temperature uniformity through specific local contouring.

RT 22.2 - Investigate the effects of surface irregularities on aerothermodynamic design and performance.

RT 22.3 - Investigate impact of thermal optimization on aerodynamic performance variables.

RT 22.4 - Study alternative material selection and thermal protection systems. Specify their requirements where temperature reductions through shaping are marginal. Determine the influence of surface irregularities/roughness on aerodynamic heating.

RO 23 - Determine the effects of transpirative or ablative processes on skin friction and heat transfer.

RT 23.1 - Investigate and describe the mechanisms of mass transfer peculiar to each process (ablation, transpiration) and the effects of these mechanisms on skin friction and heat transfer.

RT 23.2 - Develop an analytical model which characterizes the surface phenomena for each process.

RT 23.3 - Experimentally verify analytical model. Refine the model to reflect the impact of ablation and transpiration on skin friction and heat transfer.

RT 23.4 - Investigate the application of these techniques to time variant conditions corresponding to the flight profile, evaluating the impact of ablation and transpiration on overall vehicle performance.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RO 24 - Determine the effects of embedded shock, vortices, separation, and reattachment on skin friction and heat transfer for leeside flows.

RT 24.1 - Investigate phenomena associated with leeward flow in terms of separation boundaries and vortex formation so that adequate flow field description may be obtained over the Mach number/altitude range.

RT 24.2 - Investigate methods which will increase validity of experimental research on mixed boundary layer flow. This task includes correlation of vortex location and strength, definition of extent and strength of embedded shock waves, determination of separation and reattachment criteria, and verification of applicability of Reynolds Analogy.

RO 25 - Determine the aerodynamic heating effects produced by flow through gaps resulting from adjacent aircraft surfaces, and rapid changes in operational altitude.

RT 25.1 - Conduct generalized research into flow phenomena and characteristics associated with gaps created by closely adjacent surfaces. This task includes evaluation of the effects of flow field characteristics, pressure differential, and surface roughness.

RT 25.2 - Correlate generalized research data for realistic control surface aerodynamic and mechanical configuration with additional experimentation to determine change in local heat transfer rate, control effectiveness, and hinge moment.

RT 25.3 - Re-evaluate the interaction of a reaction control jet and a control surface minimizing adverse effects of control surface gaps.

RT 25.4 - Study interaction of structural breathing during climb and descent with local pressure and heat transfer conditions. This task includes considerations of baseline transpiration data, structural concept, flight profile/gap growth, and fabrication tolerances and technique.

RO 26 - Determine changes in heat transfer due to reduced radiation cooling efficiency resulting from vehicle geometric interactions (view factors).

RT 26.1 - Improve two- and three-dimensional analytical description of view factors for complex structural elements.

RT 26.2 - Evaluate structural concepts to determine influence of internal structural view factor on equilibrium surface temperature.

RT 26.3 - Evaluate configuration and engine concepts in terms of potential increased localized surface temperature due to changes in view factor caused by adjacent or intersecting surfaces.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RO 27 - Develop methods for predicting heat transfer due to radiation or gas impingement from engine exhaust.

RT 27.1 - Evaluate the severity of increases in heat transfer due to exhaust gas interaction. This task includes adequate definition of exhaust flow field and gaseous radiation, as well as application of view factor and hypersonic boundary layer data.

RT 27.2 - Determine simulation requirements (exhaust flow and heat transfer to external surface) for meaningful data return from ground tests of subscale models.

RT 27.3 - Experimentally develop methods for predicting heat transfer in the engine exhaust area and establish scaling laws.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

STRUCTURES AND MATERIALS

RO 28 - Develop efficient reusable tankage thermal protection systems for cryogenic fuels and oxidizers.

RT 28.1 - Evaluate potential of candidate materials systems (tank structure, insulation, and vapor barrier) in their operating thermal environment. This task includes consideration of chemical compatibility, physical properties, thermal performance, bonding and joining, and lifetime and duty cycles.

RT 28.2 - Assess feasibility of combining attractive materials into thermal protection concepts for cryogenic tankage. This task includes considerations of bonding and joining technique, tank penetrations, subsystems supports, thermal cycling, and equivalent panel conductivity.

RT 28.3 - Develop, fabrication, repair and non-destructive evaluation (NDE) inspection techniques and demonstrate them under simulated thermal/mechanical conditions.

RO 30 - Evolve more efficient concepts for fuselage and tank structures for both circular and non-circular applications.

RT 30.1 - Study integration of tankage into promising aerothermodynamic shapes.

RT 30.2 - Develop analytical models to allow determination of efficient and practical tank structural concepts. This task includes considerations of shell theory, tank surface/volume ratio, tank load carrying and support concept (integral vs non-integral), and geometric scaling.

RT 30.3 - Experimentally verify adequacy of analytical models to define tank structure.

RO 32 - Develop efficient reusable leading edge concepts and identify promising concepts for specific materials in relation to the flight regime.

RT 32.1 - Perform basic high temperature materials research for application in oxidizing environments. This task includes considerations of strength at temperature, creep resistance/time to rupture, oxidation resistance, and tenacity of oxide film.

RT 32.2 - Investigate applicability of coating concepts to extend basic materials limits and preserve coating integrity under realistic operating conditions. This task includes considerations of oxidation protection coatings, insulative coatings for higher surface temperature operation, and emissivity control.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RT 32.3 - Perform research integration of a coated materials system into leading edge concepts considering material compatibility with insulation and carrythroughs, feasibility of fabrication, coating sequence in manufacturing process, and joinability for major structural buildup.

RO 33 - Develop control surface technology, including thermal protection requirements, methods of attachment, sealing, methods of actuation, and thermal cycling.

RT 33.1 - Integrate available research results and define control surface physical and environmental boundaries.

RT 33.2 - Investigate the applicability of primary structural thermal protection systems to control surface design and perform additional research where required.

RT 33.3 - Demonstrate satisfactory performance of the control surface and associated hardware in a duplicated flight environment.

RO 34 - Develop long life regeneratively cooled structural concepts for application in high heat flux areas such as leading edges and propulsion systems.

RT 34.1 - Investigate the applicability of multiple/single fluid cooling concepts in the operational environment and specify required thermophysical properties of candidate heat exchanger materials.

RT 34.2 - Determine physical and chemical compatibility of candidate heat exchanger materials with heat exchange fluids in the operating temperature/pressure regime.

RT 34.3 - Analytically determine flow passage orientation and shape. This task includes considerations of heat transfer, flow velocity, operating pressure level, temperature distribution (panel ΔT and max wall temperature), and panel strength/weight.

RT 34.4 - Evaluate materials fabrication techniques for high temperature alloys. This task includes considerations of panel buildup, inspection, and integration into primary structure.

RT 34.5 - Demonstrate panel integrity and performance at desired operating conditions.

RO 35 - Provide a structure which maintains aerodynamic smoothness under actual operational conditions and use.

RT 35.1 - Establish allowable limits for surface irregularities based on prior research relative to vehicle performance and heating.

RT 35.2 - Verify compliance with surface irregularity criteria through structural tests.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RO 36 - Define the effects of combined mechanical loading and thermal stress cycling under actual environmental conditions on the life of the structural components.

RT 36.1 - Define environmental parameters affecting structural materials selection and identify candidate materials concepts.

RT 36.2 - Conduct extensive coupon testing for candidate materials as a function of time. This task includes consideration of physical properties, physical/chemical compatibility, and oxidation resistance (thermal).

RT 36.3 - Construct large-scale components and test under combined load conditions to verify coupon data and to establish a realistic measure of operating life.

RO 38 - Determine the effects of fuel slosh on the dynamics and inertia loads of low aspect ratio hypersonic aircraft with large volume fuel tankage.

RT 38.1 - Study slosh modes and intensities to determine the influence of the fluid dynamics on structural loading and tank design.

RT 38.2 - Investigate inertial forces and center of gravity perturbations produced by fuel slosh and translate this into effects on the stability and control of hypersonic aircraft throughout its flight regime. Identify those regions where this effect is significant.

RT 38.3 - Investigate methods to minimize fuel motion effects on the overall vehicle flight characteristics.

RO 39 - Determine the parameters of correlation for the analysis of the effects of near field noise on minimum gauge structures, composite structures, and non-metallics.

RT 39.1 - Examine potential hypersonic vehicles to identify those locations where the structure consists of minimum gauge, composite, and non-metallic materials; and identify the thermal/acoustical environment conditions, such as temperature/time history and power spectral density/time history.

RT 39.2 - Experimentally identify failure mechanisms of a structural element in an actual environment and develop an analytical model to describe the failure mode.

RO 40 - Develop non-destructive evaluation and inspection methods for sandwich structure, composite materials, diffusion bonded materials, and coatings.

RT 40.1 - Investigate non-destructive evaluation (NDE) methods which can potentially detect and identify structural failures.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RT 40.2 - Evaluate the effectiveness of NDE techniques through the use of "calibrated failure" specimens (calibrating output of NDE systems vs degree of failure).

RT 40.3 - Experimentally correlate degree of failure to magnitude of remaining operational life.

RO 41 - Develop a capability to accurately estimate component and structural mass fractions for all types of hypersonic aircraft designs.

RT 41.1 - Develop a matrix of weight accounting systems for each major component concept, reflecting parametric variations within the concept and specifying its applicability within discrete portions of the flight envelope.

RT 41.2 - Develop a discriminatory accumulation/recall technique for selecting and incorporating applicable portions of the matrix to arrive at integrated mass fraction estimates for major vehicle elements. Provisions should be made for a continual update (of each matrix element) of concept information and actual weight verification as that information becomes available, maintaining currency with the state of the art.

RO 42 - Verify the integrity of the structural and thermal-structural systems through full-scale section testing.

RT 42.1 - Demonstrate fully integrated structure (a major section of an operational system) and the capability to maintain individual component levels of performance under representative operating conditions. This task includes considerations of component assembly, structural interactions, structural damping, thermal protection system performance, and demonstration of maintenance/repair concepts.

RO 43 - Develop reusable thermal protection systems for the primary structure.

RT 43.1 - Correlate thermal protection system concepts with mission envelopes to provide candidate systems for development. This task includes considerations of flight profile and candidate systems whether active or passive.

RT 43.2 - Establish reusability criteria using non-destructive evaluation (NDE) concepts. This task includes considerations of mean time between failures, minimum time before maintenance, lifetime/duty cycles, and extent of maintenance and repair.

RT 43.3 - Develop (NDE) techniques and experimentally demonstrate the required reusability using full-scale structural components in a structural test/flow facility, fully simulating the operational environment.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RT 43.4 - Correlate experimental data with original analyses to determine adequacy of the analytical base and potential improvements through the use of experimental results.

0 44 - Define the mechanical and physical properties of advanced materials that have potential application in hypersonic aircraft.

RT 44.1 - Identify materials that, through their usage, can significantly improve the aircraft. This task includes considerations of metal matrix composites, high temperature titaniums, superalloys, and refractory metals.

RT 44.2 - Experimentally establish unavailable physical, chemical, and thermodynamic properties, as required for attractive candidates.

0 45 - Improve fabrication techniques for advanced materials and complex structures. These include: welding, diffusion bonding, and brazing of metals; composite forming; fabrication of sandwich structure; and fabrication of non-metallics.

RT 45.1 - Conduct basic research into fabrication techniques to identify those which have the potential to significantly improve overall aircraft performance for various structural concepts.

RT 45.2 - Specify applicable criteria to evaluate the fabrication technique, using a structural element under representative load conditions.

RT 45.3 - Perform coupon and element testing to investigate integrity of the fabricated specimen, also providing a means for refining inspection techniques.

RT 45.4 - Compile, correlate, and disseminate resultant data.

0 46 - Develop high temperature bearings, lubricants, closure seals, tires, windshields, and radomes.

RT 46.1 - Identify operating environment of the individual component under consideration. This task includes considerations of geometric location, flight envelope, and environmental cooling.

RT 46.2 - Define existing levels of material performance, as applicable to each component class, and identify requisite improvement in capability.

RT 46.3 - Evaluate existing test techniques to establish validity of data obtained, postulating new techniques where necessary.

RT 46.4 - Perform necessary parametric analysis, component test, and system demonstration to provide the required performance.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

PROPULSION

RO 48 - Develop inlet configurations that will enable the engine to achieve the desired performance over the range of desired flight conditions and engine operating modes.

RT 48.1 - Investigate geometric variables of the vehicle configuration upstream of the inlet, related to the quality of the local flow field at potential inlet locations over the operational range of α and β. Inlet placement should be evaluated in order to obtain favorable aerodynamic interference.

RT 48.2 - Experimentally study different inlet classes and describe the quality of flow delivered to the propulsion system for each inlet class as a function of operational variables such as attitude (α, β), Mach number, and Reynolds number.

RT 48.3 - Investigate scaling laws to allow determining minimum inlet size for meaningful data and to provide extrapolation rules from that base to full-scale.

RT 48.4 - Investigate inlet and forebody shapes to determine overall aerodynamic and engine airflow quality. This task includes considerations of additive drag, spill, bypass, and bleed drag, configuration L/D, aerodynamic stability, steady-state and time variant distortion, pressure recovery, and off-design operation.

RT 48.5 - Investigate the inlet problems associated with use of a common inlet for combinations of engine concepts.

RO 52 - Develop engine design concepts amenable to cooling by various techniques (regeneration, ablation, radiation, transpiration).

RT 52.1 - Investigate existing engine concepts throughout their applicable Mach number range to determine what conceptual alterations would result from considering active cooling at inception of the concept.

RT 52.2 - Define component technology levels and their design/performance requirements for the more feasible concepts in each Mach number range.

RT 52.3 - Experimentally evaluate individual component performance, using this data as a baseline to assess overall cooled-engine concept feasibility and resulting performance increments.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RO 55 - Investigate methods for reducing engine noise during takeoff and landing.

RT 55.1 - Determine the relative significance of individual component contributions to the apparent noise level by using existing turbojet and rocket engines modified to reflect advanced engine concepts. This task includes evaluation of such measurements as power spectral density, spatial intensity distribution, and engine design parameters (bypass, tip speeds, exhaust velocity, nozzle expansion, inlet guide vanes).

RT 55.2 - Evaluate the variation in perceivable noise of operation of the aircraft near the ground.

RT 55.3 - Investigate incorporating either design changes or acoustic attenuation material into the engine concept which provide acceptable noise levels and do not significantly degrade engine performance.

RT 55.4 - Establish guidelines for future testing, engine design, and aircraft operational criteria.

RO 57 - Develop and integrate engine components into a complete large-scale turboramjet system. Demonstrate compatibility and overall performance throughout an applicable flight envelope.

RT 57.1 - Perform cycle analysis for each engine concept in all operating modes to determine the desired levels of performance for individual components.

RT 57.2 - Formulate potential design concepts for each turboramjet component. This task includes considerations of materials selection, thrust/weight, operating stress levels, case temperatures and pressures, and concept reliability.

RT 57.3 - Investigate engine qualification techniques (considering facility capability) and establish a qualification and acceptance program for turboramjet engines.

RT 57.4 - Verify technology of component design and operation through experiment at operating conditions.

RT 57.5 - Integrate proven components into a demonstrator engine system and demonstrate its performance.

RT 57.6 - Demonstrate integrated (inlet/engine/nozzle concept) propulsion systems performance over the range of Mach number, altitude, and attitude.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RO 58 - Perform sufficient cycle analysis and mission analysis to select the best multi-mode cycle and size engine for application to a specific hypersonic mission aircraft.

RT 58.1 - Defines representative mission profiles in order to identify the dominant characteristics which drive installed engine performance levels.

RT 58.2 - Integrate cycle analyses and select candidate engine concepts consistent with mission requirements. This task includes studies of single mode, combination single mode, composite cycle, and dual mode engines.

RT 58.3 - Perform mission performance studies, identifying the most attractive integrated propulsion system concept satisfying the performance objectives. This task includes considerations of aerodynamic performance, installed engine performance, and aircraft configuration.

RO 59 - Develop and integrate engine components into a complete, large-scale ramjet system. Demonstrate compatibility and overall performance throughout an applicable flight envelope.

RT 59.1 - Perform cycle analysis for ramjet engine concepts to establish necessary levels of performance, operating environment, and limiting conditions for engine starting.

RT 59.2 - Formulate potential design concepts for each ramjet component. This task includes considerations of materials selection, thrust/weight, operating stress levels, case temperatures and pressures, and concept reliability.

RT 59.3 - Investigate engine qualification technique (considering facility capability) and establish a qualification and acceptance program for ramjet engines.

RT 59.4 - Verify technology of component design and operation through experiment at operating conditions.

RT 59.5 - Integrate proven components into a demonstrator engine system and demonstrate its performance.

RT 59.6 - Demonstrate integrated (inlet/engine/nozzle) propulsion systems' performance over the range of Mach number, altitude, and attitude.

RO 60 - Develop and integrate engine components into a complete significantly sized convertible scramjet module. Demonstrate compatibility and overall performance throughout an applicable flight envelope.

RT 60.1 - Perform cycle analysis for dual mode ramjet (convertible scramjet) modules to establish necessary levels of performance, operating environment, and Mach number limits for engine starting, for both the subsonic and supersonic combustion modes.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RT 60.2 - Formulate potential design concepts for each convertible scramjet component. This task includes considerations of materials selection, thrust/weight, operating stress levels, surface temperatures and pressures, and concept reliability.

RT 60.3 - Investigate engine qualification technique (considering facility capability) and establish a qualification and acceptance program for convertible scramjet engines.

RT 60.4 - Verify technology of component design and operation through experiment at operating conditions.

RT 60.5 - Integrate proven components into a demonstration engine module to serve as an operable base line for demonstration and determine its performance characteristics.

RT 60.6 - Demonstrate integrated (inlet/engine/nozzle) propulsion systems performance over the range of Mach number, altitude, and attitude.

RO 61 - Develop and integrate engine components into a complete, significantly sized scramjet module. Demonstrate compatibility and overall performance throughout an applicable flight envelope.

RT 61.1 - Perform cycle analysis for scramjet module concepts to establish necessary levels of performance, operating environment, and Mach number limits for engine starting.

RT 61.2 - Formulate potential design concepts for each scramjet module component. This task includes considerations of materials selection, thrust/weight, operating stress levels, surface temperatures and pressures, and concept reliability.

RT 61.3 - Investigate engine qualification technique (considering facility capability) and establish a qualification and acceptance program.

RT 61.4 - Verify technology of component design and operation through experiment at operating conditions.

RT 61.5 - Integrate proven components into a significantly sized engine module and demonstrate its performance.

RT 61.6 - Demonstrate integrated (inlet/engine/nozzle) propulsion systems performance over the range of Mach number, altitude, and attitude.

RO 62 - Integrate a rocket engine into a horizontal takeoff aircraft configuration and demonstrate system performance throughout an applicable flight envelope.

RT 62.1 - Investigate potential aircraft configurations and rocket engine systems (including fuel tankage concepts) and select the most promising combination for demonstration purposes.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RT 62.2 - Integrate engine and airframe into a demonstration vehicle. This task covers design, development, fabrication, and assembly of a significantly sized system.

RT 62.3 - Demonstrate operation of the engine and airframe system from launch throughout an extensive maneuvering flight envelope of Mach number, altitudes, and attitudes.

RO 63 - Develop inlet controls for hypersonic aircraft which are simple, reliable, accurate, and have rapid response.

RT 63.1 - Using established inlet and control envelope baseline high temperature actuator systems, establish adequacy of baseline capability in terms of thermal environment, and precision of control positioning and operating speed at inlet operating temperatures.

RT 63.2 - Research techniques of sensor control which contribute to desired levels of performance.

RO 64 - Evaluate suitability of auxiliary turbojets for landing of hypersonic vehicles.

RT 64.1 - Investigate the operational aspects of a turbojet assisted landing mode for hypersonic configurations to delineate advantages of power assisted descent and landing, deployment point in terminal trajectory, and thrust vector orientation.

RT 64.2 - Study design concepts to incorporate turbojet assist for landing mode, if found operationally desirable.

RT 64.3 - Determine low speed stability and handling qualities with turbojet assist and compare with baseline landing mode data for hypersonic configurations.

RO 65 - Determine nozzle configurations which produce high net thrust while maintaining efficient integration with the airframe.

RT 65.1 - Analyze the engine exhaust nozzle requirements for the different classes of engines studied. Define necessary performance and possible nozzle configurations for the range of flight conditions associated with each engine concept. Consider the implications of integrating the nozzle concepts into airframe configuration.

RT 65.2 - Establish both scaling laws and simulation requirements for the different classes of engines to permit valid data for integrated engine/airframe configurations.

RT 65.3 - Investigate the engine net thrust, afterbody, and boattail drag over a representative flight regime, identifying the features which contribute favorably to exhaust nozzle/airframe integration for the engine concepts.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RO 67 - Determine inlet/engine compatibility criteria (both steady-state and time-varying) for high-total-pressure-recovery, wide Mach range inlets.

RT 67.1 - Study the engine simulation technique currently used for wind tunnel tests. Develop techniques representative of the pneumatic/acoustic impedences and operational characteristics of hypersonic aircraft engine concepts.

RT 67.2 - Investigate techniques for duplicating the flow disturbances and their effect on the time variant engine face pressure distributions, permitting evaluation of actual engine operations in the presence of these disturbances.

RT 67.3 - Study and correlate data using the improved techniques so that descriptive parameters can be derived which will indicate the tolerance of a given engine concept to steady-state and time variant flow non-uniformities.

RT 67.4 - Translate research results into integration criteria and engine/inlet design guidelines (continually updated) which represent a current statement of the technology and provide a credible base for development of future aircraft.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

SUBSYSTEMS

RO 68 - Develop operational systems and procedures for the thermal conditioning, storage, safe handling, and logistics of cryogenic propellants which are compatible with typical airfield requirements.

RT 68.1 - Conduct basic research into subcooling (including slush) methods and analyze attractiveness in terms of capital investment, operational cost, and complexity required to significantly improve performance. This task includes study of such methods as low pressure boiloff (vacuum pumping), helium refrigeration, and isentropic expansion.

RT 68.2 - Provide a "pilot plant" subcooling system to permit experimental research into potential development problems, operational requirements, and verification of the subcooling technique as applied to large-scale continuous production.

RT 68.3 - Investigate attractive methods to provide techniques for safe, efficient storage and transport of normal boiling point and subcooled cryogenic propellants. Consideration is given to global support and minimum base/facility requirements.

RO 69 - Develop analytical correlation techniques through empirical evaluation to permit the determination of the fluid dynamic and thermodynamic characteristics of cryogenic propellants in large horizontal tankage in a vibrating, sloshing, pressurized environment.

RT 69.1 - Investigate contemporary vertical tank correlation techniques and research their capability to account for transverse geometric and acceleration characteristics. Study the parametric variations in slosh, tank outflow, and heat flux to determine the effects upon overall heat and mass transfer within the tank, propellant gas quantities, and tank pressure recovery/response rates.

RT 69.2 - Design, develop, and test subscale tankage to either substantiate available correlations or to permit developing new correlations. Research must include simulation of dynamic, pressurized, thermal aircraft environment.

RT 69.3 - Evaluate the effects of slosh suppression techniques and subcooled (including slush) vs NBP operation on pressurant collapse potential, tank pressure recovery, and minimum ullage capability.

RO 70 - Develop regenerative cryogenic heat exchangers, thermodynamic correlations, and control systems for structural and engine cooling which are compatible with representative heat loads and material temperature limits.

RT 70.1 - Perform experimental research to establish fluid correlations for film coefficient, pressure drop, and pressure oscillations in the range of fluid properties near critical temperature or pressure of the fluid.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RT 70.2 - Experimentally characterize material properties and fabrication techniques for use in high temperature hydrogen heat exchanger environments.

RT 70.3 - Develop and operate high temperature heat exchanger panels, high heat flux heaters, and high temperature control hardware (hot gas valves) to determine their suitability when exposed to a simulated aircraft environment. This will include evaluation of ultimate heat flux capabilities, and life/duty cycles, and determination of control adequacy.

RO 71 - Improve the performance of new or existing hydrocarbon fuels by increasing the heat sink potential and heat of combustion.

RT 71.1 - Experimentally determine the capability of existing JP fuels, utilizing propulsion data to establish fuel performance criteria for generic engine and cooling concepts.

RT 71.2 - Perform basic research to evaluate methods for extension of thermal limits of current fuels. This task includes considerations of deoxygenation/inert pressurization, desulfurization and hydrotreating, use of additives, and vaporized/supercritical fluid operation.

RT 71.3 - Develop catalyst systems with reaction rate/system weight and cooling flexibility characteristics consonant with high temperature/high speed aircraft operation with catalytic endothermic fuels.

RT 71.4 - Evaluate various high density, high energy blends and additives for advanced fuels and determine impact on vehicle and fuel manufacture and logistics requirements.

RT 71.5 - Determine the effects of fuel additive capabilities and fundamental combustion properties for high Mach number propulsion systems through subscale engine and cooling rig tests.

RO 72 - Determine fuel system design requirements imposed by the use of thermally stable and endothermic fuels in high temperature aircraft environments.

RT 72.1 - Perform research to establish contamination limits for the fuels. This may include testing to evaluate the compatibility of fuel system (ground and flight) materials to ensure that minimum degradation of thermally stable and endothermic fuels can be caused by dissolved substances which might either precipitate or inhibit catalytic reactions.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RT 72.2 - Investigate inert pressurization techniques and investigate the feasibility of airborne systems to ensure preservation of fuel thermal/oxidative stability. This task includes considerations of GN_2 (inert gas by direct addition), catalytic combustion (inert gas product), and fuel fog (above fuel rich limit).

RT 72.3 - Identify unique ground support and logistics requirements to effectively handle (without potential chemical reaction) and maintain fuel purity.

RO 73 - Advance the technology of cryogenic fuel system components in the areas of reduced weight and increased reliability. Particular emphasis should be applied to liquid hydrogen static and dynamic sealing and rotating machinery operating in a cryogenic environment.

RT 73.1 - Analyze existing cryogenic fuel system component concepts and evaluate potential for major performance improvements by virtue of either reduced weight or increased reliability.

RT 73.2 - Formulate potential design concepts for each component considering such factors as equivalent operational envelope, materials selection, and component control/speed.

RT 73.3 - Perform experimental research for the attractive design concepts to verify component performance levels or to experimentally investigate component improvement in an equivalent operational environment.

RO 74 - Determine rapid cryogenic servicing techniques necessary to achieve required reaction and turnaround times for military and commercial vehicles.

RT 74.1 - Investigate aircraft pumping rate operational criteria to determine fuel loading rates consistent with aircraft ground turnaround requirements.

RT 74.2 - Assess limiting geometric measuring equipment and operational parameters within which meaningful data may be acquired on reduced scale tankage systems.

RT 74.3 - Perform a parametric evaluation to fully characterize those factors having a major impact on vehicle turnaround/loading rates. This task includes considerations of chilldown rate, vent sizing, flow velocity, hazards, subcooled fuel.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RO 75 - Develop aircraft fuel tankage concepts, system operation, and control techniques for cryogenically fueled aircraft.

RT 75.1 - Evaluate various tankage/insulation concepts to determine the advantages of each configuration. Potential concepts include integral/non-integral tankage and internal/external insulation systems; which can be evaluated on the basis of installed weight, thermal efficiency, development risk, and overall system cost.

RT 75.2 - Develop fuselage/tankage sections to permit experimental determination of potential performance and to identify suitable scaling factors, the relative importance of geometric scale, and the effects of fuel flow rates, thermal environment, pressure loads, mechanical loads, and dynamic motion.

RT 75.3 - Determine control techniques for fuel utilization and management, and determine pressurization requirements during both static and dynamic environments.

RO 77 - Determine flush or recessed antenna design techniques necessary to allow operation in the elevated hypersonic temperature environment.

RT 77.1 - Investigate size, shape, and construction requirements of antenna systems for communication, navigation, identification, reconnaissance, and electronic warfare functions at the altitudes, velocities, and ranges of typical hypersonic vehicle mission trajectories.

RT 77.2 - Study the structure of vehicles which have been designed for hypersonic flight and determine feasible antenna locations for flush-mounted antenna systems. This task includes evaluation of structural integrity, thermal protection, and adequate look angles.

RT 77.3 - Perform mathematical analyses to the depth required to obtain a high degree of confidence in predicting temperature, shock and vibration profiles of the selected antenna locations for typical flight trajectories associated with hypersonic vehicles.

RT 77.4 - Survey materials technology for products that will provide the electrical characteristics required for an acceptable antenna system while under the predicted flight environments of temperature, shock, and vibration.

RT 77.5 - Design and construct sample antenna hardware for research tests of such factors as structural integrity, transmission patterns, and frequency stability.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RO 78 - Investigate stability augmentation systems capable of control in the hypersonic region, and recovery from pilot-induced oscillations.

RT 78.1 - Analyze the vehicle dynamics over the flight profile to determine stability augmentation requirements for potential operational hypersonic vehicles.

RT 78.2 - Research stability augmentation system requirements relative to flying an unstable aircraft.

RT 78.3 - Investigate and demonstrate methods to ensure qualification of desired levels of performance, prior to aircraft development.

RO 79 - Determine air data measurement techniques applicable to the hypersonic environment.

RT 79.1 - Perform a study to determine those parameters, sensors, and calibration techniques required to define the airplane environment for control and data analysis.

RT 79.2 - Investigate calibration techniques applicable to flight vehicles that can survive the flight environment and provide the necessary data.

RT 79.3 - Demonstrate proper operation of the sensors and air data system inflight environments over the Mach number, altitude, and attitude range consistent with the operational vehicle concept under consideration.

RO 80 - Develop actuation techniques and hardware to provide necessary surface motion.

RT 80.1 - Investigate surface travel and response requirements and drive system operational environment consonant with operational system flight envelope.

RT 80.2 - Review existing materials properties, determine limiting operating temperatures, their impact on vehicle design, and initiate studies directed toward providing higher temperature fluids and seals where necessary.

RT 80.3 - Investigate the relative merits of alternative control drive system selection; i.e., hydraulic vs pneumatic vs mechanical.

RT 80.4 - Perform research on basic actuation techniques and drive systems to demonstrate performance, reliability, and operational limits in a simulated operational environment.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RO 82 - Develop auxiliary power units for rocket, scram, and ramjet powered aircraft, including necessary emergency power equipment in case of primary unit failure.

RT 82.1 - Evaluate various methods/energy sources for obtaining auxiliary power for rocket, scram, and ramjet powered aircraft. Potential sources of available energy which should be considered include bleed air, ram air, aerodynamic heating, and fuel combustion. Studies will include evaluation of energy conversion techniques and the use of regenerative gas supply, fluid pumps, electric generator/motors, auxiliary turbine engines, and thermoelectric devices.

RT 82.2 - Study integration of the most promising concepts with vehicle and propulsion system to determine operational and load requirements/constraints.

RT 82.3 - Experimentally develop basic APU Components, evaluating performance, reliability, and operational constraints when subjected to the anticipated thermal/dynamic environment.

RT 82.4 - Assemble components into prototype operational systems and perform developmental testing including simulation of temperature, loads, and potential component failure modes.

RO 83 - Develop environmental control systems utilizing liquid cryogens as the heat sink, based on allowable internal wall temperatures for crew and passenger comfort and effectiveness.

RT 83.1 - Investigate the usefulness of liquid cryogens as a reliable heat sink for environmental cooling. This task includes considerations of flight heat loads, cabin and compartment cooling, and accessory heat loads.

RT 83.2 - Provide a functional prototype of an ECS system and demonstrate obtainable levels of reliability and performance under simulated operational conditions.

RO 84 - Develop environmental control systems for Mach 4 to 6 hydrocarbon fueled vehicles, based on allowable internal wall temperatures for crew and passenger comfort and effectiveness.

RT 84.1 - Investigate the suitability of current ECS concepts, as applied to this class of vehicle, and determine alternatives and combinations for achieving desired performance levels.

RT 84.2 - Provide a functional prototype of an ECS system and demonstrate obtainable levels of reliability and performance under simulated operational conditions.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RO 85 - Develop launch techniques for AAM and ASM weapons in hypersonic flight.

RT 85.1 - Investigate the potential threat/target spectrum relative to operational vehicle track to enable evaluation of end game tactics for candidate missile systems.

RT 85.2 - Study methods for integration of the candidate weapons system based on experimental data.

RT 85.3 - Establish design guidelines for combinations of operational systems concepts, threat/target spectrum, missile systems, and launch techniques applicable to development of the operational aircraft system.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

OPERATION

RO 87 - Evaluate various methods of terminal approach, landing, ground operations, and takeoff for hypersonic aircraft.

RT 87.1 - Study and compare operational procedures for the potential operational hypersonic aircraft with those existing for current operational aircraft. Identify where and to what extent differences exist.

RT 87.2 - Investigate the adequacy of existing facilities to accommodate hypersonic aircraft operational requirements. Define programs for improving existing capability where appropriate.

RT 87.3 - Investigate minimum modification approaches to existing facilities and determine impact on potential operational vehicle concepts, including the feasibility of the vehicle itself.

RT 87.4 - Experimentally demonstrate ground system capability to accommodate hypersonic aircraft.

RO 89 - Investigate man-machine compatibility as related to the decision/time aspects of course alteration of a hypersonic vehicle at both high and low Mach numbers.

RT 89.1 - Study various classes of potential operational vehicles and determine navigational requirements, degree of manual control, and pilot display concepts.

RT 89.2 - Investigate the capability of existing ground, celestial, and satellite navigational systems in terms of the navigational requirements and evaluate potential improvements to provide the needed capability.

RT 89.3 - Investigate the navigational and information display systems to determine which combinations best satisfy the mission/vehicle requirements. This task considers fuel reserves/loiter time, diversion to alternate bases, and vehicle range/speed envelope.

RO 93 - Investigate effects of vehicle dynamics on crew performance capability and passenger comfort in hypersonic flight.

RT 93.1 - Establish the definition of passenger comfort (comfort index) and tolerances as a function of vehicle motion, and interior thermal environment for commercial operations. This task includes mission analysis, operational concept, environmental control/physical comforts, motion simulation/degree of constraint, general public acceptance and use.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RT 93.2 - Establish the definition of crew performance as a function of force, vehicle motion, and interior thermal environment. This task includes considerations of mission analysis, operational concepts, environmental control, professional crew, and scientist/astronaut.

RT 93.4 - Investigate the feasibility of techniques to supplement human tolerances and responses to allow maximum attainment of aircraft performance. Establish design criteria for modifying the transmission of abrupt forces and motions to insure satisfactory ride quality.

RO 94 - Develop abort and crew escape systems and procedures for hypersonic aircraft.

RT 94.1 - Analyze the missions of different classes of hypersonic aircraft. Include military systems, launch vehicles, and commercial vehicles. Investigate and establish the abort and crew escape criteria for different points on the flight trajectory from departure through landing. Consider airborne crew escape, ground crew/passenger escape, crashes/egress over hot structure, and fuel storage/disposal.

RT 94.2 - Investigate methods to provide the necessary procedures, vehicle concepts, and devices to attain a level of safety consistent with vehicle mission and flight condition.

RT 94.3 - Evaluate procedures as they impact the hypersonic aircraft concept. Consider such factors as concept feasibility, aircraft design, vehicle manufacture, and systems operation.

RT 94.4 - Investigate methods to adequately demonstrate the desired abort/crew escape procedures and systems. Perform the experimental research necessary to qualify the abort procedures and escape methods.

RO 96 - Define and demonstrate the capability to stay within specified operational margins and not exceed aircraft placards (i.e., duct pressure, temperature, stability, dynamic pressure, and load factor limits).

RT 96.1 - Define the limits on operational parameters throughout the flight path and maneuvering envelope for different hypersonic aircraft concepts.

RT 96.2 - Investigate suitable crew warning techniques which may also provide automatic corrective action where necessary. Experimentally investigate attractive concepts such as adoptive control, audio warning, visual presentation/display, and control limiting devices.

FIGURE 3-12 (CONTINUED)
PHASE II RESEARCH TASKS

RO 97 - Develop leak detection methods for cryogenic propellant tanks.

RT 97.1 - Investigate the principles of fuel leak detection for flight vehicle cryogenic tankage and fuel systems and current methods for determination of external leakage. Postulate and evaluate potential new concepts where appropriate.

RT 97.2 - Experimentally determine the effectiveness of a network of sensing systems.

RT 97.3 - Investigate operation of most promising systems under simulated thermal and mechanical environment, and scale the system to representative flight weight size.

RO 99 - Investigate techniques for shortening takeoff runs by using forced rotation, including gimballed rocket and canard techniques.

RT 99.1 - Investigate effect of techniques applicable to forced rotation on the overall aerodynamic characteristics such as canards, auxiliary rockets, and gimballed main rockets.

RT 99.2 - Analyze the feasibility of the technique relative to such considerations as control system requirements, thrust required and control, pilot orientation, airframe integrity, and runway consideration.

RT 99.3 - Investigate crew aircraft operational techniques which may result in shorter takeoff runs.

RT 99.4 - Demonstrate techniques consistent with providing technology level required for the potential operational hypersonic aircraft under consideration.

RO 100 - Develop practical ground hold methods for cryogenic systems leading to quick response times and high operational readiness.

RT 100.1 - Perform systems analysis and studies to identify ground cooldown/thermal maintenance systems size, complexity and cost envelopes.

RT 100.2 - Experimentally identify major factors limiting flow rates for rapid chill/fill techniques, including identification of benefits attributable to prechilling (or subcooling) the fuel, and the influence of any residual fuel in the tanks after flight.

RT 100.3 - Identify impact of each candidate ground system on design and operation of the flight vehicle: Tradeoff ground hold concept vs rapid chilldown/fill techniques.

FIGURE 3-12 (Continued)
PHASE II RESEARCH TASKS

RT 100.4 - Demonstrate combinations of rapid filling ground hold techniques to identify most promising system for shortest reaction/turnaround times.

RO 102 - <u>Develop inspection and repair techniques for hypersonic vehicle structures.</u>

RT 102.1 - Compile testing, inspection, and repair techniques so that a comprehensive view of the scope and impact of this objective may be assessed as related to an operational hypersonic vehicle.

RT 102.2 - Investigate methods to incorporate these procedures into a useful, workable program for an operational system. In a simulated operational situation, develop the candidate techniques and provide the required training to achieve an operational level of competence.

3.4.2 PRESENTATION OF RESEARCH TASK INTRINSIC VALUES - Intrinsic values for each of the Research Tasks are presented in Figures 3-13 through 3-21. These values are limited in each case by the intrinsic value of the corresponding Research Objective.

In order to reduce research requirements mechanization to manageable proportions, the Research Task intrinsic values are summed for each Research Objective to form a task intrinsic value sum. These sums are then used in the reminder of the Phase II research requirements analysis to obtain the research value of the candidate ground facilities and flight research vehicles.

3.5 RESEARCH VALUE ANALYSIS

The purpose of the research requirements analysis is to provide research value inputs to the selection of the best combination of ground facilities and flight research vehicles. An initial step in determining facility research values is establishment of the research capabilities of existing facilities, considered collectively, to satisfy each of the Research Objectives pertaining to a particular operational system. Next, the percentage which can be accomplished of the research involved in each Research Objective is determined for each candidate new ground facility and flight research vehicle (in conjunction with existing facilities). When these percentages are combined with the task intrinsic value sums, a value results for each new facility in relation to the tasks under each Research Objective. These values are then summed over all the objectives applicable to a particular operational system to determine the facility research value for each candidate facility relative to that operational system. These research value summations can be used to determine the relative research effectiveness of each ground facility and flight research vehicle.

3.5.1 EXISTING FACILITIES CAPABILITY - The capability of existing ground facilities to satisfy the research requirements associated with each of the nine operational systems is presented in Figure 3-22, in terms of the percentage of the desired research achievable by the spectrum of existing U.S. facilities. These values were determined by specialists in each of the technology areas (aerodynamics, thermodynamics, structures and materials, propulsion, subsystems, and operation).

In line with efforts to streamline and improve the research value analysis, the number of operational systems considered was reduced from nine to four for the remainder of the Phase II analysis. Evaluation of research requirements results to this point in the study revealed that four operational systems, L_2, C_1, M_1 and M_2 were representative of the spectrum of nine potential systems. System L_2 is representative of the class which also includes C_2 and covers launch vehicle systems as well as Mach 8 to 10 turbojet/convertible scramjet systems. System C_1 is similar to L_1 and represents Mach 5 to 7 turboramjet vehicles for launch and commercial applications. The Mach 4.5 interceptor, M_1, is the only system in its class. The Mach 12 system, M_2, is representative of the class which also includes L_3, L_4 and M_3, covering launch systems and military aircraft employing rocket plus scramjet propulsion systems. Reference to the facility capability data presented in Figure 3-22 substantiates, in general, this selection of representative operational systems.

FIGURE 3-13
RESEARCH TASK INTRINSIC VALUES

OPERATIONAL SYSTEM NO. 1-(L1)

OBJ. NO.	OBJECTIVE INTRINSIC VALUE	TASK INTRINSIC VALUES TASK= 1	2	3	4	5	6	TASK INTRINSIC VALUE SUM
1	56.0	50.4	35.3	25.2	40.3	40.3	25.2	216.7
2	56.6	50.9	45.8	40.8	40.8			178.3
3	70.5	70.5	63.4	56.4				190.3
4	65.0	52.6	58.5	46.8				157.9
5	56.6	56.6	45.3	50.9				152.8
6	54.7	43.8	54.7	49.2	43.8			191.4
7	57.5	41.4	51.7					93.1
9	50.9	48.7	43.8	39.0				131.5
10	47.9	43.1	38.8					81.9
11	52.6	42.1	52.6	47.3	42.1			184.1
12	59.9	53.9	48.5	48.5				150.9
14	39.2	35.3	39.2	31.4	39.2			145.0
15	40.4	36.4	29.1	32.7				98.2
16	56.6	56.6	50.9					107.5
17	51.9	46.7	37.4					84.1
19	56.8	51.2	41.0					92.2
20	54.9	49.3	54.8					104.1
22	52.6	47.3	42.6	42.6	37.9			170.4
23	39.5	39.5	35.5	35.5	31.6			142.2
24	56.5	50.8	56.5					107.3
25	45.9	33.0	36.7	29.4	33.0			132.2
26	55.3	44.8	49.8	39.8				134.4
27	41.9	33.5	26.8	30.2				90.5
28	73.5	66.1	66.1	73.5				205.8
30	57.8	37.0	46.2	32.4				115.6
32	58.4	47.3	42.0	52.6				141.9
33	61.6	49.3	39.4	49.3				138.0
34	70.9	63.8	56.7	56.7	63.8	70.9		312.0
35	36.5	29.6	32.8					62.4
36	61.5	44.3	49.2	39.4				132.8
38	37.4	33.7	30.7	30.3				94.7
39	41.3	33.0	29.7					62.9
40	59.0	42.5	47.8	53.1				143.4
41	51.4	51.4	46.3					97.7
42	62.5	62.5						62.5
43	7 .6	65.3	58.1	72.6	58.1			254.1
44	64.8	52.5	58.3					110.8
45	64.0	57.6	46.1	51.8	40.3			195.8
46	53.4	43.3	38.4	33.6	48.1			163.4
48	66.0	52.8	66.0	46.2	59.4	46.2		270.6
52	58.3	37.3	42.0	46.6				125.9
57	68.8	55.0	55.0	48.2	61.9	68.8	61.9	350.9
58	64.4	46.4	52.2	58.0				156.5
59	67.4	53.9	53.9	60.7	53.9	67.4	60.7	350.5
63	52.5	37.8	47.2					85.0
65	58.7	47.5	47.5	52.8				147.9
67	65.4	47.1	47.1	53.0	58.9			206.0
68	40.3	29.0	32.7	25.8				87.0
69	36.9	25.8	36.9	33.2				95.9
70	46.1	36.9	41.5	46.1				124.5
71	33.4	24.0	30.1	21.0	18.0	21.0		114.2
72	36.6	25.6	23.1	17.9				66.6
73	41.9	30.2	26.4	37.7				94.3
75	45.8	36.6	45.8	41.2				123.7
77	26.5	16.0	16.0	18.2	20.5	22.8		93.5
78	39.5	35.5	32.0	28.4				96.0
79	29.9	18.8	24.2	26.9				70.0
80	41.0	32.8	36.9	36.9	41.0			147.6
82	32.8	26.2	26.2	29.5	32.8			114.8
83	38.7	27.9	34.8					62.7
87	37.9	30.3	27.3	24.3	27.3			109.2
89	42.7	30.7	34.6	38.4				103.8
93	29.3	23.7	23.7	26.4	21.1			94.9
94	39.4	35.5	35.5	31.5	39.4			141.8
96	35.1	25.3	31.6					56.9
97	36.4	26.2	29.5	32.8				88.5
102	37.5	30.0	37.5					67.5

FIGURE 3-14
RESEARCH TASK INTRINSIC VALUES
OPERATIONAL SYSTEM NO. 2-(L2)

OBJ. NO.	OBJECTIVE INTRINSIC VALUE	TASK INTRINSIC VALUES TASK= 1	2	3	4	5	6	TASK INTRINSIC VALUE SUM
1	58.1	52.3	36.6	26.1	41.8	41.8	26.1	224.8
2	58.0	52.2	47.0	41.8	41.8			182.7
3	70.9	70.9	63.8	56.7				191.4
4	66.1	53.5	59.5	47.6				160.6
5	58.1	58.1	46.5	52.3				156.9
6	56.2	45.0	56.2	50.6	45.0			196.7
7	58.9	42.4	53.0					95.4
9	62.0	49.6	44.6	39.7				133.9
10	48.9	44.0	39.6					83.6
11	53.5	42.8	53.5	48.1	42.8			187.2
12	61.4	55.3	49.7	49.7				154.7
14	40.9	36.8	40.9	32.7	40.9			151.3
15	41.6	37.4	30.0	33.7				101.1
16	57.8	57.5	52.0					109.8
17	53.2	47.9	38.3					86.2
18	34.4	31.0	27.9	27.9				86.7
19	58.4	52.6	42.0					94.6
20	54.8	49.3	54.8					104.1
22	52.6	47.3	42.6	42.6	37.9			170.4
23	39.5	39.5	35.5	35.5	31.6			142.2
24	56.5	51.8	56.5					107.3
25	45.9	33.0	36.7	29.4	33.0			132.2
26	55.3	44.8	49.8	39.8				134.4
27	41.9	33.5	26.8	30.2				90.5
28	73.5	66.1	66.1	73.5				205.8
30	57.8	37.0	46.2	32.4				115.6
32	58.4	47.3	42.0	52.6				141.9
33	61.6	49.3	39.4	49.3				138.0
34	70.9	63.8	56.7	56.7	63.8	70.9		312.0
35	36.5	29.6	32.8					62.4
36	61.5	44.3	49.2	39.4				132.8
38	37.4	33.7	30.3	30.3				94.2
39	41.3	33.0	29.7					62.8
40	59.0	42.5	47.8	53.1				143.4
41	51.4	51.4	46.3					97.7
42	62.5	62.5						62.5
43	72.6	65.3	58.1	72.6	58.1			254.1
44	64.8	52.5	58.3					110.8
45	64.0	57.6	46.1	51.8	40.3			195.8
46	53.4	43.3	38.4	33.6	48.1			163.4
48	66.6	53.3	66.6	46.6	59.9	46.6		273.1
52	58.8	37.6	42.3	47.0				127.0
58	65.1	46.9	52.7	58.6				158.2
60	72.4	57.9	57.9	65.2	65.2	72.4	65.2	383.7
63	52.3	37.7	47.1					84.7
65	58.1	47.1	47.1	52.3				146.4
67	65.6	47.2	47.2	53.1	59.0			206.6
68	40.3	29.0	32.2	25.8				87.0
69	36.9	25.8	36.9	33.2				95.9
70	46.1	36.9	41.5	46.1				124.5
71	33.4	24.0	30.1	21.0	18.0	21.0		114.2
72	36.6	25.6	23.1	17.9				66.6
73	41.9	30.2	26.4	37.7				94.3
75	45.8	36.6	45.8	41.2				123.7
77	28.5	16.0	16.0	18.2	20.5	22.8		93.5
78	39.5	35.5	32.0	28.4				96.0
79	29.9	18.8	24.2	26.9				70.0
80	41.0	32.8	36.9	36.9	41.0			147.6
82	32.8	26.2	26.2	29.5	32.8			114.8
83	38.7	27.9	34.8					62.7
87	37.9	30.3	27.3	24.3	27.3			109.2
89	42.7	30.7	34.6	38.4				103.8
93	29.3	23.7	23.7	26.4	21.1			94.9
94	39.4	35.5	35.5	31.5	39.4			141.8
96	35.1	25.3	31.6					56.9
97	36.4	26.2	29.5	32.8				88.5
102	37.5	30.0	37.5					67.5

FIGURE 3-15
RESEARCH TASK INTRINSIC VALUES
OPERATIONAL SYSTEM NO. 3-(L3)

OBJ. NO.	OBJECTIVE INTRINSIC VALUE	TASK INTRINSIC VALUES TASK= 1	2	3	4	5	6	TASK INTRINSIC VALUE SUM
1	58.1	52.3	36.6	26.1	41.8	41.8	26.1	224.8
2	58.0	52.2	47.0	41.8	41.8			182.7
3	70.9	70.9	63.6	56.7				191.4
4	66.1	53.5	59.5	47.6				160.6
5	58.1	58.1	46.5	52.3				156.9
6	56.2	45.0	56.2	50.6	45.0			196.7
7	58.9	42.4	53.0					95.4
9	62.0	49.6	44.6	39.7				133.9
10	48.9	44.0	39.6					83.6
11	53.5	42.8	53.5	48.1	42.8			187.2
12	61.4	55.3	49.7	49.7				154.7
14	40.9	36.8	40.9	32.7	40.9			151.3
15	41.6	37.4	30.0	33.7				101.1
16	57.8	57.8	52.0					109.8
17	53.2	47.9	38.3					86.2
18	34.4	31.0	27.9	27.9				86.7
19	58.4	52.6	42.0					94.6
20	54.8	49.3	54.8					104.1
22	52.6	47.3	42.6	42.6	37.9			170.4
23	39.5	39.5	35.5	35.5	31.6			142.2
24	56.5	50.8	56.5					107.3
25	45.9	33.0	36.7	29.4	33.0			132.2
26	55.3	44.8	49.8	39.8				134.4
27	41.9	33.5	26.8	30.2				90.5
28	73.5	66.1	66.1	73.5				205.8
30	57.8	37.0	46.2	32.4				115.6
32	58.4	47.3	42.0	52.6				141.9
33	61.6	49.3	39.4	49.3				138.0
34	70.9	63.8	56.7	56.7	63.8	70.9		312.0
35	36.5	29.6	32.8					62.4
36	61.5	44.3	49.2	39.4				132.8
38	37.4	33.7	30.3	30.3				94.2
39	41.3	33.0	29.7					62.8
40	59.0	42.5	47.8	[illegible]				143.4
41	51.4	51.4	46.3					97.7
42	62.5	62.5						62.5
43	72.6	65.3	58.1	72.6	58.1			254.1
44	64.8	52.5	58.3					110.8
45	64.0	57.6	46.1	51.8	40.3			195.8
46	53.4	43.3	38.4	33.6	48.1			163.4
58	84.5	69.8	68.4	76.0				215.3
62	54.1	37.9	48.7	54.1				140.7
64	47.5	35.6	40.1	44.5				120.3
68	40.3	29.0	32.2	25.8				87.0
69	37.2	26.0	37.2	33.5				96.7
73	42.0	30.2	26.5	37.8				94.5
75	46.5	37.2	46.5	41.8				125.5
77	27.7	15.5	15.5	17.7	19.9	22.2		90.9
78	40.8	36.7	33.0	29.4				99.1
79	30.5	19.2	24.7	27.4				71.4
80	41.5	33.2	37.3	37.3	41.5			149.4
82	32.6	26.1	26.1	29.3	32.6			114.1
83	39.1	28.2	35.2					63.3
87	39.0	31.2	28.1	25.0	28.1			112.3
89	43.3	31.2	35.1	39.0				105.2
93	30.5	24.7	24.7	27.4	22.0			98.8
94	40.0	36.0	36.0	32.0	40.0			144.0
96	35.9	25.8	32.3					58.2
97	37.5	27.0	30.4	33.7				91.1
99	30.6	27.5	24.5	21.4	30.6			104.0
102	38.3	30.6	38.3					68.9

FIGURE 3–16
RESEARCH TASK INTRINSIC VALUES

OPERATIONAL SYSTEM NO. 4–(L4)

OBJ. NO.	OBJECTIVE INTRINSIC VALUE	TASK INTRINSIC VALUES						TASK INTRINSIC VALUE SUM
		TASK= 1	2	3	4	5	6	
1	56.1	52.3	36.6	26.1	41.8	41.8	25.1	224.8
2	58.[illegible]	57.2	47.0	41.8	41.8			182.7
3	70.9	70.9	63.8	56.7				191.4
4	66.1	53.5	59.5	47.6				160.6
5	58.1	58.1	46.5	52.3				156.9
6	56.2	45.9	55.2	50.6	45.0			196.7
7	58.9	42.4	53.0					95.4
9	62.0	49.6	44.6	39.7				133.9
10	48.9	44.0	39.6					83.6
11	53.5	42.8	53.5	48.1	42.8			187.2
12	61.4	55.3	49.7	49.7				154.7
14	40.9	36.8	40.9	32.7	40.9			151.3
15	41.6	37.4	30.0	33.7				101.1
16	57.8	57.8	52.0					109.8
17	53.2	47.9	38.3					86.2
18	34.4	31.0	27.9	27.9				86.7
19	58.4	52.6	42.0					94.6
20	54.8	49.3	54.8					104.1
22	52.6	47.3	42.6	42.6	37.9			170.4
23	39.5	39.5	35.5	35.5	31.6			142.2
24	56.5	50.8	56.5					107.3
25	45.9	33.0	36.7	29.4	33.0			132.2
26	55.3	44.8	49.8	39.8				134.4
27	41.9	33.5	26.8	30.2				90.5
28	73.5	66.1	66.1	73.5				205.8
30	57.8	37.0	46.2	32.4				115.6
32	58.4	47.3	42.0	52.6				141.9
33	61.6	49.3	39.4	49.3				138.0
34	70.9	63.8	56.7	56.7	63.8	70.9		312.0
35	36.5	29.6	32.8					62.4
36	61.5	44.3	49.2	39.4				132.8
38	37.4	33.7	30.3	30.3				94.2
39	41.3	33.0	29.7					62.8
40	59.0	42.5	47.8	53.1				143.4
41	51.4	51.4	46.3					97.7
42	62.5	62.5						62.5
43	72.6	65.3	58.1	72.6	58.1			254.1
44	64.8	52.5	56.3					110.8
45	64.0	57.6	46.1	51.8	40.3			195.8
46	53.4	43.3	38.4	33.6	48.1			163.4
48	73.7	59.0	73.7	51.6	66.3	51.6		302.2
52	67.7	43.3	48.7	54.2				146.2
58	70.0	50.4	56.7	63.0				170.1
61	73.0	58.4	58.4	65.7	65.7	73.0	65.7	386.9
62	41.8	29.3	37.6	41.8				108.7
63	61.6	44.4	55.4					99.8
64	36.6	26.4	29.6	32.9				88.9
65	66.9	54.2	54.2	60.2				168.6
67	73.1	52.6	52.6	59.2	65.8			230.3
68	39.6	28.5	31.7	25.3				85.5
69	36.5	25.5	36.5	32.8				94.9
70	45.9	36.7	41.3	45.9				123.9
73	41.2	29.7	26.0	37.1				92.7
75	45.3	36.2	45.3	40.8				122.3
77	27.5	15.4	15.4	17.6	19.8	22.0		90.2
78	39.3	35.4	31.8	28.3				95.5
79	30.0	18.9	24.3	27.0				70.2
81	40.5	32.4	36.4	36.4	40.5			145.8
82	31.9	25.5	25.5	28.7	31.9			111.6
83	38.1	27.4	34.3					61.7
87	39.0	31.2	28.1	25.0	28.1			112.3
89	43.3	31.2	35.1	39.0				105.2
93	30.5	24.7	24.7	27.4	22.0			98.8
94	40.0	36.0	36.0	32.0	40.0			144.0
96	35.9	25.8	32.3					58.2
97	37.5	27.0	30.4	33.7				91.1
99	30.6	27.5	24.5	21.4	30.6			104.0
102	38.3	30.6	38.3					68.9

FIGURE 3-17
RESEARCH TASK INTRINSIC VALUES
Research Task Intrinsic Values
OPERATIONAL SYSTEM NO. 5-(C1)

OBJ. NO.	OBJECTIVE INTRINSIC VALUE	TASK INTRINSIC VALUES TASK= 1	2	3	4	5	6	TASK INTRINSIC VALUE SUM
1	55.9	50.3	35.2	25.2	40.2	40.2	25.2	216.3
2	56.0	50.4	45.4	40.3	40.3			176.4
3	70.6	70.6	63.5	56.5				190.6
4	64.9	52.6	58.4	46.7				157.7
5	56.0	56.0	44.8	50.4				151.2
6	53.8	43.0	53.8	48.4	43.0			188.2
7	56.4	40.6	50.8					91.4
9	60.7	48.6	43.7	38.8				131.1
12	59.0	53.1	47.8	47.8				148.7
14	37.7	33.9	37.7	30.2	37.7			139.5
15	39.6	35.6	28.5	32.1				96.2
16	55.5	55.5	49.9					105.4
17	50.5	45.4	36.4					81.8
19	56.1	50.5	40.4					90.9
20	53.5	48.1	53.5					101.6
22	50.8	45.7	41.1	41.1	36.6			164.6
24	54.9	49.4	54.9					104.3
25	43.0	31.0	34.4	27.5	31.0			123.8
26	54.6	44.2	49.1	39.3				132.7
27	40.2	32.2	25.7	28.9				86.8
28	73.5	66.1	66.1	73.5				205.8
30	57.8	37.0	46.2	32.4				115.6
32	58.4	47.3	42.0	52.6				141.9
33	61.6	49.3	39.4	49.3				138.0
34	70.9	63.8	56.7	56.7	63.8	70.9		312.0
35	36.5	29.6	32.8					62.4
36	61.5	44.3	49.2	39.4				132.8
38	37.4	33.7	30.3	30.3				94.2
39	41.3	33.0	29.7					62.8
40	59.0	42.5	47.8	53.1				143.4
41	51.4	51.4	46.3					97.7
42	62.5	62.5						62.5
43	72.6	65.3	58.1	72.6	58.1			254.1
44	64.8	52.5	58.3					110.8
45	64.0	57.6	46.1	51.8	40.3			195.8
46	53.4	43.3	38.4	33.6	48.1			163.4
48	69.4	55.5	69.4	48.6	62.5	48.6		284.5
52	61.8	39.6	44.5	49.4				133.5
55	30.5	22.0	19.5	24.4	17.1			83.0
57	73.6	58.9	58.9	51.5	66.2	73.6	66.2	375.4
58	68.0	49.0	55.1	61.2				165.2
59	70.2	56.2	56.2	63.2	56.2	70.2	63.2	365.0
63	57.9	41.7	52.1					93.8
65	64.1	51.9	51.9	57.7				161.5
67	68.9	49.6	49.6	55.8	62.0			217.0
68	40.8	29.4	32.6	26.1				88.1
69	37.4	26.2	37.4	33.7				97.2
70	46.4	37.1	41.8	46.4				125.3
71	33.7	24.3	30.3	21.2	18.2	21.2		115.3
72	37.[illegible]	25.9	23.3	18.1				67.3
73	42.4	30.5	26.7	38.2				95.4
74	32.0	23.0	25.9	28.8				77.8
75	45.4	37.1	46.4	41.8				125.3
77	29.0	16.2	16.2	18.6	20.9	23.2		95.1
78	39.9	35.9	32.3	28.7				97.0
79	30.3	19.1	24.5	27.3				70.9
80	41.4	33.1	37.3	37.3	41.4			149.0
82	33.3	26.6	26.6	30.0	33.3			116.5
83	39.1	28.2	35.2					63.3
87	37.9	30.3	27.3	24.3	27.3			109.2
89	42.7	30.7	34.6	38.4				103.8
93	29.3	23.7	23.7	26.4	21.1			94.9
94	39.4	35.5	35.5	31.5	39.4			141.8
96	35.1	25.3	31.6					56.9
97	36.4	26.2	29.5	32.8				88.5
102	37.5	30.0	37.5					67.5

FIGURE 3-18
RESEARCH TASK INTRINSIC VALUES
OPERATIONAL SYSTEM NO. 6-(C2)

OBJ. NO.	OBJECTIVE INTRINSIC VALUE	TASK INTRINSIC VALUES						TASK INTRINSIC VALUE SUM
		TASK= 1	2	3	4	5	6	
1	58.3	52.5	36.7	26.2	42.0	42.0	26.2	225.6
2	57.6	51.8	46.7	41.5	41.5			181.4
3	71.1	71.1	64.0	56.9				192.0
4	66.1	53.5	59.5	47.6				160.6
5	57.8	57.8	46.2	52.0				156.1
6	55.5	44.4	55.5	49.9	44.4			194.2
7	58.1	41.8	52.3					94.1
9	62.0	49.6	44.6	39.7				133.9
12	60.8	54.7	49.2	49.2				153.2
14	39.9	35.9	39.9	31.9	39.9			147.6
15	41.0	36.9	29.5	33.2				99.6
16	57.0	57.0	51.3					108.3
17	52.1	46.9	37.5					84.4
18	32.9	29.6	26.6	26.6				82.9
19	57.8	52.0	41.6					93.6
20	53.5	48.1	53.5					101.6
22	50.8	45.7	41.1	41.1	36.6			164.6
24	54.9	49.4	54.9					104.3
25	43.0	31.0	34.4	27.5	31.0			123.8
26	54.6	44.2	49.1	39.3				132.7
27	40.2	32.2	25.7	28.9				86.8
28	73.5	66.1	66.1	73.5				205.8
30	57.8	37.0	46.2	32.4				115.6
32	58.4	47.3	42.0	52.6				141.9
33	61.6	49.3	39.4	49.3				138.0
34	70.9	63.8	56.7	56.7	63.8	70.9		312.0
35	36.5	29.6	32.8					62.4
36	61.5	44.3	49.2	39.4				132.8
38	37.4	33.7	30.3	30.3				94.2
39	41.3	33.0	29.7					62.8
40	59.0	42.5	47.8	53.1				143.4
41	51.4	51.4	46.3					97.7
42	62.5	62.5						62.5
43	72.6	65.3	58.1	72.6	58.1			254.1
44	64.8	52.5	58.3					110.8
45	64.0	57.6	46.1	51.8	40.3			195.8
46	53.4	43.3	39.4	33.6	48.1			163.4
48	70.3	56.2	70.3	49.2	63.3	49.2		288.2
52	62.7	40.1	45.1	50.2				135.4
55	31.1	22.4	19.9	24.9	17.4			84.6
58	69.1	49.8	56.0	62.2				167.9
60	76.0	69.8	60.8	68.4	68.4	76.0	65.4	402.8
63	58.5	42.1	52.6					94.8
65	64.4	52.2	52.2	58.0				162.3
67	69.5	50.0	50.0	56.3	62.5			218.9
68	40.8	29.4	32.6	26.1				88.1
69	37.4	26.2	37.4	33.7				97.2
70	46.4	37.1	41.8	46.4				125.3
71	33.7	24.3	30.3	21.2	18.2	21.2		115.3
72	37.0	25.9	23.3	18.1				67.3
73	42.4	30.5	26.7	38.2				95.4
74	32.0	23.0	25.9	28.8				77.8
75	46.4	37.1	46.4	41.8				125.3
77	29.0	16.2	16.2	18.6	20.9	23.2		95.1
78	39.9	35.9	32.3	28.7				97.0
79	30.3	19.1	24.5	27.3				70.9
80	41.4	33.1	37.3	37.3	41.4			149.0
82	33.3	26.6	26.6	30.0	33.3			115.5
83	39.1	28.2	35.2					63.3
87	37.9	30.3	27.3	24.3	27.3			109.2
89	42.7	30.7	34.6	38.4				103.8
93	29.3	23.7	23.7	26.4	21.1			94.9
94	39.4	35.5	35.5	31.5	39.4			141.8
96	35.1	25.3	31.6					56.9
97	36.4	26.2	29.5	32.8				88.5
102	37.5	30.0	37.5					67.5

FIGURE 3-19
RESEARCH TASK INTRINSIC VALUES

OPERATIONAL SYSTEM NO. 7-(M1)

OBJ. NO.	OBJECTIVE INTRINSIC VALUE	TASK INTRINSIC VALUES						TASK INTRINSIC VALUE SUM
		TASK= 1	2	3	4	5	6	
1	55.9	50.3	35.2	25.2	40.2	40.2	25.2	216.3
2	56.0	50.4	45.4	40.3	40.3			176.4
3	70.6	70.6	63.5	56.5				190.6
4	64.9	52.6	58.4	46.7				157.7
5	56.0	56.0	44.8	50.4				151.2
6	53.8	43.0	53.8	48.4	43.0			188.3
7	56.4	40.6	50.8					91.4
9	60.7	48.6	43.7	38.8				131.1
12	59.0	53.1	47.8	47.8				148.7
14	37.7	33.9	37.7	30.2	37.7			139.5
15	39.6	35.6	28.5	32.1				96.2
16	55.5	55.5	49.9					105.4
17	50.5	45.4	36.4					81.8
19	56.1	50.5	40.4					90.9
20	53.5	48.1	53.5					101.6
22	50.8	45.7	41.1	41.1	36.6			164.6
24	54.9	49.4	54.9					104.3
25	43.0	31.0	34.4	27.5	31.0			123.8
26	54.6	44.2	49.1	39.3				132.7
27	40.2	32.2	25.7	28.9				86.8
30	58.2	37.2	46.6	32.6				116.4
32	58.3	47.2	42.0	52.5				141.7
33	61.3	49.0	39.2	49.0				137.3
34	69.3	62.4	55.4	55.4	62.4	69.3		304.9
35	36.0	29.2	32.4					61.6
36	60.9	43.8	48.7	39.0				131.5
39	40.4	32.3	29.1					61.4
40	58.5	42.1	47.4	52.6				142.2
41	51.5	51.5	46.3					97.8
42	62.3	62.3						62.3
43	72.9	65.6	58.3	72.9	58.3			255.1
44	64.6	52.3	58.1					110.5
45	63.4	57.1	45.6	51.4	39.9			194.0
46	53.0	42.9	38.2	33.4	47.7			162.2
4[illegible]	66.0	52.8	66.0	46.2	59.4	46.2		270.6
52	58.3	37.3	42.0	46.6				125.9
57	68.8	55.0	55.0	48.2	61.9	68.8	61.9	350.9
58	64.4	46.4	52.2	58.0				156.5
59	67.4	53.9	53.9	60.7	53.9	67.4	60.7	350.5
63	52.5	37.8	47.2					85.0
65	58.7	47.5	47.5	52.8				147.9
67	65.4	47.1	47.1	53.0	58.9			206.0
71	35.7	25.7	32.1	22.5	19.3	22.5		122.1
72	38.5	26.9	24.3	18.9				70.1
77	30.4	17.0	17.0	19.5	21.9	24.3		99.7
78	42.6	38.3	34.5	30.7				103.5
79	31.2	19.7	25.3	28.1				73.0
80	44.4	35.5	40.0	40.0	44.4			159.8
82	35.0	28.0	28.0	31.5	35.0			122.5
84	40.7	33.0	36.6					69.6
85	41.7	33.4	41.7	37.5				112.6
87	37.9	30.3	27.3	24.3	27.3			109.2
89	42.7	30.7	34.6	38.4				103.8
93	29.3	23.7	23.7	26.4	21.1			94.9
94	39.4	35.5	35.5	31.5	39.4			141.8
96	35.1	25.3	31.6					56.9
97	36.4	26.2	29.5	32.8				88.5
102	37.5	30.0	37.5					67.5

FIGURE 3-20
RESEARCH TASK INTRINSIC VALUES
OPERATIONAL SYSTEM NO. 8-(M2)

OBJ. NO.	OBJECTIVE INTRINSIC VALUE	TASK INTRINSIC VALUES TASK= 1	2	3	4	5	6	TASK INTRINSIC VALUE SUM
1	58.3	52.5	36.7	26.2	42.0	42.0	26.2	225.6
2	57.6	51.8	46.7	41.5	41.5			181.4
3	71.1	71.1	64.0	56.9				192.0
4	66.1	53.5	59.5	47.6				160.6
5	57.8	57.8	46.2	52.0				156.1
6	55.5	44.4	55.5	49.9	44.4			194.2
7	58.1	41.8	52.3					94.1
9	62.0	49.6	44.6	39.7				133.9
12	60.8	54.7	49.2	49.2				153.2
14	39.9	35.9	39.9	31.9	39.9			147.6
15	41.0	36.9	29.5	33.2				99.6
16	57.0	57.0	51.3					108.3
17	52.1	46.9	37.5					84.4
18	32.9	29.6	26.6	26.6				82.9
19	57.8	52.0	41.6					93.6
20	53.5	48.1	53.5					101.6
22	50.8	45.7	41.1	41.1	36.6			164.6
24	54.9	49.4	54.9					104.3
25	43.0	31.0	34.4	27.5	31.0			123.8
26	54.6	44.2	49.1	39.3				132.7
27	40.2	32.2	25.7	28.9				86.8
28	73.5	66.1	66.1	73.5				205.8
30	57.8	37.0	46.2	32.4				115.6
32	58.4	47.3	42.0	52.6				141.9
33	61.6	49.3	39.4	49.3				138.0
34	70.9	63.8	56.7	56.7	63.8	70.9		312.0
35	36.5	29.6	32.8					62.4
36	61.5	44.3	49.2	39.4				132.8
38	37.4	33.7	30.3	30.3				94.2
39	41.3	33.0	29.7					62.8
40	59.0	42.5	47.8	53.1				143.4
41	51.4	51.4	46.3					97.7
42	62.5	62.5						62.5
43	72.6	65.3	58.1	72.6	58.1			254.1
44	64.8	52.5	58.3					110.8
45	64.0	57.6	46.1	51.8	40.3			195.8
46	53.4	43.3	38.4	33.6	48.1			163.4
48	73.7	59.0	73.7	51.6	66.3	51.6		302.2
52	67.7	43.3	48.7	54.2				146.2
58	70.0	50.4	56.7	63.0				170.1
61	73.0	58.4	58.4	65.7	65.7	73.0	65.7	386.9
62	41.8	29.3	37.6	41.8				108.7
63	61.6	44.4	55.4					99.8
64	36.6	26.4	29.6	32.9				88.9
65	66.9	54.2	54.2	60.2				168.6
67	73.1	52.6	52.6	59.2	65.8			230.3
68	39.9	28.7	31.9	25.5				86.2
69	37.0	25.9	37.0	33.3				96.2
70	46.2	37.0	41.6	46.2				124.7
73	41.5	29.9	26.1	37.3				93.4
74	31.3	22.5	25.4	28.2				76.1
75	46.0	36.8	46.0	41.4				124.2
77	28.6	16.0	16.0	18.3	20.6	22.9		93.8
78	39.6	35.6	32.1	28.5				96.2
79	30.6	19.3	24.8	27.5				71.6
80	40.8	32.6	36.7	36.7	40.8			146.9
82	32.6	26.1	26.1	29.3	32.6			114.1
83	38.2	27.5	34.4					61.9
85	39.1	31.3	39.1	35.2				105.6
87	39.6	31.7	29.5	25.3	28.5			114.0
89	43.7	31.5	35.4	39.3				106.2
93	30.8	24.9	24.9	27.7	22.2			99.8
94	40.9	36.8	36.8	32.7	40.9			147.2
96	36.4	26.2	32.8					59.0
97	37.9	27.3	30.7	34.1				92.1
99	31.3	28.2	25.0	21.9	31.3			106.4
100	32.4	23.3	26.2	23.3	29.2			102.1
102	39.1	31.3	39.1					70.4

FIGURE 3-21
RESEARCH TASK INTRINSIC VALUES
OPERATIONAL SYSTEM NO. 9-(M3)

OBJ. NO.	OBJECTIVE INTRINSIC VALUE	TASK INTRINSIC VALUES TASK= 1	2	3	4	5	6	TASK INTRINSIC VALUE SUM
1	58.3	52.5	36.7	26.2	42.0	42.0	26.2	225.6
2	57.6	51.8	46.7	41.5	41.5			181.4
3	71.1	71.1	64.0	56.9				192.0
4	66.1	53.5	59.5	47.6				160.6
5	57.8	57.8	46.2	52.0				156.1
6	55.5	44.4	55.5	49.9	44.4			194.2
7	58.1	41.8	52.3					94.1
9	62.0	49.6	44.6	39.7				133.9
12	60.8	54.7	49.2	49.2				153.2
14	39.9	35.9	39.9	31.9	39.9			147.6
15	41.0	36.9	29.5	33.2				99.6
16	57.0	57.0	51.3					108.3
17	52.1	46.9	37.5					84.4
18	32.9	29.6	26.6	26.6				82.9
19	57.8	52.0	41.6					93.6
21	53.5	48.1	53.5					101.6
22	50.8	45.7	41.1	41.1	36.6			164.6
24	54.9	49.4	54.9					104.3
25	43.0	31.0	34.4	27.5	31.0			123.8
26	54.6	44.2	49.1	39.3				132.7
27	40.2	32.2	25.7	28.9				86.8
28	73.5	66.1	66.1	73.5				205.8
30	57.8	37.0	46.2	32.4				115.6
32	58.4	47.3	42.0	52.6				141.9
33	61.6	49.3	39.4	49.3				138.0
34	70.9	63.8	56.7	56.7	63.8	70.9		312.0
35	36.5	29.6	32.8					62.4
36	61.5	44.3	49.2	39.4				132.8
38	37.4	33.7	30.3	30.3				94.2
39	41.3	33.0	29.7					62.8
40	59.0	42.5	47.8	53.1				143.4
41	51.4	51.4	46.3					97.7
42	62.5	62.5						62.5
43	72.6	65.3	58.1	72.6	58.1			254.1
44	64.8	52.5	58.3					110.8
45	64.0	57.6	46.1	51.8	40.3			195.8
46	53.4	43.3	38.4	33.6	48.1			163.4
48	73.7	59.0	73.7	51.6	66.3	51.6		302.2
52	67.7	43.3	48.7	54.2				146.2
58	70.0	50.4	56.7	63.0				170.1
61	73.0	58.4	58.4	65.7	65.7	73.0	65.7	386.9
62	41.8	29.3	37.6	41.8				108.7
63	61.6	44.4	55.4					99.8
64	36.6	26.4	29.6	32.9				88.9
65	66.9	54.2	54.2	60.2				168.6
67	73.1	52.6	52.6	59.2	65.8			230.3
68	39.9	28.7	31.9	25.5				86.2
69	37.0	25.9	37.0	33.3				96.2
70	46.2	37.0	41.6	46.2				124.7
73	41.5	29.9	26.1	37.3				93.4
74	31.3	22.5	25.4	28.2				76.1
75	46.0	36.8	46.0	41.4				124.2
77	28.6	16.0	16.0	18.3	20.6	22.9		93.8
78	39.6	35.6	32.1	28.5				96.2
79	30.6	19.3	24.8	27.5				71.6
80	40.8	32.6	36.7	36.7	40.8			146.9
82	32.6	26.1	26.1	29.3	32.6			114.1
83	38.2	27.5	34.4					61.9
85	39.1	31.3	39.1	35.2				105.6
87	39.6	31.7	28.5	25.3	28.5			114.0
89	43.7	31.5	35.4	39.3				106.2
93	30.8	24.9	24.9	27.7	22.2			99.8
94	40.9	36.8	36.8	32.7	40.9			147.2
96	36.4	26.2	32.0					59.0
97	37.9	27.3	30.7	34.1				92.1
99	31.3	28.2	25.0	21.9	31.3			106.4
100	32.4	25.3	26.2	23.3	29.2			102.1
102	39.1	31.3	39.1					70.4

FIGURE 3-22

PERCENTAGE OF RESEARCH ACHIEVABLE IN EXISTING FACILITIES

	OPERATIONAL SYSTEM								
	1 L1	2 L2	3 L3	4 L4	5 C1	6 C2	7 M1	8 M2	9 M3
OBJECTIVE									
1	53	45	45	45	53	45	72	45	45
2	43	36	36	36	43	36	56	36	36
3	43	28	28	28	43	28	56	28	28
4	37	31	31	31	37	31	48	31	31
5	37	31	31	31	37	31	48	31	31
6	43	36	36	36	43	36	56	36	36
7	43	31	31	31	43	31	56	31	31
9	37	31	31	31	37	31	48	31	31
10	36	36	36	36	0	0	0	0	0
11	45	45	45	45	0	0	0	0	0
12	37	23	23	23	37	23	48	23	23
14	31	31	31	31	31	31	31	31	31
15	23	23	23	23	23	23	23	23	23
16	33	23	23	23	33	23	43	23	23
17	27	23	23	23	27	23	35	23	23
18	0	40	40	40	0	40	0	40	40
19	50	28	28	28	50	28	65	28	28
20	35	27	27	27	35	27	40	27	27
22	35	27	27	27	35	27	40	27	27
23	50	38	38	38	0	0	0	0	0
24	35	27	27	27	35	27	40	27	27
25	35	27	27	27	35	27	40	27	27
26	35	27	27	27	35	27	40	27	27
27	76	47	47	47	76	47	85	47	47
29	46	35	35	35	46	35	0	35	35
30	80	80	80	80	80	80	80	80	80
32	50	38	38	38	50	38	69	38	38
33	53	34	34	34	53	34	74	34	34
34	80	16	80	16	80	16	80	16	16
35	34	26	26	26	34	26	48	26	26
36	40	31	31	31	40	31	56	31	31
38	36	36	36	36	36	36	0	36	36
39	57	57	57	57	57	57	57	57	57
40	57	57	57	57	57	57	57	57	57
41	57	57	57	57	57	57	57	57	57
42	42	32	32	32	42	32	58	32	32
43	45	35	35	35	45	35	64	35	35
44	57	44	44	44	57	44	80	44	44
45	57	44	44	44	57	44	80	44	44
46	45	35	35	35	45	35	64	35	35
48	57	18	0	8	57	18	57	8	8
52	53	19	0	21	53	19	83	21	21
55	0	0	0	0	80	50	0	0	0
57	40	0	0	0	40	0	70	0	0
58	70	50	90	50	70	50	70	50	50
59	23	0	0	0	23	0	40	0	0
60	0	13	0	0	0	13	0	0	0
61	0	0	0	17	0	0	0	17	17
62	0	0	30	30	0	0	0	30	30
63	57	22	0	8	57	22	57	8	8
64	0	0	61	61	0	0	0	61	61
65	57	12	0	10	57	12	57	10	10
67	40	20	0	13	40	20	40	13	13
68	90	90	90	90	90	90	0	90	90
69	17	17	17	17	17	17	0	17	17
70	47	29	0	20	47	29	0	20	20
71	95	95	0	0	95	95	95	0	0
72	40	40	0	0	40	40	40	0	0
73	89	89	89	89	89	89	0	89	89
74	0	0	0	0	100	95	0	100	100
75	27	27	27	27	27	27	0	27	27
77	100	95	89	89	100	95	100	89	89
78	50	47	45	45	50	47	60	45	45
79	100	95	89	100	100	95	100	100	100
80	100	95	89	89	100	95	100	89	89
82	100	100	100	100	100	100	100	100	100
83	100	95	89	89	100	95	0	89	89
84	0	0	0	0	0	0	100	0	0
85	0	0	0	0	0	0	43	10	10
87	14	11	12	12	14	11	17	12	12
89	12	9	10	10	12	9	14	10	10
93	57	57	57	57	57	57	57	57	57
94	20	15	17	17	24	15	31	17	17
96	15	12	12	12	15	12	19	12	12
97	30	30	30	30	30	30	30	30	30
99	0	0	15	15	0	0	0	15	15
100	0	0	0	0	0	0	0	70	70
102	70	70	70	70	70	70	70	70	70

3.5.2 FACILITY RESEARCH CAPABILITY - Research capability of the candidate ground facilities and flight vehicles is presented in terms of the percentage of research included in the tasks under the Research Objectives which each candidate facility (in conjunction with existing facilities) can achieve. Assessments of the research capability of each new ground facility and each candidate flight facility were made by technical specialists, considering the following three distinct criteria:

(a) Physical Environmental Simulation

- To what extent are key parameters (e.g. noise, pressure, temperature, Mach No., loads, etc.) simulated, either individually or in combination, in a static or time-variant manner?
- What is the capability of the facility to accommodate a wide range of test conditions contributing to a broad research base, in terms of multi-point research, wide parametric variation capability, and research time available for satisfying the objective as it relates to a reasonable research program?

(b) Configuration Arrangement and Size Similitude

- What is the capability of the facility to accommodate a model or experimental specimen, in terms of the limits of scaling factors, experimental section, and model size?
- To what extent can unknown interactions be uncovered?

(c) Verification and Demonstration Capability

- To what extent can operational flight hardware be tested?
- To what extent can operational flight profiles and vehicle utilization be simulated?
- To what extent can the actual operational flight environment characteristics be proven?

The percentage of each Research Objective which can be achieved by each candidate ground facility and flight research vehicle, augmented by the spectrum of existing ground test facilities, is presented in Figures 3-23 through 3-26 for the four representative operational systems. Facilities one through nine are new ground facilities, described in Section 2, while new facilities identified as 207 through 284 (columns 10 through 16) are candidate flight research vehicles, whose characteristics are also defined in Section 2. New facilities identified as C/1 through C/5 are selected combinations of the listed new ground facilities and are described in Section 7. The research capability of the spectrum of existing facilities is presented in these figures, allowing the incremental capability of new candidate facilities to be determined by subtracting existing facility values from new facility values.

FIGURE 3–23
PERCENTAGE OF RESEARCH ACHIEVABLE IN EACH FACILITY
OPERATIONAL SYSTEM NO. 2–(L2)

OBJ. NO.	EXISTING FACILITY PERCENTAGE	CAPABILITY OF NEW FACILITIES + EXISTING FACILITIES																				
		1 GD3	2 GD20	3 GD7	4 E6	5 E20	6 E8	7 E9	8 S2	9 M20	10 207	11 212	12 232	13 233	14 257	15 260	16 284	17 C/1	18 C/2	19 C/3	20 C/4	21 C/5
1	45	59	59	45	45	45	45	45	45	45	73	90	73	73	87	83	63	59	59	59	59	59
2	36	62	62	36	36	36	36	36	36	36	77	83	77	77	83	83	63	62	62	62	62	68
3	28	51	59	43	28	28	28	28	28	28	63	63	70	67	73	70	67	68	68	68	68	65
4	31	45	51	37	46	46	31	31	31	31	57	57	63	63	70	70	63	59	62	62	62	[illegible]
5	31	46	56	39	31	31	31	31	31	31	63	73	77	77	83	80	65	68	68	68	68	[illegible]
6	36	47	55	43	36	36	36	36	36	36	67	73	67	60	77	70	60	71	72	72	72	72
7	31	38	57	47	33	33	45	45	31	31	50	40	63	57	63	57	57	69	72	75	75	75
9	31	42	56	37	42	42	47	47	31	31	50	60	60	50	63	50	50	60	65	67	67	67
10	36	41	59	42	36	36	36	36	36	36	63	43	63	63	63	70	63	67	67	67	67	67
11	45	47	57	56	45	45	45	45	45	45	63	53	73	73	78	73	73	63	63	63	63	63
12	23	45	52	37	27	37	32	32	23	23	50	53	57	57	60	57	57	61	67	70	70	70
14	31	58	58	31	31	31	31	31	31	31	70	70	73	73	80	80	73	58	58	58	58	58
15	23	38	48	32	29	35	23	23	23	23	43	60	50	50	65	50	50	58	69	69	69	69
16	23	29	37	33	27	31	38	37	23	23	53	53	63	63	67	57	63	47	57	67	67	67
17	23	37	47	33	27	32	37	35	23	23	53	53	63	63	67	57	63	52	58	65	65	65
18	40	42	50	50	42	42	50	50	40	40	50	50	80	80	80	80	60	52	55	63	63	63
19	28	35	46	40	28	28	28	28	28	28	60	60	67	63	70	63	63	63	63	63	63	63
20	27	31	40	37	29	37	42	41	27	27	64	64	88	88	88	88	88	51	55	65	65	65
22	27	31	48	39	60	65	68	37	27	27	44	64	88	88	88	88	88	53	71	77	77	77
23	38	40	45	42	38	50	60	60	38	38	68	68	91	91	91	91	91	48	52	65	65	65
24	27	43	56	39	27	27	27	27	27	27	64	64	78	78	88	78	78	66	66	66	66	66
25	27	32	39	35	27	39	40	38	27	27	69	69	82	82	92	82	82	50	55	59	59	59
26	27	29	31	28	27	32	36	35	59	27	69	69	82	82	92	92	82	35	41	49	67	57
27	47	50	56	54	48	56	57	56	47	47	71	71	92	81	92	81	81	59	62	67	67	67
28	35	35	35	35	38	38	38	38	70	47	67	63	75	75	85	75	75	38	38	38	70	78
30	80	80	80	80	80	80	80	80	86	80	80	80	80	80	85	80	80	80	80	80	86	86
32	38	38	38	38	38	47	48	46	67	47	70	65	75	75	85	75	75	38	47	57	67	73
33	34	37	37	37	35	47	50	50	57	47	62	58	75	75	85	75	75	37	47	52	73	78
34	16	17	17	17	16	16	53	49	32	27	28	26	75	28	35	28	28	17	17	53	67	77
35	26	36	36	36	26	37	47	45	50	31	52	49	60	60	68	60	60	40	47	52	69	78
36	31	31	31	31	31	40	50	50	50	39	58	54	65	65	74	65	65	31	40	50	70	82
38	36	48	48	48	38	38	38	63	38	38	75	70	75	75	85	75	75	58	58	58	68	68
39	57	61	63	63	61	61	61	71	62	62	75	70	75	75	85	75	75	63	70	75	88	90
40	57	57	57	57	57	57	57	72	67	67	75	70	75	75	85	75	75	57	57	57	72	93
41	57	57	57	57	57	57	57	57	76	62	75	70	75	75	85	75	75	57	57	57	76	81
42	32	32	32	32	32	32	32	32	90	32	75	70	75	75	85	75	75	32	32	32	90	90
43	35	35	35	35	38	52	51	50	58	38	67	63	75	75	85	75	75	35	38	53	80	85
44	44	44	44	44	44	44	44	44	50	80	75	70	75	75	85	75	75	44	44	44	50	86
45	44	44	44	44	44	44	44	44	50	80	75	70	75	75	85	75	75	44	44	44	50	88
46	35	35	35	35	35	35	35	35	50	60	67	63	75	75	85	75	75	35	35	35	50	80
48	18	38	48	41	18	41	37	18	18	18	37	41	60	41	83	41	39	56	63	68	68	68
52	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	26	46	56	61
58	50	50	50	50	55	65	65	65	50	50	70	70	70	70	70	70	70	50	55	65	65	65
60	13	17	28	28	13	13	43	40	23	13	20	20	53	13	83	13	13	37	37	56	59	59
63	22	32	38	32	22	40	25	25	45	32	50	40	69	22	88	22	22	45	47	64	68	69
65	12	25	35	32	12	35	44	42	12	12	45	12	68	12	79	12	12	40	48	57	57	57
67	20	43	50	45	47	63	47	45	20	20	50	43	61	20	70	20	20	53	60	70	70	70
68	90	90	90	90	90	90	90	90	100	90	100	100	100	100	100	100	100	90	90	90	100	100
69	17	17	17	17	17	17	17	17	47	27	60	60	83	83	91	91	83	17	17	17	47	55
70	29	29	29	29	29	29	63	61	37	34	48	48	67	47	72	47	47	29	29	63	69	71
71	95	95	95	95	95	95	95	95	95	100	95	95	95	95	95	95	95	95	95	95	95	100
72	40	40	40	40	40	40	40	40	100	40	40	60	40	40	60	40	40	40	40	40	100	100
73	89	89	89	89	89	89	89	89	100	89	100	100	100	100	100	100	100	89	89	89	100	100
75	27	27	27	27	27	27	27	27	73	37	60	63	83	80	90	83	80	27	27	27	73	82
77	95	95	95	95	95	100	100	100	95	75	97	97	100	100	100	100	100	95	100	100	100	100
78	47	55	63	58	50	50	50	50	47	47	73	67	77	77	87	87	60	75	75	75	75	75
79	95	95	95	95	100	100	100	95	95	95	97	97	100	100	100	100	100	95	98	100	100	100
80	95	95	95	95	95	95	95	95	100	95	97	97	100	100	100	100	100	95	95	95	100	100
82	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
83	95	95	95	95	95	95	95	95	100	95	97	97	100	100	100	100	100	95	95	95	100	100
87	11	50	11	11	30	40	11	11	11	11	77	77	90	90	93	90	60	52	65	75	75	75
89	9	33	49	33	9	9	9	9	9	9	60	80	73	73	[illegible]	73	9	69	49	69	69	69
93	57	67	72	65	57	57	57	57	57	57	77	77	87	87	93	87	57	77	77	77	77	77
94	15	15	15	15	15	15	15	15	57	27	80	80	80	80	80	80	60	15	15	15	57	67
96	12	43	53	40	33	43	40	38	12	12	80	77	83	80	90	80	53	12	12	12	37	67
97	30	30	30	30	30	30	30	30	90	34	80	80	80	80	80	80	80	30	30	30	90	95
102	70	70	70	70	70	70	70	70	80	63	75	75	85	85	90	85	85	70	70	70	80	93
		GD3	GD20	GD7	E6	E20	E8	E9	S2	M20	207	212	232	233	257	260	284	C/1	C/2	C/3	C/4	C/5

FIGURE 3-24
PERCENTAGE OF RESEARCH ACHIEVABLE IN EACH FACILITY
OPERATIONAL SYSTEM NO. 5-(C1)

OBJ. NO.	EXISTING FACILITY PERCENTAGE	CAPABILITY OF NEW FACILITIES + EXISTING FACILITIES																				
		1 GD3	2 GD20	3 GD7	4 E6	5 E20	6 E8	7 E9	8 S2	9 M20	10 207	11 212	12 232	13 233	14 257	15 260	16 284	17 C/1	18 C/2	19 C/3	20 C/4	21 C/5
1	53	59	59	53	53	53	53	53	53	53	73	90	73	73	87	83	63	59	59	59	59	59
2	43	62	59	43	43	43	43	43	43	43	77	83	77	77	83	83	63	73	73	73	73	73
3	43	53	59	43	43	43	43	43	43	43	80	80	73	70	77	73	63	65	65	65	65	65
4	37	45	51	37	46	46	43	43	37	37	57	57	63	63	70	70	63	59	61	61	61	61
5	37	46	54	37	37	37	37	37	37	[illegible]	63	73	77	77	77	77	50	68	68	68	68	68
6	43	57	50	43	43	43	43	43	43	43	67	73	67	60	77	70	57	77	77	77	77	77
7	43	43	59	43	43	43	43	43	43	43	70	70	70	57	70	57	57	69	69	69	69	69
9	37	50	58	37	37	37	37	37	37	37	50	60	60	50	63	50	50	70	70	70	70	70
12	37	48	53	37	47	37	37	37	37	37	47	60	60	47	60	47	47	60	68	68	68	68
14	31	63	31	31	31	31	31	31	48	31	70	70	73	73	80	80	73	63	63	63	77	77
15	23	43	49	37	23	23	23	23	23	23	43	60	50	50	60	50	50	61	61	61	61	61
16	33	37	47	33	39	49	43	43	33	33	63	63	63	63	63	63	63	47	56	66	66	66
17	27	42	49	27	27	37	33	33	27	27	53	53	63	63	63	63	63	55	60	68	68	68
19	50	67	67	50	50	50	50	50	50	50	70	70	73	73	73	73	73	87	87	87	87	87
20	35	51	54	48	35	75	81	71	35	35	80	80	38	88	88	88	88	62	69	90	90	90
22	35	51	54	35	43	75	81	71	35	35	80	80	88	88	88	88	88	61	68	82	82	82
24	35	51	54	48	35	75	81	71	35	35	80	80	38	88	88	88	88	58	78	88	88	88
25	35	51	54	48	35	84	86	88	35	35	86	86	92	92	92	92	92	65	88	90	90	90
26	35	39	44	42	35	44	46	46	53	43	86	86	92	92	92	92	92	50	60	72	81	85
27	76	76	76	76	76	84	87	88	76	76	86	86	92	81	92	81	81	76	86	89	89	89
28	46	46	46	46	49	49	49	49	81	58	72	72	80	80	90	80	80	49	49	49	81	89
30	80	80	80	80	80	80	80	80	86	80	80	80	80	[illegible]	80	80	80	80	80	80	86	86
32	50	50	50	50	50	59	[illegible]	58	79	59	[illegible]	74	80	80	80	90	80	50	59	69	79	85
33	53	56	56	56	54	[illegible]	[illegible]	[illegible]	76	66	80	80	80	80	80	80	80	56	66	71	91	97
34	80	81	91	81	80	80	[illegible]	100	96	91	80	80	80	80	80	80	80	81	81	100	100	100
35	34	44	44	44	34	45	55	53	58	39	64	64	64	64	64	64	64	48	55	60	77	85
36	40	40	40	40	40	49	59	59	59	48	70	70	70	70	70	70	70	40	49	59	79	91
38	36	49	48	48	38	38	38	63	38	[illegible]	80	80	80	80	80	80	80	58	58	58	58	68
39	57	61	63	63	61	61	61	71	62	62	80	80	80	80	80	80	80	63	70	75	88	90
40	57	57	57	57	57	57	57	72	67	67	80	90	80	60	80	80	80	57	57	57	72	93
41	57	57	57	57	57	57	57	57	76	62	80	80	80	80	80	80	80	57	57	57	76	81
42	42	42	42	42	42	42	42	42	100	42	80	80	80	80	80	80	80	42	42	42	100	100
43	45	45	45	45	48	62	61	60	68	48	80	80	80	80	80	80	80	45	48	67	70	95
44	57	57	57	57	57	57	57	67	63	93	80	80	80	80	80	80	80	57	57	57	[illegible]	99
45	57	57	57	57	57	57	57	63	63	93	80	80	80	80	80	80	80	57	57	57	63	100
46	45	45	45	45	45	45	45	60	60	70	80	80	80	90	90	80	80	45	45	45	60	90
48	57	70	67	57	57	69	57	57	57	57	67	80	57	57	57	57	57	80	90	90	90	90
52	53	53	53	53	70	70	63	63	53	53	70	73	53	53	53	53	53	53	70	83	83	85
55	80	80	80	80	92	92	80	80	80	80	95	100	85	80	95	80	80	80	92	92	92	92
57	40	40	40	40	83	87	40	40	40	40	47	57	40	40	40	40	40	40	87	87	87	87
58	70	70	70	70	75	80	70	70	70	70	80	80	80	80	80	80	80	70	80	80	80	80
59	23	23	30	23	73	77	23	23	23	23	50	83	23	23	23	23	23	23	77	77	77	77
63	57	63	67	57	57	67	57	57	57	57	67	80	57	57	70	57	57	63	73	73	73	73
65	57	63	68	57	57	68	57	57	57	57	67	77	57	57	57	57	57	72	81	81	81	81
67	40	62	50	[illegible]	55	60	40	40	40	40	57	60	40	40	40	40	40	63	85	85	85	85
68	90	90	90	90	90	90	90	90	100	90	100	100	100	100	100	100	100	90	90	90	100	100
69	17	17	17	17	17	17	17	17	47	27	80	80	83	33	91	91	63	17	17	17	47	55
70	47	47	47	47	47	47	81	79	55	52	63	63	80	80	80	80	80	47	47	81	87	89
71	95	95	95	95	95	95	95	95	95	100	95	95	95	95	95	95	95	95	95	95	95	100
72	40	40	40	40	40	40	40	40	100	40	40	60	40	40	60	[illegible]	40	40	40	40	100	100
73	89	89	89	89	89	89	89	89	100	89	100	100	100	100	100	100	100	89	89	89	100	100
74	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
75	27	27	27	27	27	27	27	27	73	37	83	90	83	80	90	83	80	27	27	27	73	82
77	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
78	50	58	66	61	53	53	53	53	50	50	73	77	77	77	87	87	60	78	79	78	78	78
79	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
80	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
82	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
83	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
87	14	50	14	14	30	[illegible]	14	14	14	14	77	83	90	90	93	90	60	52	65	75	75	75
89	12	33	49	33	12	[illegible]	12	12	12	12	80	83	73	73	83	73	12	69	69	69	69	69
93	57	67	72	65	57	57	57	57	57	57	77	77	90	90	83	87	57	77	77	77	77	77
94	24	24	24	24	24	24	24	24	[illegible]	27	80	80	80	80	80	80	60	24	24	24	57	67
95	15	43	53	40	[illegible]	53	40	38	15	15	80	81	80	70	80	70	50	15	15	15	57	67
97	30	30	30	30	30	30	30	30	90	34	90	90	90	90	90	90	90	30	30	30	90	95
102	70	70	70	70	70	70	70	70	80	83	80	80	90	90	90	90	90	70	70	70	80	93
		GD3	GD20	GD7	E6	E20	E8	E9	S2	M20	207	212	232	233	257	260	284	C/1	C/2	C/3	C/4	C/5

FIGURE 3-25
PERCENTAGE OF RESEARCH ACHIEVABLE IN EACH FACILITY
OPERATIONAL SYSTEM NO. 7-(M1)

OBJ. NO.	EXISTING FACILITY PERCENTAGE	CAPABILITY OF NEW FACILITIES + EXISTING FACILITIES																				
		1 GD3	2 GD20	3 GD7	4 E6	5 E20	6 E8	7 E9	8 S2	9 M20	10 207	11 212	12 232	13 233	14 257	15 260	16 284	17 C/1	18 C/2	19 C/3	20 C/4	21 C/5
1	72	80	80	72	72	72	72	72	72	72	94	100	94	94	100	100	84	80	80	80	80	80
2	56	76	73	56	56	56	56	56	56	56	91	97	91	91	97	97	77	87	87	87	87	87
3	56	67	73	56	56	56	56	56	56	56	94	94	87	84	91	87	77	79	79	79	79	79
4	48	57	63	48	58	58	55	55	48	48	69	69	75	75	82	82	75	71	73	73	73	73
5	48	58	66	48	48	48	48	48	48	48	75	85	89	89	89	89	62	80	80	80	80	80
6	56	71	64	56	56	56	56	56	56	56	81	87	81	74	91	84	71	91	91	91	91	91
7	56	56	73	56	56	56	56	56	56	56	84	84	84	71	94	71	71	83	83	83	83	83
9	48	62	70	48	48	48	48	48	48	48	62	72	72	62	75	62	62	62	82	82	82	82
12	48	60	65	48	59	48	48	48	48	48	59	72	72	59	72	59	59	72	80	80	80	80
14	31	63	31	31	31	31	31	31	48	31	70	70	73	73	80	80	73	63	63	63	77	77
15	23	43	49	32	23	23	23	23	23	23	43	60	50	50	60	50	50	61	61	61	61	61
16	43	48	58	43	50	60	54	54	43	43	74	74	74	74	74	74	74	58	67	77	77	77
17	35	51	58	35	35	46	44	42	35	35	62	62	72	72	72	72	72	64	69	77	77	77
19	65	84	79	65	65	65	65	65	65	65	87	87	90	90	90	90	90	100	100	100	100	100
20	40	57	60	54	40	81	87	77	40	40	86	86	94	94	94	94	94	68	75	96	96	96
22	40	57	60	40	49	81	87	77	40	40	86	86	94	94	94	94	94	67	74	88	88	88
24	40	57	60	54	40	81	87	77	40	40	86	86	94	94	94	94	94	64	84	94	94	94
25	40	57	60	54	40	90	92	94	40	40	92	92	98	98	98	98	98	71	94	96	96	96
26	40	44	50	48	40	50	52	52	59	49	92	92	98	98	98	98	98	75	66	78	87	91
27	85	85	85	85	85	96	97	98	85	85	96	96	100	91	100	91	91	86	96	99	99	99
30	80	80	80	80	80	80	80	80	86	80	80	80	80	80	80	80	80	80	80	80	86	86
32	69	69	69	69	69	80	81	79	100	80	95	95	100	100	100	100	100	71	80	90	100	100
33	74	79	79	79	77	89	92	92	99	89	100	100	100	100	100	100	100	79	89	94	100	100
34	80	81	91	81	80	80	100	100	96	91	80	80	80	80	80	80	80	81	81	100	100	100
35	48	59	59	59	48	60	70	68	73	54	79	79	79	79	79	79	79	63	70	75	92	100
36	56	56	56	56	56	67	77	77	77	66	88	88	88	88	88	88	88	58	67	77	97	100
39	57	61	63	63	61	61	61	71	62	62	83	80	80	80	60	80	80	63	70	75	88	90
40	57	57	57	57	57	57	57	72	67	67	80	80	80	80	80	80	80	57	57	57	72	93
41	57	57	57	57	57	57	57	57	76	62	80	80	80	80	80	80	80	57	57	57	76	81
42	58	58	58	58	58	58	58	58	100	98	98	98	98	98	98	98	98	58	58	58	100	100
43	64	64	64	64	69	83	82	81	89	69	100	100	100	100	100	100	100	66	69	84	100	100
44	80	80	80	80	80	80	80	92	88	100	100	100	100	100	100	100	100	80	80	80	88	100
45	80	80	80	80	80	80	80	88	88	100	100	100	100	100	100	100	100	80	80	80	88	100
46	64	64	64	64	64	64	64	81	81	91	100	100	100	100	100	100	100	66	66	66	81	100
48	57	70	67	57	57	69	57	57	57	57	67	80	57	57	57	57	57	80	90	90	90	90
52	83	83	83	83	100	100	93	93	83	83	100	100	83	83	83	83	83	83	100	100	100	100
57	70	70	70	70	100	100	70	70	70	70	77	87	70	70	70	70	70	70	100	100	100	100
58	70	70	70	70	75	80	70	70	70	70	80	80	80	80	80	80	80	70	80	80	80	80
59	40	40	47	40	90	100	40	40	40	40	67	100	40	40	40	40	40	40	100	100	100	100
63	57	63	67	57	57	67	57	57	57	57	67	80	57	57	70	57	57	63	73	73	73	73
65	57	63	68	57	57	68	57	57	57	57	67	77	57	57	57	57	57	72	81	81	81	81
67	40	52	50	40	55	60	40	40	40	40	57	60	40	40	40	40	40	63	85	85	85	85
71	95	95	95	95	95	95	95	95	95	100	95	95	95	95	95	95	95	95	95	95	95	100
72	40	40	40	40	40	40	40	49	100	40	40	60	40	40	60	40	40	40	40	40	100	100
77	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
78	60	68	76	71	63	63	63	63	60	60	83	87	87	87	97	97	70	88	88	88	88	88
79	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
80	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
82	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
84	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
85	43	53	43	43	43	56	43	43	55	47	90	90	90	90	90	90	90	53	61	61	75	79
87	17	53	17	17	33	43	17	17	17	17	80	86	93	93	96	93	63	55	68	78	78	78
89	14	35	51	35	14	14	14	14	14	14	82	85	75	75	85	75	14	71	71	71	71	71
93	57	67	7	65	57	57	57	57	57	57	77	77	90	90	83	87	57	77	77	77	77	77
94	31	31	31	31	31	31	31	31	64	34	87	87	87	87	87	87	67	31	31	31	64	74
96	19	47	57	44	37	47	44	42	19	19	84	91	84	74	84	74	54	19	19	19	61	71
97	30	30	30	30	30	30	30	30	90	34	90	90	90	90	90	90	90	30	30	30	90	95
102	70	70	70	70	70	70	70	70	80	83	80	80	90	90	90	90	90	70	70	70	80	93
		GD3	GD20	GD7	E6	E20	E6	E9	S2	M20	207	212	232	233	257	260	284	C/1	C/2	C/3	C/4	C/5

FIGURE 3-26
PERCENTAGE OF RESEARCH ACHIEVABLE IN EACH FACILITY
OPERATIONAL SYSTEM NO. 8-([illegible])

OBJ. NO.	EXISTING FACILITY PERCENTAGE	CAPABILITY OF NEW FACILITIES + EXISTING FACILITIES																				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
		GD3	GD20	GD7	E6	E20	E8	E9	S2	M20	207	212	232	233	257	260	284	C/1	C/2	C/3	C/4	C/5
1	45	59	59	45	45	45	45	45	45	45	73	90	73	73	77	83	63	59	59	59	59	59
2	36	62	62	36	36	36	36	36	36	36	77	83	87	77	73	77	63	62	62	62	62	68
3	28	51	59	43	28	28	28	28	28	28	63	63	80	67	73	70	67	68	68	68	68	68
4	31	45	51	37	46	46	31	31	31	31	57	57	73	63	70	70	63	59	62	62	62	62
5	31	46	56	39	31	31	31	31	31	31	63	73	83	77	77	77	65	68	68	68	68	68
6	36	47	55	43	36	36	36	36	36	36	67	73	77	63	73	73	57	71	72	72	72	72
7	31	38	57	47	33	33	45	45	31	31	50	40	73	63	63	63	57	69	72	75	75	75
9	31	42	56	37	42	42	47	67	31	31	50	60	67	60	60	50	50	60	65	67	67	67
12	23	45	52	37	27	37	32	32	23	23	50	53	67	57	60	57	57	61	67	70	70	70
14	31	58	58	31	31	31	31	31	31	31	70	70	80	70	70	73	70	58	58	58	58	58
15	23	38	49	32	29	35	23	23	23	23	43	55	73	60	60	60	60	53	69	69	69	69
16	23	29	37	33	27	31	38	37	23	23	53	53	67	63	63	63	63	47	57	67	67	67
17	23	37	47	33	27	32	37	35	23	23	53	53	67	63	63	63	63	52	58	65	65	65
18	40	42	50	50	42	42	50	50	40	40	60	50	85	80	80	80	80	52	55	63	63	63
19	28	35	46	40	28	28	28	28	28	28	60	60	77	63	70	63	63	63	63	63	63	63
20	27	31	40	37	35	70	75	68	27	27	64	64	88	88	78	88	88	59	66	85	85	85
22	27	31	48	39	60	65	68	37	27	27	64	64	88	88	78	88	88	53	71	77	77	77
24	27	43	56	39	27	27	27	27	27	27	64	64	88	78	78	78	[illegible]	66	66	66	66	66
25	27	32	39	35	27	39	40	38	[illegible]	27	69	69	92	82	82	82	82	50	55	59	59	59
26	27	29	31	28	27	32	36	[illegible]	[illegible]	27	69	69	92	82	82	82	62	36	41	49	67	67
27	47	50	56	54	48	56	57	[illegible]	[illegible]	47	71	71	92	81	81	81	81	59	62	67	67	67
28	35	35	35	35	38	38	38	[illegible]	[illegible]	47	72	67	90	85	80	85	85	35	38	38	70	[illegible]
30	80	80	80	80	80	80	80	80	[illegible]	80	80	80	90	85	80	85	85	80	80	80	86	86
32	38	38	38	38	38	47	48	46	67	47	74	70	90	85	80	85	85	38	47	57	67	73
33	34	37	37	37	35	47	50	50	57	47	65	62	90	85	80	85	85	37	47	52	73	78
34	16	17	17	17	16	16	53	49	32	27	30	28	90	31	80	31	31	17	17	53	67	77
35	26	36	36	36	26	37	47	45	50	31	56	52	72	68	64	68	68	40	47	52	69	78
36	31	31	31	31	31	40	50	50	50	39	62	58	78	74	70	74	74	31	40	50	70	82
38	36	48	48	48	38	38	38	63	38	38	80	75	90	85	80	85	85	58	58	58	68	68
39	57	61	63	63	61	61	61	71	62	62	80	75	90	85	80	85	85	63	70	75	88	90
40	57	57	57	57	57	57	57	72	67	67	80	75	90	85	80	85	85	57	57	57	72	93
41	57	57	57	57	57	57	57	57	76	62	80	75	90	85	80	85	85	57	57	57	76	81
42	32	32	32	32	32	32	32	32	90	32	80	75	90	85	80	85	85	32	32	32	90	90
43	35	35	35	35	38	52	51	50	58	38	72	67	90	85	80	85	85	35	38	53	80	85
44	44	44	44	44	44	44	44	44	50	80	80	75	90	85	80	85	85	44	44	44	50	86
45	44	44	44	44	44	44	44	44	50	80	80	75	90	85	80	85	85	44	44	44	50	88
46	35	35	35	35	35	35	35	35	50	60	72	67	90	85	80	85	85	35	35	35	50	80
48	8	38	48	41	8	41	37	8	8	8	10	10	57	17	47	17	17	56	63	68	68	68
52	21	21	21	21	21	21	21	21	21	21	27	27	87	21	70	21	21	21	26	46	56	61
58	50	50	50	50	55	65	65	65	50	50	70	70	70	70	70	70	70	50	55	65	65	65
61	17	20	29	29	17	17	45	42	25	17	17	17	77	17	70	17	17	39	39	58	64	64
62	30	45	30	30	30	38	30	30	35	30	100	30	90	90	30	100	90	45	49	49	54	54
63	8	18	24	18	8	26	11	11	31	18	28	18	67	8	60	8	8	27	29	46	50	51
64	61	68	61	61	61	70	61	61	61	61	71	61	71	71	66	71	71	68	77	77	77	77
65	10	25	35	32	10	35	44	42	10	10	33	10	87	10	80	10	10	40	48	57	57	57
67	13	36	43	38	40	56	40	38	13	13	27	17	70	13	60	13	13	46	53	63	63	63
68	90	90	90	90	90	90	90	90	100	90	100	100	100	100	100	100	100	90	90	90	100	100
69	17	17	17	17	17	17	17	17	47	27	60	60	83	83	91	91	83	17	17	17	47	55
70	20	20	20	20	20	20	54	52	28	25	37	37	80	47	80	47	47	20	20	54	60	62
73	89	89	89	89	89	89	89	89	100	89	100	100	[illegible]	100	100	100	100	89	89	89	100	100
74	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
75	27	27	27	27	27	27	27	27	73	37	60	63	93	80	80	80	80	27	27	27	73	82
[illegible]	89	89	89	89	89	95	95	95	89	89	100	100	100	100	100	100	100	89	95	98	98	98
[illegible]	45	55	63	58	50	50	50	50	45	45	73	67	87	77	87	87	60	75	75	75	75	75
[illegible]	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
80	89	89	89	89	89	89	89	89	94	89	93	93	100	100	100	100	100	89	89	89	94	94
82	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
83	89	89	89	89	89	89	89	89	94	89	93	93	100	100	100	100	100	89	89	89	94	94
85	10	30	35	30	10	30	35	32	20	15	25	20	60	53	60	53	53	40	47	58	61	73
87	12	50	12	12	30	40	12	12	12	12	73	77	93	90	90	90	60	52	65	75	75	75
89	10	33	49	33	10	10	10	10	10	10	53	53	87	83	83	83	10	69	69	69	69	69
93	57	67	72	65	57	57	57	57	57	57	73	73	90	90	83	87	57	77	77	77	77	77
94	17	17	17	17	17	17	17	17	57	27	80	80	80	80	80	80	60	17	17	17	57	67
96	12	43	53	40	33	43	40	28	12	12	70	63	90	90	90	90	53	12	12	12	57	67
97	30	30	30	30	30	30	30	30	90	34	80	80	80	80	80	80	80	30	30	30	90	95
99	15	35	15	15	15	37	15	15	15	15	15	23	15	15	73	93	15	35	43	43	43	43
100	70	70	70	70	70	70	70	70	87	72	100	100	100	100	100	100	100	70	70	70	87	89
102	70	70	70	70	70	70	70	70	80	83	75	75	90	85	85	85	85	70	70	70	80	93
		GD3	GD20	GD7	E6	E20	E8	E9	S2	M20	207	212	232	233	257	260	284	C/1	C/2	C/3	C/4	C/5

3.5.3 FACILITY RESEARCH VALUE - Facility research values are used in the selection of the most attractive ground facilities and flight research vehicles for refinement in Phase III. These facility research values are found by multiplying the task intrinsic value sum determined for each Research Objective by the facility capability value determined for that objective and then adding over all the objectives which pertain to the operational system in question. Figures 3-27 through 3-30 present the products of task intrinsic value sums times facility capability values. The resulting facility research values are shown as totals of these products at the bottom of each figure. These figures correspond to the four representative potential operational systems (I2, C1, M1, and M2). The totals for the task intrinsic value sums and the existing facility values are also shown at the bottom of each page for reference.

In each figure, the research values per objective, as well as the facility research values shown as totals at the bottom of each column, represent the value of the new facilities in conjunction with existing facilities. A candidate facility which could satisfy all of the research requirements of each Research Task under a given objective would have a research value for that objective equal to the task intrinsic value sum for that objective. The incremental value relative to a given Research Objective of each new facility, by itself, can be determined by comparing its value relative to the given objective with the existing facilities value for that objective. In number of cases, it can be seen that candidate ground facilities are not applicable to the Research Tasks associated with a particular objective and provide no increase over the exising facility value in the achievement of the objective. Similarly, the incremental facility research value of each new facility, by itself, can be determined by comparing the facility research value shown at the bottom of the column for that facility to the total existing facility value shown at the bottom of the existing facilities column.

3.5.4 RESEARCH VALUE SUMMARY FOR BASELINE FACILITIES - Facility research values for the four representative operational systems are summarized in Figure 3-31. The research value sums presented at the top of the page for each candidate research facility correspond to the column totals shown in Figures 3-27 through 3-30, and these values are converted to percent of the total required research at the bottom of the page. These research values include, of course, the contribution of existing facilities.

All facility capabilities and facility research values presented in this section are measured with respect to "baseline" facilities. Characteristics of these facilities were established at the beginning of Phase II and the basic research requirements analysis considered only these "baseline" systems.

Many tradeoffs accomplished on the flight research vehicles resulted in improved configurations, identified as "near-optimum" systems, which were considered in the final selection of vehicles to be carried into Phase III. These tradeoffs are described in Section 4, and the facility research values for the "near-optimum" flight research vehicles are presented in Section 4.6.

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FOLDOUT FRAME 1

FIGURE 3-27
(U) VALUE OF RESEARCH ACHIEVABLE IN EACH FACILITY
Operational System No. 2–(L2)

OBJ. NO.	TASK INTRINSIC VALUE SUM	VALUE OF EXISTING FACILITIES	VALUE OF NEW FACILITIES + EXISTING FACILITIES														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
			GD3	GD20	GD7	E6	E20	E8	E9	S2	M20	207	212	232	233	257	260
1	224.8	101.2	132.7	132.7	101.2	101.2	101.2	101.2	101.2	101.2	101.2	164.1	202.4	164.1	164.1	195.6	186.6
2	182.7	65.8	113.3	113.3	65.8	65.8	65.8	65.8	65.8	65.8	65.8	140.7	151.6	140.7	140.7	151.6	151.6
3	191.4	53.6	97.6	112.9	82.3	53.6	53.6	53.6	53.6	53.6	53.6	120.6	120.6	134.0	128.3	139.7	134.0
4	160.6	49.8	72.3	81.9	59.4	73.9	73.9	49.8	49.8	49.8	49.8	91.6	91.6	101.2	101.2	112.4	112.4
5	156.9	48.6	72.2	87.8	61.2	48.6	48.6	48.6	48.6	48.6	48.6	98.8	114.5	120.8	120.8	130.2	125.5
6	196.7	70.0	92.4	108.2	84.6	70.8	70.8	70.8	70.8	70.8	70.8	131.8	143.6	131.8	118.0	151.5	137.7
7	95.4	29.6	36.3	54.4	44.8	31.5	31.5	42.9	42.9	29.6	29.6	47.7	38.2	60.1	54.4	60.1	54.4
9	133.9	41.5	56.2	75.0	49.6	56.2	56.2	62.9	62.9	41.5	41.5	67.0	80.4	80.4	67.0	84.4	47.0
10	83.6	30.1	34.3	49.3	35.1	30.1	30.1	30.1	30.1	30.1	30.1	52.7	36.0	52.7	52.7	52.7	58.5
11	187.3	84.3	88.0	106.7	104.9	84.3	84.3	84.3	84.3	84.3	84.3	118.0	99.2	135.7	136.7	146.1	136.7
12	154.7	35.6	69.6	80.5	57.2	41.8	57.2	49.5	49.5	35.6	35.6	77.4	82.0	89.2	88.2	92.8	88.2
14	151.3	46.9	87.8	87.8	46.9	46.9	46.9	46.9	46.9	46.9	46.9	105.9	105.9	110.5	110.5	121.1	121.1
15	101.1	23.3	38.4	48.5	32.3	29.3	35.4	23.3	23.3	23.3	23.3	43.5	60.7	50.5	50.5	55.7	50.5
16	109.8	25.3	31.8	40.6	36.2	29.7	34.0	41.7	40.6	25.3	25.3	58.2	58.2	69.2	69.2	73.6	73.6
17	86.2	19.8	31.9	40.5	28.4	23.3	27.6	31.9	30.2	19.8	19.8	45.7	45.7	54.3	54.3	57.7	57.7
18	86.7	34.7	36.4	43.3	43.3	36.4	36.4	43.3	43.3	34.7	34.7	43.3	43.3	69.4	69.4	69.4	69.4
19	94.6	26.5	33.1	43.5	37.8	26.5	26.5	26.5	26.5	26.5	26.5	56.8	56.8	63.4	59.6	66.1	59.6
20	104.1	28.1	32.3	41.6	38.5	30.2	38.5	43.7	42.7	28.1	28.1	66.6	66.6	91.6	91.6	91.6	91.6
22	170.4	46.0	52.8	81.8	66.5	102.3	110.8	115.9	63.1	46.0	46.0	109.1	109.1	150.0	150.0	150.0	150.0
23	142.2	54.0	56.9	64.0	59.7	54.0	71.1	85.3	85.3	54.0	54.0	96.7	96.7	129.4	129.4	129.4	129.4
24	107.3	29.0	46.2	60.1	41.9	29.0	29.0	29.0	29.0	29.0	29.0	68.7	68.7	83.7	83.7	94.5	83.7
25	132.2	35.7	42.3	51.6	46.3	35.7	51.6	52.9	50.2	35.7	35.7	91.2	91.2	108.4	108.4	121.6	108.4
26	134.4	36.3	39.0	41.7	37.6	36.3	43.0	48.4	47.0	79.3	36.3	92.7	92.7	110.2	110.2	110.2	123.6
27	90.5	42.5	45.3	50.7	48.9	43.4	50.7	51.6	50.7	42.5	42.5	64.3	64.3	83.3	73.3	83.3	73.3
28	205.8	72.0	72.0	72.0	72.0	78.2	78.2	78.2	78.2	144.1	96.7	137.9	129.7	154.3	154.3	174.9	154.3
30	115.6	92.5	92.5	92.5	92.5	92.5	92.5	92.5	92.5	99.4	92.5	92.5	92.5	92.5	92.5	98.3	92.5
32	[illegible]	53.9	53.9	53.9	53.9	53.9	66.7	68.1	65.3	95.1	66.7	99.3	92.2	105.4	106.4	120.6	106.4
33	[illegible]	46.9	51.1	51.1	51.1	48.3	64.9	69.0	69.0	78.7	64.9	85.6	80.0	103.5	103.5	117.3	103.5
34	312.0	49.9	53.0	53.0	53.0	49.9	49.9	165.3	152.9	99.8	84.2	87.3	81.1	234.0	87.3	265.2	87.3
35	62.4	16.2	22.5	22.5	22.5	16.2	23.1	29.3	28.1	31.2	19.3	32.5	30.6	37.4	37.4	42.4	37.4
36	132.8	41.2	41.2	41.2	41.2	41.2	53.1	66.4	66.4	66.4	51.8	77.0	71.7	86.3	86.3	98.3	86.3
38	94.2	33.9	45.2	45.2	45.2	35.8	35.8	35.8	59.4	35.8	35.8	70.7	66.0	70.7	70.7	80.1	70.7
39	62.8	35.8	38.3	39.5	39.5	38.3	38.3	38.3	44.6	38.9	38.9	47.1	43.9	47.1	47.1	53.4	47.1
40	143.4	81.7	81.7	81.7	81.7	81.7	81.7	81.7	103.2	96.1	96.1	107.5	100.4	107.5	107.5	121.9	107.5
41	97.7	55.7	55.7	55.7	55.7	55.7	55.7	55.7	55.7	74.2	60.5	73.2	68.4	73.2	73.2	93.0	73.2
42	62.5	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	56.2	20.0	46.9	43.7	46.9	46.9	53.1	46.9
43	254.1	88.9	88.9	88.9	88.9	96.6	132.1	129.6	127.0	147.5	96.6	170.2	160.1	190.6	190.6	215.0	190.6
44	110.8	48.8	48.8	48.8	48.6	48.8	48.8	48.8	48.8	55.4	88.6	83.1	77.6	83.1	83.1	94.2	83.1
45	195.6	86.2	86.2	86.2	85.2	86.2	86.2	86.2	86.2	97.9	156.7	146.9	137.1	146.9	146.9	166.5	146.9
46	163.4	57.2	57.2	57.2	57.2	57.2	57.2	57.2	57.2	81.7	98.0	109.5	102.9	122.6	122.6	138.9	122.6
48	273.1	49.2	103.8	131.1	112.0	49.2	112.0	101.0	49.2	49.2	49.2	101.0	112.0	163.8	112.0	226.6	112.0
52	127.0	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1
58	158.2	79.1	79.1	79.1	79.1	87.0	102.8	102.8	102.8	79.1	79.1	110.7	110.7	113.7	110.7	110.7	110.7
60	383.7	49.9	65.2	107.4	107.4	49.9	49.9	165.0	153.5	88.3	49.9	76.7	76.7	203.4	49.9	318.5	49.9
63	84.7	18.6	27.1	32.2	27.1	18.6	33.9	21.2	21.2	38.1	27.1	42.4	33.9	58.5	18.6	74.6	18.6
65	146.4	17.6	36.6	51.2	46.9	17.6	51.2	64.4	61.5	17.6	17.6	65.9	17.6	99.6	17.6	115.7	17.6
67	206.6	41.3	88.9	103.3	93.0	97.1	130.2	97.1	93.0	41.3	41.3	103.3	88.9	126.1	41.3	144.6	41.3
68	87.0	78.3	78.3	78.3	78.3	78.3	78.3	78.3	78.3	87.0	78.3	87.0	87.0	87.0	87.0	87.0	87.0
69	95.9	16.3	16.3	16.3	16.3	16.3	16.3	16.3	15.3	45.1	25.9	57.6	57.6	79.6	79.6	87.3	87.3
70	124.5	36.1	36.1	36.1	36.1	36.1	36.1	78.4	75.9	46.1	42.3	59.7	59.7	83.4	58.5	89.6	58.5
71	114.2	108.5	108.5	108.5	108.5	108.5	108.5	108.5	108.5	108.5	114.2	108.5	108.5	108.5	108.5	108.5	108.5
72	66.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6	66.6	26.6	26.6	40.0	26.6	26.6	40.0	26.6
73	94.2	83.9	83.9	83.9	83.9	83.9	83.9	83.9	83.9	94.3	83.9	94.3	94.3	94.3	94.3	94.3	94.3
75	123.7	33.4	33.4	33.4	33.4	33.4	33.4	33.4	33.4	90.3	45.8	74.2	77.9	102.6	98.9	111.3	102.6
77	93.5	88.8	88.8	88.8	88.8	88.8	93.5	93.5	93.5	88.8	88.8	90.7	90.7	93.5	93.5	93.5	93.5
78	96.0	45.1	52.8	60.5	55.7	48.0	48.0	48.0	48.0	45.1	45.1	70.1	64.3	73.9	73.9	83.5	83.5
79	70.0	66.5	66.5	66.5	66.5	70.0	70.0	70.0	66.5	66.5	66.5	67.9	67.9	70.0	70.0	70.0	70.0
80	147.6	140.2	140.2	140.2	140.2	140.2	140.2	140.2	140.2	147.6	140.2	143.2	143.2	147.6	147.6	147.6	147.6
82	114.8	114.8	114.8	114.8	114.8	114.8	114.8	114.8	114.8	114.8	114.8	114.8	114.8	114.8	114.8	114.8	114.8
83	62.7	59.6	59.6	59.6	59.6	59.6	59.6	59.6	59.6	62.7	59.6	60.8	60.8	62.7	62.7	62.7	62.7
87	139.2	12.0	54.6	12.0	12.0	32.7	43.7	12.0	12.0	12.0	12.0	84.0	84.0	98.2	98.2	131.5	98.2
89	103.8	9.3	34.2	50.8	34.2	9.3	9.3	9.3	9.3	9.3	9.3	62.3	83.0	75.7	75.7	90.3	75.7
93	94.9	54.1	63.6	68.4	61.7	54.1	54.1	54.1	54.1	54.1	54.1	73.1	73.1	82.6	82.6	88.3	82.6
94	141.8	21.3	21.3	21.3	21.3	21.3	21.3	21.3	21.3	80.8	38.3	113.5	113.5	113.5	113.5	113.5	113.5
96	56.9	6.8	24.5	30.1	22.7	18.8	24.5	22.7	21.6	6.8	6.8	45.5	43.8	47.2	45.5	51.2	45.5
97	88.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	79.6	30.1	70.8	70.8	70.8	70.8	70.8	70.8
102	67.5	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	54.0	56.0	50.6	50.6	57.4	57.4	60.7	57.4
TOTAL	8905.1	3295.0	3949.7	4306.3	3844.0	3539.1	3898.7	4142.5	4035.6	4098.0	3653.3	5599.5	5547.1	6563.5	5922.3	7256.5	[illegible]055.9
			GD3	GD20	GD7	E6	E20	E8	E9	S2	M20	207	212	232	233	257	260

FOLDOUT FRAME 2

.7

BLE IN EACH FACILITY

No. 2–(L2)

OF NEW FACILITIES + EXISTING FACILITIES

5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
E20	E8	E9	S2	M20	207	212	232	233	257	260	284	C/1	C/2	C/3	C/4	C/5
01.2	101.2	101.2	101.2	101.2	164.1	202.4	164.1	164.1	195.6	186.6	141.7	132.7	132.7	132.7	132.7	132.7
5.8	65.8	65.8	65.8	65.8	140.7	151.6	140.7	140.7	151.6	151.6	115.1	113.3	113.3	113.3	113.3	124.2
3.6	53.6	53.6	53.6	53.6	120.6	120.6	134.0	128.3	139.7	134.0	128.3	130.2	130.2	130.2	130.2	130.2
73.9	49.8	49.8	45.8	49.8	91.6	91.6	101.2	101.2	112.4	112.4	101.2	94.8	99.6	94.8	99.5	99.6
8.6	48.6	48 6	48.6	48.6	98.8	114.5	120.8	120.8	130.2	125.5	102.0	106.7	106.7	106.7	106.7	106.7
0.8	70.8	70.8	70.8	70.8	131.8	143.6	131.8	118.0	151.5	137.7	118.0	139.7	141.6	141.6	141.6	141.6
31.5	42.9	42.9	29.6	29.6	47.7	38.2	60.1	54.4	60.1	54.4	54.4	65.8	68.7	71.6	71.6	71.6
56.2	62.9	62.9	41.5	41.5	67.0	80.4	80.4	67.0	84.4	67.0	67.0	80.4	87.0	89.7	89.7	89.7
30.1	30.1	30.1	30.1	30.1	52.7	36.0	52.7	52.7	52.7	58.5	52.7	56.0	56.0	56.0	56.0	56.0
4.3	84.3	84.3	84.3	84.3	118.0	99.2	136.7	136.7	146.1	136.7	136.7	118.0	118.0	118.0	118.0	118.0
7.2	49.5	49.5	35.6	35.6	77.4	82.0	89.2	88.2	92.8	88.2	88.2	94.4	103.7	108.3	108.3	108.3
46.9	46.9	46.9	46.9	46.9	105.9	105.9	110.5	110.5	121.1	121.1	110.5	87.8	87.8	87.8	87.8	87.8
5.4	23.3	23.3	23.3	23.3	43.5	60.7	50.5	50.5	55.7	50.5	50.5	58.6	69.8	69.8	69.8	69.8
4.0	41.7	40.6	25.3	25.3	58.2	58.2	69.2	69.2	73.6	73.6	69.2	51.6	62.6	73.6	73.6	73.6
7.6	31.9	30.2	19.8	19.8	45.7	45.7	54.3	54.3	57.7	57.7	54.3	44.8	50.0	56.0	56.0	56.0
6.4	43.3	43.3	34.7	34.7	43.3	43.3	69.4	69.4	59.4	69.4	69.4	45.1	47.7	54.6	54.6	54.6
6.5	26.5	26.5	26.5	26.5	56.8	56.8	63.4	59.6	66.2	59.6	59.6	59.6	59.6	59.6	59.6	59.6
88.5	43.7	42.7	28.1	28.1	66.6	66.6	91.6	91.6	91.6	91.6	91.6	53.1	57.3	67.7	67.7	67.7
0.8	115.9	63.1	46.0	46.0	109.1	109.1	150.0	150.0	150.0	150.0	150.0	90.3	121.0	131.2	131.2	131.2
1.1	85.3	85.3	54.0	54.0	96.7	96.7	129.4	129.4	129.4	129.4	129.4	68.3	73.9	92.4	92.4	92.4
9.0	29.0	29.0	29.0	29.0	68.7	68.7	83.7	83.7	94.5	83.7	83.7	70.9	70.9	70.9	70.9	70.9
1.6	52.9	50.2	35.7	35.7	91.2	91.2	108.4	108.4	121.6	108.4	108.4	66.1	72.7	78.0	78.0	78.0
3.0	48.4	47.0	79.3	36.3	92.7	92.7	110.2	110.2	115.2	123.6	110.2	48.4	55.1	65.8	90.0	90.0
0.7	51.6	50.7	42.5	42.5	64.3	64.3	83.3	73.3	83.3	73.3	73.3	53.4	56.1	60.6	60.6	60.6
78.2	78.2	78.2	144.1	96.7	137.	129.7	154.3	154.3	174.9	154.3	154.3	78.2	78.2	78.2	144.1	160.5
2.5	92.5	92.5	99.4	92.5	92.	92.5	92.5	92.5	98.3	92.5	92.5	92.5	92.5	92.5	99.4	99.4
6.7	68.1	65.3	95.1	66.7	99.3	92.2	106.4	106.4	120.6	106.4	106.4	53.9	66.7	80.9	95.1	103.6
4.9	69.0	69.0	78.7	64.9	85.6	80.0	103.5	103.5	117.3	103.5	103.5	51.1	64.9	71.8	100.7	107.6
9.9	165.3	152.9	99.8	84.2	87.3	81.1	234.0	87.3	265.2	87.3	87.3	53.	53.0	165.3	209.0	243.2
3.1	29.3	28.1	31.2	19.3	32.5	30.6	37.4	37.4	42.4	37.4	37.4	25.0	29.3	32.5	43.1	48.7
3.1	66.4	66.4	66.4	51.8	77.0	71.7	86.3	86.3	98.3	86.3	86.3	41.2	53.1	66.4	93.0	108.9
5.8	35.8	59.4	35.8	35.8	70.7	66.0	70.7	70.7	80.1	70.7	70.7	54.7	54.7	54.7	64.1	64.1
8.3	38.3	44.6	38.9	38.9	47.1	43.9	47.1	47.1	53.4	47.1	47.1	39.5	43.9	47.1	55.2	56.5
1.7	81.7	103.2	96.1	96.1	107.5	100.4	107.5	107.5	121.9	107.5	107.5	81.7	81.7	81.7	103.2	133.3
5.7	55.7	55.7	74.2	60.5	73.2	68.4	73.2	73.2	93.0	73.2	73.2	55.7	55.7	55.7	74.2	79.1
0.0	20.0	20.0	56.2	20.0	46.9	43.7	46.9	46.9	53.1	46.9	46.9	20.0	20.0	20.0	56.2	56.2
2.1	129.6	127.0	147.4	96.6	170.2	160.1	190.6	190.6	216.0	190.6	190.6	88.9	96.6	134.7	203.3	216.0
8.8	48.8	48.8	55.4	88.6	83.1	77.6	83.1	83.1	94.2	83.1	83.1	48.8	48.8	48.8	55.4	95.3
6.2	86.2	86.2	97.9	156.7	146.9	137.1	146.9	146.9	166.5	146.9	146.9	86.2	86.2	86.2	97.9	172.3
7.2	57.2	57.2	81.7	98.0	109.5	102.9	122.6	122.6	138.9	122.6	122.6	57.2	57.2	57.2	81.7	130.7
2.0	101.0	49.2	49.2	49.2	101.0	112.0	163.8	112.0	226.6	112.0	106.5	152.9	172.0	185.7	185.7	185.7
4.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	24.1	33.0	58.4	71.1	77.5
2.8	102.8	102.8	79.1	79.1	110.7	110.7	110.7	110.7	110.7	110.7	110.7	79.1	87.0	102.8	102.8	102.8
9.9	165.0	153.5	88.3	49.9	76.7	76.7	203.4	49.9	318.5	49.9	49.9	142.0	142.0	214.9	226.4	226.4
3.9	21.2	21.2	38.1	27.1	42.4	33.9	58.5	18.6	74.6	18.6	18.6	38.1	39.8	54 2	57.6	58.5
1.2	64.4	61.5	17.6	17.6	65.9	17.6	99.6	17.6	115.7	17.6	17.6	58.6	70.3	83.5	83.5	83.5
0.2	97.1	93.0	41.3	41.3	103.3	88.9	126.1	41.3	144.6	41.3	41.3	109.5	124.0	144.6	144.6	144.6
8.3	78.3	78.3	87.0	78.3	87.0	87.0	87.0	87.0	87.0	87.0	87.0	78.3	78.3	78.3	87.0	87.0
6.3	16.3	15.3	45.1	25.9	57.6	57.6	79.6	79.6	87.3	37.3	79.6	16.3	16.3	16.3	45.1	52.8
6.1	78.4	75.9	46.1	42.3	59.7	59.7	83.4	58.5	89.6	58.5	58.5	36.1	36.1	78.4	85.9	88.4
8.5	108.5	108.5	108.5	114.2	108.5	108.5	108.5	108.5	108.5	108.5	108.5	108.5	108.5	108.5	108.5	114.2
6.6	26.6	26.6	66.6	26.6	26.6	40.0	26.6	26.6	40.0	26.6	26.6	26.6	26.6	26.6	66.6	66.6
3.9	83.9	83.9	94.3	83.9	94.3	94.3	94.3	94.3	94.3	94.3	94.3	83.9	83.9	83.9	94.3	94.3
3.4	33.4	33.4	90.3	45.8	74.2	77.9	102.6	98.9	111.3	102.6	98.9	33.4	33.4	33.4	90.3	101.4
3.5	93.5	93.5	88.8	88.8	90.7	90.7	93.5	93.5	93.5	93.5	93.5	88.8	93.5	93.5	93.5	93.5
8.0	48.0	48.0	45.1	45.1	70.1	64.3	73.9	[illegible]	83.5	83.5	57.6	72.0	72.0	72.0	72.0	72.0
0.0	70.0	66.5	66.5	66.5	67.9	67.9	70.0	70.0	70.0	70.0	70.0	66.5	68.6	70.0	70.0	70.0
0.2	140.2	140.2	147.6	140.2	143.2	143.2	147.6	147.6	147.6	147.6	147.6	140.2	140.2	140.2	147.6	147.6
4.8	114.8	114.8	114.8	114.8	[illegible]	114.8	114.8	114.8	114.8	114.8	114.8	114.8	114.8	114.8	114.8	114.8
9.6	59.6	59.6	62.7		[illegible]	60.8	62.7	62.7	62.7	62.7	62.7	59.6	59.6	59.6	62.7	62.7
3.7	12.0	12.0	[illegible]		[illegible]	[illegible]	98.2	98.2	131.5	98.2	65.5	56.8	70.9	81.9	81.9	81.9
9.3	9.3	9.3			[illegible]	[illegible]	75.7	75.7	90.3	75.7	9.3	71.6	71.6	71.6	71.6	71.6
4.1	54.1	54.1	54.		[illegible]	[illegible]	82.6	82.6	88.3	32.6	54.1	73.1	73.1	73.1	73.1	73.1
1.3	21.3	21.3	30.		[illegible]	[illegible]	113.5	113.5	113.5	113.5	85.1	21.3	21.3	21.3	80.8	95.0
4.5	22.7	21.6	[illegible]	[illegible]		[illegible]	67.2	65.5	51.2	45.5	30.1	6.8	6.8	6.8	32.4	38.1
6.5	26.5	26.5		[illegible]		[illegible]	70.8	70.8	70.8	70.8	70.8	26.5	26.5	26.5	79.6	84.0
7.2	47.2	47.2	[illegible]	[illegible]			7.4	57.4	60.7	57.4	57.4	47.2	47.2	47.2	54.0	62.8
8.7	4142.5	4035.	[illegible]	[illegible]	[illegible]	[illegible]	6563.5	5922.3	7256.5	5055.9	5662.3	4689.9	4941.6	5457.1	6218.8	6593.9
20	E8	E9	[illegible]	[illegible]	[illegible]	[illegible]	232	233	257	260	284	C/1	C/2	C/3	C/4	C/5

FOLDOUT FRAME 1

F

VALUE OF RESEARC

Operation

OBJ. NO.	TASK INTRINSIC VALUE SUM	VALUE OF EXISTING FACILITIES	VALUE OF NEW FACILITIES + EXISTING FACILITIES													
			1 GD3	2 GD20	3 GD7	4 E6	5 E20	6 E8	7 E9	8 S2	9 M20	10 207	11 212	12 232	13 233	14 257
1	216.3	114.7	127.6	127.6	114.7	114.7	114.7	114.7	114.7	114.7	114.7	157.9	194.7	157.9	157.9	188.2
2	176.4	75.9	109.4	104.1	75.9	75.9	75.9	75.9	75.9	75.9	75.9	135.8	146.4	135.8	135.8	146.4
3	190.6	82.0	101.0	112.5	82.0	82.0	82.0	82.0	82.0	82.0	82.0	152.5	152.5	139.2	133.4	146.8
4	157.7	58.4	71.0	80.4	58.4	72.5	72.5	67.8	67.8	58.4	58.4	89.9	89.9	99.4	99.4	110.4
5	151.2	55.9	69.6	81.6	55.9	55.9	55.9	55.9	55.9	55.9	55.9	95.3	110.4	116.4	116.4	116.4
6	188.3	81.0	107.3	94.1	81.0	81.0	81.0	81.0	81.0	81.0	81.0	126.2	137.5	126.2	113.0	145.0
7	91.4	39.3	39.3	53.9	39.3	39.3	39.3	39.3	39.3	39.3	39.3	64.0	64.0	64.0	52.1	64.0
9	131.1	48.5	65.6	76.0	48.5	48.5	48.5	48.5	48.5	48.5	48.5	65.6	78.7	78.7	65.6	82.6
12	148.7	55.0	71.4	78.8	55.0	69.9	55.0	55.0	55.0	55.0	55.0	69.9	89.2	89.2	69.9	89.2
14	139.5	43.2	87.9	43.2	43.2	43.2	43.2	43.2	43.2	67.0	43.2	97.6	97.6	101.8	101.8	111.6
15	96.2	22.1	41.4	47.2	30.8	22.1	22.1	22.1	22.1	22.1	22.1	41.4	57.7	48.1	48.1	57.7
16	105.4	34.8	39.0	49.6	34.8	41.1	51.7	45.3	45.3	34.8	34.8	66.4	66.4	66.4	66.4	66.4
17	81.8	22.1	34.4	40.1	22.1	22.1	30.3	28.6	27.0	22.1	22.1	43.4	43.4	51.5	51.5	51.5
19	90.9	45.4	60.9	56.3	45.4	45.4	45.4	45.4	45.4	45.4	45.4	63.6	63.6	66.3	66.3	66.3
20	101.6	35.6	51.8	54.9	48.8	35.6	76.2	82.3	72.2	35.6	35.6	81.3	81.3	89.5	89.5	89.5
22	164.6	57.6	83.9	88.9	57.6	70.8	123.4	133.3	116.9	57.6	57.6	131.7	131.7	144.8	144.8	144.8
24	104.3	36.5	53.2	56.3	50.1	36.5	78.2	84.5	74.1	36.5	36.5	83.4	83.4	91.8	91.8	91.8
25	123.8	43.3	63.2	66.9	59.4	43.3	104.0	106.5	109.0	43.3	43.3	106.5	106.5	113.9	113.9	113.9
26	132.7	46.4	50.4	58.4	55.7	46.4	58.4	61.0	61.0	70.3	57.1	114.1	114.1	122.1	122.1	122.1
27	86.8	66.0	66.0	66.0	66.0	66.0	74.7	75.5	76.4	66.0	66.0	74.7	74.7	79.9	70.3	79.9
28	205.8	94.7	94.7	94.7	94.7	100.8	100.6	100.8	100.8	166.7	119.4	148.2	148.2	164.6	164.6	164.6
30	115.6	92.5	92.5	92.5	92.5	92.5	92.5	92.5	92.5	99.4	92.5	92.5	92.5	92.5	92.5	92.5
32	141.9	71.0	71.0	71.0	71.0	71.0	83.7	85.1	82.3	112.1	83.7	105.0	105.0	113.5	113.5	113.5
33	138.0	73.1	77.3	77.3	77.3	74.5	91.1	95.2	95.2	104.9	91.1	110.4	110.4	110.4	110.4	110.4
34	317.0	249.6	252.7	252.7	252.7	249.6	249.6	312.0	312.0	299.5	283.9	249.6	249.6	249.6	249.6	249.6
35	62.4	21.2	27.5	27.5	27.5	21.2	28.1	34.3	33.1	36.2	24.3	39.9	39.9	39.9	39.9	39.9
36	132.8	53.1	53.1	53.1	53.1	53.1	65.1	78.4	78.4	78.4	63.8	93.0	93.0	93.0	93.0	93.0
38	94.2	33.9	45.2	45.2	45.2	35.8	35.8	35.8	59.4	35.8	35.8	75.4	75.4	75.4	75.4	75.4
39	62.8	35.8	38.3	39.5	39.5	38.3	38.3	38.3	44.6	38.9	38.9	50.2	50.2	50.2	50.2	50.2
40	143.4	81.7	81.7	81.7	81.7	81.7	81.7	81.7	103.2	96.1	96.1	114.7	114.7	114.7	114.7	114.7
41	97.7	55.7	55.7	55.7	55.7	55.7	55.7	55.7	55.7	74.2	60.5	78.1	78.1	78.1	78.1	78.1
42	62.5	26.2	26.2	26.2	26.2	26.2	26.2	26.2	26.2	62.5	26.2	50.0	50.0	50.0	50.0	50.0
43	254.1	114.3	114.3	114.3	114.3	122.0	157.5	155.0	152.5	172.8	122.0	203.3	203.3	203.3	203.3	203.3
44	110.8	63.2	63.2	63.2	63.2	63.2	63.2	63.2	74.2	69.8	103.1	88.6	88.6	88.6	88.6	88.6
45	195.8	111.6	111.6	111.6	111.6	111.6	111.6	111.6	123.4	123.4	182.1	156.7	156.7	156.7	156.7	156.7
46	163.4	73.5	73.5	73.5	73.5	73.5	73.5	73.5	98.0	98.0	114.4	130.7	130.7	130.7	130.7	130.7
48	284.5	162.2	199.2	190.6	162.2	162.2	196.3	162.2	162.2	162.2	162.2	190.6	227.6	162.2	162.2	162.2
52	133.5	70.7	70.7	70.7	70.7	93.4	93.4	84.1	84.1	70.7	70.7	93.4	97.4	70.7	70.7	70.7
55	83.0	66.4	66.4	66.4	66.4	76.3	76.3	66.4	66.4	66.4	66.4	78.8	33.0	70.5	66.4	78.8
57	375.4	150.1	150.1	150.1	150.1	311.5	326.6	150.1	150.1	150.1	150.1	176.4	214.0	150.1	150.1	150.1
58	165.2	115.7	115.7	115.7	115.7	123.9	132.2	115.7	115.7	115.7	115.7	132.2	132.2	132.2	132.2	132.2
59	365.0	84.0	84.0	109.5	84.0	266.5	281.1	84.0	84.0	84.0	84.0	182.5	303.0	84.0	84.0	84.0
63	93.8	53.5	59.1	62.8	53.5	53.5	62.8	53.5	53.5	53.5	53.5	62.8	75.0	53.5	53.5	65.7
65	161.5	92.1	101.8	109.8	92.1	92.1	109.8	92.1	92.1	92.1	92.1	108.2	124.4	92.1	92.1	92.1
67	217.0	86.8	112.9	108.5	86.8	119.4	130.2	86.8	86.8	86.8	86.8	123.7	130.2	86.8	86.8	86.8
68	88.1	79.3	79.3	79.3	79.3	79.3	79.3	79.3	79.3	88.1	79.3	88.1	88.1	88.1	88.1	88.1
69	97.2	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	45.7	26.3	77.8	77.8	80.7	80.7	88.5
70	125.3	58.9	58.9	58.9	58.9	58.9	58.9	101.5	99.0	68.9	65.1	78.9	78.9	100.2	100.2	100.2
71	115.3	109.5	109.5	109.5	109.5	109.5	109.5	109.5	109.5	109.5	115.3	109.5	109.5	109.5	109.5	109.5
72	67.3	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	67.3	26.9	26.9	40.4	26.9	26.9	40.6
73	95.4	84.9	84.9	84.9	84.9	84.9	84.9	84.9	84.9	95.4	84.9	95.4	95.4	95.4	95.4	95.4
74	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8
75	125.3	33.8	33.8	33.8	33.8	33.8	33.8	33.8	33.8	91.5	46.4	104.0	112.8	104.0	100.2	112.8
77	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1
78	97.0	48.5	56.2	64.0	59.1	51.4	51.4	51.4	51.4	48.5	48.5	70.8	74.7	74.7	74.7	84.4
79	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9
80	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0
82	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5
83	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3
87	109.2	15.3	54.6	15.3	15.3	32.7	43.7	15.3	15.3	15.3	15.3	84.0	90.6	98.2	98.2	101.5
89	103.8	12.5	34.2	50.8	34.2	12.5	12.5	12.5	12.5	12.5	12.5	83.0	86.1	75.7	75.7	86.1
93	94.9	54.1	63.6	68.4	61.7	54.1	54.1	54.1	54.1	54.1	54.1	73.1	73.1	85.4	85.4	78.8
94	141.8	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	80.8	38.3	113.5	113.5	113.5	113.5	113.5
96	56.9	8.5	24.5	30.1	22.7	18.8	24.5	22.7	21.6	8.5	8.5	45.5	45.5	45.5	39.8	45.5
97	88.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	79.6	30.1	79.6	79.6	79.6	79.6	79.6
102	67.5	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	54.0	56.0	54.0	54.0	60.7	60.7	60.7
TOTAL	8897.7	4425.6	4955.9	5019.9	4569.2	4941.7	5372.2	4971.2	5024.2	5153.8	4773.6	6553.0	6953.4	6507.2	6420.9	5676.1
			GD3	GD20	GD7	E6	E20	E8	E9	S2	M20	207	212	232	233	257

FOLDOUT FRAME 2

FIGURE 3-28
VALUE OF RESEARCH ACHIEVABLE IN EACH FACILITY
Operational System No. 5–(C1)

OF NEW FACILITIES + EXISTING FACILITIES

5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
20	E8	E9	S2	H20	207	212	232	233	257	260	284	C/1	C/2	C/3	C/4	C/5
4.7	114.7	114.7	114.7	114.7	157.9	194.7	157.9	157.9	188.2	179.6	136.3	127.6	127.6	127.6	127.6	127.6
5.9	75.9	75.9	75.9	75.9	135.8	146.4	135.8	135.8	146.4	146.4	111.1	128.8	128.8	128.8	128.8	128.8
2.0	82.0	82.0	82.0	82.0	152.5	152.5	139.2	133.4	146.8	139.2	120.1	123.9	123.9	123.9	123.9	123.9
2.5	67.8	67.8	53.4	58.4	89.9	89.9	99.4	99.4	110.4	110.4	99.4	93.0	96.2	96.2	96.2	96.2
5.9	55.9	55.9	55.9	55.9	95.3	110.4	116.4	116.4	116.4	116.4	75.6	102.8	102.8	102.8	102.8	102.8
1.0	81.0	81.0	81.0	81.0	126.2	137.5	126.2	113.0	145.0	131.8	107.3	145.0	145.0	145.0	145.0	145.0
9.3	39.3	39.3	39.3	39.3	64.0	64.0	64.0	52.1	64.0	52.1	52.1	63.0	63.0	63.0	63.0	63.0
8.5	48.5	48.5	48.5	48.5	65.6	78.7	78.7	65.6	82.6	65.6	65.6	91.8	91.8	91.8	91.8	91.8
5.0	55.0	55.0	55.0	55.0	69.9	89.2	89.2	69.9	89.2	69.9	69.9	89.2	101.1	101.1	101.1	101.1
3.2	43.2	43.2	67.0	43.2	97.6	97.6	101.8	101.8	111.6	111.6	101.8	87.9	87.9	87.9	107.4	107.4
2.1	22.1	22.1	22.1	22.1	41.4	57.7	48.1	48.1	57.7	48.1	48.1	58.7	58.7	58.7	58.7	58.7
1.7	45.3	45.3	34.8	34.8	66.4	66.4	66.4	66.4	66.4	66.4	66.4	49.6	59.1	69.6	69.6	69.6
0.3	28.6	27.0	22.1	22.1	43.4	43.4	51.5	51.5	51.5	51.5	51.5	45.0	49.1	55.6	55.6	55.6
5.4	45.4	45.4	45.4	45.4	63.6	63.6	65.3	66.3	66.3	66.3	66.3	79.1	79.1	79.1	79.1	79.1
6.2	82.3	72.2	35.6	35.6	81.3	81.3	89.5	89.5	89.5	89.5	89.5	63.0	70.1	91.5	91.5	91.5
3.4	133.3	116.9	57.6	57.6	131.7	131.7	144.8	144.8	144.8	144.8	144.8	100.4	111.9	135.0	135.0	135.0
8.2	84.5	74.1	36.5	36.5	83.4	83.4	91.8	91.8	91.8	91.8	91.8	[illegible]	81.4	91.8	91.8	91.8
4.0	106.5	109.0	43.3	43.3	106.5	106.5	113.9	113.9	113.9	113.9	113.9	80.5	109.0	111.5	111.5	111.5
8.4	61.0	61.0	70.3	57.1	114.1	114.1	122.1	122.1	122.1	122.1	122.1	66.3	79.6	95.5	107.5	112.8
4.7	75.5	76.4	66.0	66.0	74.7	74.7	79.9	70.3	79.9	70.3	70.3	66.0	74.7	77.3	77.3	77.3
0.8	100.8	100.8	166.7	119.4	148.2	148.2	164.6	164.6	164.6	164.6	164.6	100.8	100.8	100.8	166.7	183.2
2.5	92.5	92.5	99.4	92.5	92.5	92.5	92.5	92.5	92.5	92.5	92.5	92.5	92.5	92.5	99.4	99.4
3.7	85.1	82.3	112.1	83.7	105.0	105.0	113.5	113.5	113.5	113.5	113.5	71.0	83.7	97.9	112.1	120.6
1.1	95.2	95.2	104.9	91.1	110.4	110.4	113.4	110.4	110.4	110.4	110.4	77.3	91.1	98.0	125.6	133.8
9.6	312.0	312.0	299.5	283.9	249.6	249.6	249.6	249.6	249.6	249.6	249.6	252.7	252.7	312.0	312.0	312.0
8.1	34.3	33.1	36.2	24.3	39.9	39.9	39.9	39.9	39.9	39.9	39.9	30.0	34.3	37.4	48.1	53.1
5.1	78.4	78.4	78.4	63.8	93.0	93.0	93.0	93.0	93.0	93.0	93.0	53.1	65.1	78.4	104.9	120.9
5.8	35.8	59.4	35.8	35.8	75.4	75.4	75.4	75.4	75.4	75.4	75.4	54.7	54.7	54.7	54.1	64.1
8.3	38.3	44.6	38.9	38.9	50.2	50.2	50.2	50.2	50.2	50.2	50.2	39.5	43.9	47.1	55.2	56.5
1.7	81.7	103.2	96.1	96.1	114.7	114.7	114.7	114.7	114.7	114.7	114.7	81.7	81.7	81.7	103.2	133.3
5.7	55.7	55.7	74.2	60.5	78.1	78.1	78.1	78.1	78.1	78.1	78.1	55.7	55.7	55.7	74.2	79.1
6.2	26.2	26.2	62.5	26.2	50.0	50.0	50.0	50.0	50.0	50.0	50.0	26.2	26.2	26.2	62.5	62.5
7.5	155.0	152.5	172.8	122.0	203.3	203.3	203.3	203.3	203.3	203.3	203.3	114.3	122.0	160.1	228.7	241.4
3.2	63.2	74.2	69.8	103.1	88.6	88.6	88.6	88.6	88.6	88.6	88.6	63.2	63.2	63.2	69.8	109.7
1.6	111.6	123.4	123.4	182.1	156.7	156.7	156.7	156.7	156.7	156.7	156.7	111.6	111.6	111.6	123.4	195.8
3.5	73.5	98.0	98.0	114.4	130.7	130.7	130.7	130.7	130.7	130.7	130.7	73.5	73.5	73.5	98.0	147.1
6.3	162.2	162.2	162.2	162.2	190.6	227.6	162.2	162.2	162.2	162.2	162.2	227.6	256.1	256.1	256.1	256.1
3.4	84.1	84.1	70.7	70.7	93.4	97.4	70.7	70.7	70.7	70.7	70.7	70.7	93.4	110.8	110.8	110.8
6.3	66.4	66.4	66.4	66.4	78.8	83.0	70.5	66.4	78.8	66.4	66.4	66.4	76.3	76.3	76.3	76.3
.6	150.1	150.1	150.1	150.1	170.4	214.0	150.1	150.1	150.1	150.1	150.1	150.1	326.6	326.6	326.6	326.6
2.2	115.7	115.7	115.7	115.7	132.2	132.2	132.2	132.2	132.2	132.2	132.2	115.7	132.2	132.2	132.2	132.2
1.1	84.0	84.0	84.0	84.0	182.5	303.0	84.0	84.0	84.0	84.0	84.0	84.0	281.1	281.1	281.1	281.1
2.8	53.5	53.5	53.5	53.5	62.8	75.0	53.5	53.5	65.7	53.5	53.5	59.1	68.5	68.5	68.5	68.5
9.8	92.1	92.1	92.1	92.1	108.2	124.4	92.1	92.1	92.1	92.1	92.1	116.3	130.8	130.8	130.8	130.8
0.2	86.8	86.8	86.8	86.8	123.7	130.2	86.8	86.8	86.8	86.8	86.8	136.7	184.5	184.5	184.5	184.5
9.3	79.3	79.3	88.1	79.3	56.1	88.1	88.1	88.1	88.1	88.1	88.1	79.3	79.3	79.3	88.1	88.1
6.5	16.5	16.5	45.7	26.3	77.8	77.8	80.7	80.7	88.5	88.5	80.7	16.5	16.5	16.5	45.7	53.5
8.9	101.5	99.0	68.9	65.1	78.9	78.9	100.2	100.2	100.2	100.2	100.2	58.9	58.9	101.5	109.0	111.5
.5	109.5	109.5	109.5	115.3	109.5	109.5	109.5	109.5	109.5	109.5	109.5	109.5	109.5	109.5	109.5	115.3
6.9	26.9	26.9	67.3	26.9	26.9	40.4	26.9	26.9	40.4	26.9	26.9	26.9	26.9	26.9	67.3	67.3
4.9	84.9	84.9	95.4	84.9	95.4	95.4	95.4	95.4	95.4	95.4	95.4	84.9	84.9	84.9	95.4	95.4
7.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8	77.8
3.8	33.8	33.8	91.5	46.4	104.0	112.8	104.0	100.2	112.8	104.0	100.2	33.8	33.8	33.8	91.5	102.7
.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1	95.1
1.4	51.4	51.4	48.5	48.5	70.8	74.7	74.7	74.7	84.4	84.4	58.2	75.6	75.6	75.6	75.6	75.6
0.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9
.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0	149.0
6.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5
3.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3
3.7	15.3	15.3	15.3	15.3	84.0	90.6	98.2	98.2	101.5	98.2	65.5	56.8	70.9	81.9	81.9	81.9
2.5	12.5	12.5	12.5	12.5	83.0	86.1	75.7	75.7	86.1	[illegible]	12.5	71.6	71.6	71.6	71.6	71.6
4.1	54.1	54.1	54.1	54.1	73.1	73.1	85.4	85.4	78.8	82.6	54.1	73.1	73.1	73.1	73.1	73.1
4.0	34.0	34.0	80.8	38.3	113.5	113.5	113.5	113.5	113.5	113.5	85.1	34.0	34.0	34.0	80.8	95.0
4.5	22.7	21.6	8.5	8.5	45.5	49.5	45.5	39.8	45.5	39.8	28.4	8.5	8.5	8.5	32.4	38.1
6.5	26.5	26.5	79.6	30.1	79.6	79.6	79.6	79.6	79.6	79.6	79.6	26.5	26.5	26.5	79.6	84.0
7.2	47.2	47.2	54.0	56.0	54.0	54.0	60.7	60.7	60.7	60.7	60.7	47.2	47.2	47.2	54.0	62.8
2.2	4971.2	5024.2	5153.8	4773.6	6553.0	6953.4	6507.2	6420.9	6676.1	6516.8	6131.1	5422.6	6133.1	6434.9	7108.1	7438.3
20	E8	E9	S2	H20	207	212	232	233	257	260	284	C/1	C/2	C/3	C/4	C/5

FOLDOUT FRAME 1

FIGURE 3-29
VALUE OF RESEARCH ACHIEVABLE IN EACH FACILITY
Operational System No. 7-(M1)

OBJ. NO.	TASK INTRINSIC VALUE SUM	VALUE OF EXISTING FACILITIES	VALUE OF NEW FACILITIES + EXISTING FACILITIES													
			1 GD3	2 GD20	3 GD7	4 E6	5 E20	6 E8	7 E9	8 S2	9 M20	10 207	11 212	12 232	13 233	14 257
1	216.3	155.8	173.1	173.1	155.8	155.8	155.8	155.8	155.8	155.8	155.8	203.4	216.3	203.4	203.4	216.3
2	176.4	98.8	134.1	128.8	98.8	98.8	98.8	98.8	98.8	98.8	98.8	160.5	171.1	160.5	160.5	171.1
3	190.6	106.7	127.7	139.2	106.7	106.7	106.7	106.7	106.7	106.7	106.7	179.2	179.2	155.8	160.1	173.5
4	157.7	75.7	89.9	99.4	75.7	91.5	91.5	86.7	86.7	75.7	75.7	108.8	108.8	118.3	118.3	129.3
5	151.2	72.6	87.7	99.8	72.6	72.6	72.6	72.6	72.6	72.6	72.6	113.4	128.5	134.6	134.6	134.6
6	188.3	105.4	133.7	120.5	105.4	105.4	105.4	105.4	105.4	105.4	105.4	152.5	163.8	152.5	139.3	171.4
7	91.4	51.2	51.2	66.7	51.2	51.2	51.2	51.2	51.2	51.2	51.2	76.7	76.7	76.7	64.9	76.7
9	131.1	62.9	81.3	91.5	62.9	62.9	62.9	62.9	62.9	62.9	62.9	81.3	94.4	94.4	81.3	98.3
12	148.7	71.4	89.2	96.6	71.4	87.7	71.4	71.4	71.4	71.4	71.4	87.7	107.0	107.0	87.7	107.0
14	139.5	43.2	87.9	43.2	43.2	43.2	43.2	43.2	43.2	67.0	43.2	97.6	97.6	101.8	101.8	111.6
15	96.2	22.1	41.4	47.2	30.8	22.1	22.1	22.1	22.1	22.1	22.1	41.4	57.7	48.1	48.1	57.7
16	105.4	45.3	50.6	61.2	45.3	52.7	63.3	56.9	56.9	45.3	45.3	78.0	78.0	78.0	78.0	78.0
17	81.8	28.6	41.7	47.4	28.6	28.6	37.6	36.0	34.4	28.5	28.6	50.7	50.7	58.9	58.9	58.9
19	90.9	59.1	76.3	71.8	59.1	59.1	59.1	59.1	59.1	59.1	59.1	79.1	79.1	81.8	81.8	81.8
20	101.6	40.7	57.9	61.0	54.9	40.7	82.3	88.4	78.3	40.7	40.7	87.4	87.4	95.6	95.6	95.6
22	164.6	65.8	93.8	98.8	65.8	80.7	133.3	143.2	126.7	65.8	65.8	141.5	141.5	154.7	154.7	154.7
24	104.3	41.7	59.5	62.6	56.3	41.7	84.5	90.7	80.3	41.7	41.7	89.7	89.7	98.1	98.1	98.1
25	123.8	49.5	70.6	74.3	66.9	49.5	111.5	113.9	116.4	49.5	49.5	113.9	113.9	121.4	121.4	121.4
26	132.7	53.1	58.4	66.3	63.7	53.1	66.3	69.0	69.0	78.3	65.0	122.1	122.1	130.0	130.0	130.0
27	86.8	73.8	73.8	73.8	73.8	73.8	83.4	84.2	85.1	73.8	73.8	83.4	83.4	86.8	79.0	86.8
30	116.4	93.1	93.1	93.1	93.1	93.1	93.1	93.1	93.1	100.1	93.1	93.1	93.1	93.1	93.1	93.1
32	141.7	57.8	97.8	97.8	97.8	97.8	113.3	114.8	111.9	141.7	113.3	134.6	134.6	141.7	141.7	141.7
33	137.3	101.6	108.5	108.5	108.5	105.7	122.2	126.3	126.3	135.9	122.2	137.3	137.3	137.3	137.3	137.3
34	304.9	243.9	247.0	247.0	247.0	243.9	243.9	304.9	304.9	292.7	277.5	243.9	243.9	243.9	243.9	243.9
35	61.6	29.5	36.3	36.3	36.3	29.5	36.9	43.1	41.9	44.9	33.2	48.6	48.6	48.6	48.6	48.6
36	131.5	73.7	73.7	73.7	73.7	73.7	88.1	101.3	101.3	101.3	86.8	115.8	115.8	115.8	115.8	115.8
39	61.4	35.0	37.5	38.7	38.7	37.5	37.5	37.5	43.6	38.1	38.1	49.1	49.1	49.1	49.1	49.1
40	142.2	81.0	81.0	81.0	81.0	81.0	81.0	81.0	102.4	95.2	95.2	113.7	113.7	113.7	113.7	113.7
41	97.8	55.8	55.8	55.8	55.8	55.8	55.8	55.8	55.8	64.4	60.7	78.3	78.3	78.3	78.3	78.3
42	62.3	36.1	36.1	36.1	36.1	36.1	36.1	36.1	36.1	62.3	61.1	61.1	61.1	61.1	61.1	61.1
43	255.1	163.3	163.3	163.3	163.3	176.1	211.8	209.2	206.7	227.1	176.1	255.1	255.1	255.1	255.1	255.1
44	110.5	88.4	88.4	88.4	88.4	88.4	88.4	88.4	101.6	97.2	110.5	110.5	110.5	110.5	110.5	110.5
45	194.0	155.2	155.2	155.2	155.2	155.2	155.2	155.2	170.7	170.7	194.0	194.0	194.0	194.0	194.0	194.0
46	162.2	103.8	103.8	103.8	103.8	103.8	103.8	103.8	131.4	131.4	147.6	162.2	162.2	162.2	162.2	162.2
48	270.6	154.2	189.4	181.3	154.2	154.2	186.7	154.2	154.2	154.2	154.2	181.3	216.5	154.2	154.2	154.2
52	125.9	104.5	104.5	104.5	104.5	125.9	125.9	117.1	117.1	104.5	104.5	125.9	125.	104.5	104.5	104.5
57	350.9	245.6	245.6	245.6	245.6	350.9	350.9	245.6	245.6	245.6	245.6	270.2	305.3	245.6	245.6	245.6
58	156.5	109.5	109.5	109.5	109.5	117.4	125.2	109.5	109.5	109.5	109.5	125.2	125.2	125.2	125.2	125.2
59	350.5	140.2	140.2	164.7	140.2	315.4	350.5	140.2	140.2	140.2	140.2	234.8	350.5	140.2	140.2	140.2
63	85.0	48.5	53.6	57.0	48.5	48.5	57.0	48.5	48.5	48.5	48.5	57.0	68.0	48.5	48.5	59.5
65	147.9	84.3	93.2	100.6	84.3	84.3	100.6	84.3	84.3	84.3	84.3	99.1	113.9	84.3	84.3	84.3
67	206.0	82.4	107.1	103.0	82.4	113.3	123.6	82.4	82.4	82.4	82.4	117.4	123.6	82.4	82.4	82.4
71	122.1	116.0	116.0	116.0	116.0	116.0	116.0	116.0	116.0	116.0	122.1	116.0	116.0	116.0	116.0	116.0
72	70.1	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	70.1	28.0	28.0	42.0	28.0	28.0	42.0
77	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7
78	103.5	62.1	70.4	78.7	73.5	65.2	65.2	65.2	65.2	62.1	62.1	85.9	90.1	90.1	90.1	100.4
79	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0
80	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8
82	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5
84	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6
85	112.6	48.4	59.7	48.4	48.4	48.4	63.1	48.4	48.4	61.9	52.9	101.3	101.3	101.3	101.3	101.3
87	109.2	18.6	57.9	18.6	18.6	36.0	46.9	18.6	18.6	18.6	18.6	87.3	93.9	101.5	101.5	104.8
89	103.8	14.5	36.3	52.9	36.3	14.5	14.5	14.5	14.5	14.5	14.5	85.1	88.2	77.8	77.8	88.2
93	94.9	54.1	63.6	68.4	61.7	54.1	54.1	54.1	54.1	54.1	54.1	73.1	73.1	85.4	85.4	78.8
94	141.8	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0	90.8	48.2	123.4	123.4	123.4	123.4	123.4
96	56.9	10.8	26.7	32.4	25.0	21.0	26.7	25.0	23.9	10.8	10.8	47.8	51.7	47.8	42.1	47.8
97	88.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	79.6	30.1	79.6	79.6	79.6	79.6	79.6
102	67.5	47.2	47.2	47.2	47.2	47.2	47.2	47.2	47.2	54.0	56.0	54.0	54.0	60.7	60.7	60.7
TOTAL	7947.1	4646.0	5201.2	5254.0	4786.8	5091.1	5547.4	5163.1	5203.8	5211.9	4936.2	6562.9	6911.4	6494.2	6417.5	6621.0
			GD3	GD20	GD7	E6	E20	E8	E9	S2	M20	207	212	232	233	257

FOLDOUT FRAME 2

3-29

:VABLE IN EACH FACILITY

em No. 7–(M1)

VALUE OF NEW FACILITIES + EXISTING FACILITIES

	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
	E20	E8	E9	S2	M20	207	212	232	233	257	260	284	C/1	C/2	C/3	C/4	C/5
.8	155.8	155.8	155.8	155.8	155.8	203.4	216.3	203.4	203.4	216.3	216.3	181.7	173.1	173.1	173.1	173.1	173.1
.8	98.8	98.8	98.8	98.8	98.8	160.5	171.1	160.5	160.5	171.1	171.1	135.8	153.5	153.5	153.5	153.5	153.5
.7	106.7	106.7	106.7	106.7	106.7	179.2	179.2	155.8	160.1	173.5	165.8	146.8	150.6	150.6	150.6	150.6	150.6
.5	91.5	86.7	86.7	75.7	75.7	108.8	108.8	118.3	118.3	129.3	129.3	118.3	112.0	115.1	115.1	115.1	115.1
.6	72.6	72.6	72.6	72.6	72.6	113.4	128.5	134.6	134.6	134.6	134.6	93.7	121.0	121.0	121.0	121.0	121.0
.4	105.4	105.4	105.4	105.4	105.4	152.5	163.8	152.5	139.3	171.4	158.2	133.7	171.4	171.4	171.4	171.4	171.4
.2	51.2	51.2	51.2	51.2	51.2	76.7	76.7	75.7	64.9	76.7	64.9	64.9	75.8	75.8	75.8	75.8	75.8
.9	62.9	62.9	62.9	62.9	62.9	81.3	94.4	94.4	81.3	98.3	81.3	81.3	107.5	107.5	107.5	107.5	107.5
.7	71.4	71.4	71.4	71.4	71.4	87.7	107.0	107.0	87.7	107.0	87.7	87.7	107.0	118.9	118.9	118.9	118.9
.2	43.2	43.2	43.2	67.0	43.2	97.6	97.6	101.8	101.8	111.6	111.6	101.8	87.9	87.9	87.9	107.4	107.4
.1	22.1	22.1	22.1	22.1	22.1	41.4	57.7	48.1	48.1	57.7	48.1	48.1	58.7	58.7	58.7	58.7	58.7
.7	63.3	56.9	56.9	45.3	45.3	78.0	78.0	78.0	78.0	78.0	78.0	78.0	61.2	70.7	81.2	81.2	81.2
.6	37.6	36.0	34.4	28.6	28.6	50.7	50.7	58.9	58.9	58.9	58.9	58.9	52.4	56.4	63.0	63.0	63.0
.1	59.1	59.1	59.1	59.1	59.1	79.1	79.1	81.8	81.8	81.8	81.8	81.8	90.9	90.9	90.9	90.9	90.9
.7	82.3	88.4	78.3	40.7	40.7	87.4	87.4	95.6	95.6	95.6	95.6	95.6	69.1	76.2	97.6	97.6	97.6
.7	133.3	143.2	123.7	65.8	65.8	141.5	141.5	154.7	154.7	154.7	154.7	154.7	110.3	121.8	144.8	144.8	144.8
.7	84.5	90.7	80.3	41.7	41.7	89.7	89.7	98.1	98.1	98.1	98.1	93.1	66.8	87.6	98.1	98.1	98.1
.5	111.5	113.9	116.4	49.5	49.5	113.9	113.9	121.4	121.4	121.4	121.4	121.4	87.9	116.4	118.9	118.9	118.9
.1	66.3	69.0	69.0	78.3	65.0	122.1	122.1	130.0	130.0	130.0	130.0	130.0	74.3	87.6	103.5	115.4	120.7
.8	83.4	84.2	85.1	73.8	73.8	83.4	83.4	86.8	79.0	86.8	79.0	79.0	74.7	83.4	86.0	86.0	86.0
.1	93.1	93.1	93.1	100.1	93.1	93.1	93.1	93.1	93.1	93.1	93.1	93.1	93.1	93.1	93.1	100.1	100.1
.8	113.3	114.8	111.9	141.7	113.3	134.6	134.6	141.7	141.7	141.7	141.7	141.7	100.6	113.3	127.5	141.7	141.7
.7	122.2	126.3	126.3	135.9	122.2	137.3	137.3	137.3	137.3	137.3	137.3	137.3	108.5	122.2	129.1	137.3	137.3
.9	243.9	304.9	304.9	292.7	277.5	243.9	243.9	243.9	243.9	243.9	243.9	243.9	247.0	247.0	304.9	304.9	304.9
.5	36.9	43.1	41.9	44.9	33.2	48.6	48.6	48.6	48.6	48.6	48.6	48.6	38.8	43.1	46.2	56.6	61.6
.7	88.1	101.3	101.3	101.3	86.8	115.8	115.8	115.8	115.8	115.8	115.8	115.8	76.3	88.1	101.3	127.6	131.5
.5	37.5	37.5	43.6	38.1	38.1	49.1	49.1	49.1	49.1	49.1	49.1	49.1	38.7	43.0	46.1	54.0	55.3
.0	81.0	81.0	102.4	95.2	95.2	113.7	113.7	113.7	113.7	113.7	113.7	113.7	81.0	81.0	81.0	102.4	132.2
.8	55.8	55.8	55.8	74.4	60.7	78.3	78.3	78.3	78.3	78.3	78.3	78.3	55.8	55.8	55.8	74.4	79.3
.1	36.1	36.1	36.1	62.3	61.1	61.1	61.1	61.1	61.1	61.1	61.1	61.1	36.1	36.1	36.1	62.3	62.3
1	211.8	209.2	206.7	227.1	176.1	255.1	255.1	255.1	255.1	255.1	255.1	255.1	168.4	176.1	214.3	255.1	255.1
.4	88.4	88.4	101.6	97.2	110.5	110.5	110.5	110.5	110.5	110.5	110.5	110.5	88.4	88.4	88.4	97.2	110.5
.2	155.2	155.2	170.7	170.7	194.0	194.0	194.0	194.0	194.0	194.0	194.0	194.0	155.2	155.2	155.2	170.7	194.0
.8	103.8	103.8	131.4	131.4	147.6	162.2	162.2	162.2	162.2	162.2	162.2	162.2	107.0	107.0	107.0	131.4	162.2
.2	186.7	154.2	154.2	154.2	154.2	181.3	216.5	154.2	154.2	154.2	154.2	154.2	216.5	243.5	243.5	243.5	243.5
.9	125.9	117.1	117.1	104.5	104.5	125.9	125.9	104.5	104.5	104.5	104.5	104.5	104.5	125.9	125.9	125.9	125.9
.9	350.9	245.6	245.6	245.6	245.6	270.2	305.3	245.6	245.6	245.6	245.6	245.6	245.6	350.9	350.9	350.9	350.9
.4	125.2	109.5	109.5	109.5	109.5	125.2	125.2	125.2	125.2	125.2	125.2	125.2	109.5	125.2	125.2	125.2	125.2
.4	350.5	140.2	140.2	140.2	140.2	234.8	350.5	140.2	140.2	140.2	140.2	140.2	140.2	350.5	350.5	350.5	350.5
.5	57.0	48.5	48.5	48.5	48.5	57.0	68.0	48.5	48.5	59.5	48.5	48.5	53.6	62.1	62.1	62.1	62.1
.3	100.6	84.3	84.3	84.3	84.3	99.1	113.9	84.3	84.3	84.3	84.3	84.3	106.5	119.8	119.8	119.8	119.8
.3	123.6	82.4	82.4	82.4	82.4	117.4	123.6	82.4	82.4	82.4	82.4	82.4	129.8	175.1	175.1	175.1	175.1
.0	116.0	116.0	116.0	116.0	122.1	116.0	116.0	116.0	116.0	116.0	116.0	116.0	116.0	116.0	116.0	116.0	122.1
.0	28.0	28.0	28.0	70.1	28.0	28.0	42.0	28.0	28.0	42.0	28.0	28.0	28.0	28.0	28.0	70.1	70.1
.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7	99.7
.2	65.2	65.2	65.2	62.1	62.1	85.9	90.1	90.1	90.1	100.4	100.4	72.5	91.1	91.1	91.1	91.1	91.1
.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0
.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8	159.8
.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5
.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6	69.6
.4	63.1	48.4	48.4	61.9	52.9	101.3	101.3	101.3	101.3	101.3	101.3	101.3	59.7	68.7	68.7	84.4	88.9
.0	46.9	18.6	18.6	18.6	18.6	87.3	93.9	101.5	101.5	104.8	101.5	68.8	60.0	74.2	85.1	85.1	85.1
.5	14.5	14.5	14.5	14.5	14.5	85.1	88.2	77.8	77.8	88.2	77.8	14.5	73.7	73.7	73.7	73.7	73.7
.1	54.1	54.1	54.1	54.1	54.1	73.1	73.1	85.4	85.4	78.8	82.6	54.1	73.1	73.1	73.1	73.1	73.1
.0	44.0	44.0	44.0	90.8	48.2	123.4	123.4	123.4	123.4	123.4	123.4	95.0	44.0	44.0	44.0	90.8	105.0
.0	26.7	25.0	23.9	10.8	10.8	47.8	51.7	47.8	42.1	47.3	42.1	30.7	10.8	10.8	10.8	34.7	40.4
.5	26.5	26.5	26.5	79.6	30.1	79.6	79.6	79.6	79.6	79.6	79.6	79.6	26.5	26.5	26.5	79.6	84.0
.2	47.2	47.2	47.2	54.0	56.0	54.0	54.0	60.7	60.7	60.7	60.7	60.7	47.2	47.2	47.2	54.0	62.8
.1	5547.4	5163.1	5203.8	5211.9	4936.2	6562.9	6911.4	6494.2	6417.5	6621.0	6493.9	6126.6	5661.7	630[illegible].9	6545.2	6994.8	7155.9
	E20	E8	E9	S2	M20	207	212	232	233	257	260	284	C/1	C/2	C/3	C/4	C/5

FOLDOUT FRAME 1

FIGU
VALUE OF RESEARCH AC
Operational S

OBJ. NO.	TASK INTRINSIC VALUE SUM	VALUE OF EXISTING FACILITIES	VALUE OF NEW FACILITIES + EXISTING FACILITIES												
			1	2	3	4	5	6	7	8	9	10	11	12	13
			GD3	GD20	GD7	E6	E20	E8	E9	S2	M20	207	212	232	233
1	225.6	101.5	133.1	133.1	101.5	101.5	101.5	101.5	101.5	101.5	101.5	164.7	203.1	164.7	164.7
2	181.4	65.3	112.5	112.5	65.3	65.3	65.3	65.3	65.3	65.3	65.3	139.7	150.6	157.9	139.7
3	192.0	53.8	97.9	113.3	82.5	53.8	53.8	53.8	53.8	53.8	53.8	120.9	120.9	153.6	128.6
4	160.6	49.8	72.3	81.9	59.4	73.9	73.9	49.8	49.8	49.8	49.8	91.6	91.6	117.3	101.2
5	156.1	48.4	71.6	87.4	60.9	48.4	48.4	48.4	48.4	48.4	48.4	98.3	113.9	129.5	120.2
6	194.3	69.9	91.3	106.8	83.5	69.9	69.9	69.9	69.9	69.9	69.9	130.1	141.8	149.6	122.4
7	94.1	29.2	35.8	53.6	44.2	31.1	31.1	42.4	42.4	29.2	29.2	47.1	37.6	68.7	59.3
9	133.9	41.5	56.2	75.0	49.6	56.2	56.2	62.9	62.9	41.5	41.5	67.0	80.4	89.7	67.0
12	153.2	35.2	68.9	79.7	56.7	41.4	56.7	49.0	49.0	35.2	35.2	76.6	81.2	102.7	87.3
14	147.6	45.8	85.6	85.6	45.8	45.8	45.8	45.8	45.8	45.8	45.8	103.3	103.3	118.1	103.3
15	99.6	22.9	37.9	47.8	31.9	28.9	34.9	22.9	22.9	22.9	22.9	42.8	54.8	72.7	59.8
16	108.3	24.9	31.4	40.1	35.7	29.2	33.6	41.2	40.1	24.9	24.9	57.4	57.4	72.6	68.2
17	84.4	19.4	31.2	39.7	27.9	22.8	27.0	31.2	29.5	19.4	19.4	44.7	44.7	56.5	53.2
18	82.9	33.2	34.8	41.5	41.5	34.8	34.8	41.5	41.5	33.2	33.2	49.7	41.5	70.5	66.3
19	93.6	26.2	32.8	43.1	37.5	26.2	26.2	26.2	26.2	26.2	26.2	56.2	56.2	72.1	57.0
20	101.6	27.4	31.5	40.7	37.6	35.6	71.2	76.2	69.1	27.4	27.4	65.1	65.1	89.5	89.5
22	164.6	44.4	51.0	79.0	64.2	98.8	107.0	111.9	60.9	44.4	44.4	105.3	105.3	144.8	144.8
24	104.3	28.2	44.9	58.4	40.7	28.2	28.2	28.2	28.2	28.2	28.2	66.8	66.8	91.8	81.4
25	123.8	33.4	39.6	48.3	43.3	33.4	48.3	49.5	47.1	33.4	33.4	85.4	85.4	113.9	101.5
26	132.7	35.8	38.5	41.1	37.1	35.8	42.5	47.8	46.4	78.3	35.8	91.5	91.5	122.1	108.8
27	86.8	40.8	43.4	48.6	46.9	41.7	48.6	49.5	48.6	40.8	40.8	61.7	61.7	79.9	70.3
28	205.8	72.0	72.0	72.0	72.0	78.2	78.2	78.2	78.2	144.1	96.7	148.2	137.9	185.2	174.9
30	115.6	92.5	92.5	92.5	92.5	92.5	92.5	92.5	92.5	99.4	92.5	92.5	92.5	104.0	98.3
32	141.9	53.9	53.9	53.9	53.9	53.9	66.7	68.1	65.3	95.1	66.7	105.0	99.3	127.7	120.6
33	138.0	46.9	51.1	51.1	51.1	48.3	54.9	69.0	69.0	78.7	64.9	91.1	85.6	124.2	117.3
34	312.0	49.9	53.0	53.0	53.0	49.9	49.9	165.3	152.9	99.8	84.2	93.6	87.3	280.8	96.7
35	62.4	16.2	22.5	22.5	22.5	16.2	23.1	29.3	28.1	31.2	19.3	35.0	32.5	44.9	42.4
36	132.8	41.2	41.2	41.2	41.2	41.2	53.1	66.4	66.4	66.4	51.8	82.4	77.0	103.6	98.3
38	94.2	33.9	45.2	45.2	45.2	35.8	35.8	35.8	59.4	35.8	35.8	75.4	70.7	84.8	80.1
39	62.8	35.8	38.3	39.5	39.5	38.3	38.3	38.3	44.6	38.9	38.9	50.2	47.1	56.5	53.4
40	143.4	81.7	81.7	81.7	81.7	81.7	81.7	81.7	103.2	96.1	96.1	114.7	107.5	129.0	121.9
41	97.7	55.7	55.7	55.7	55.7	55.7	55.7	55.7	55.7	74.2	60.5	78.1	73.2	87.9	63.0
42	62.5	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	56.2	20.0	50.0	46.9	56.2	52.1
43	254.1	88.9	88.9	88.9	88.9	96.6	132.1	129.6	127.0	147.4	96.6	183.0	170.2	228.7	215.0
44	110.8	48.8	48.8	48.8	48.8	48.8	48.8	48.8	48.8	55.4	88.6	88.6	83.1	99.7	94.2
45	195.8	86.2	86.2	86.2	86.2	86.2	86.2	86.2	86.2	97.9	156.7	156.7	145.9	176.3	166.5
46	163.4	57.2	57.2	57.2	57.2	57.2	57.2	57.2	57.2	81.7	98.0	117.7	109.5	147.1	138.9
48	302.2	24.2	114.8	145.0	123.9	24.2	123.9	111.8	24.2	24.2	24.2	30.2	30.2	172.2	51.4
52	146.2	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7	39.5	39.5	127.2	30.7
58	170.1	85.0	85.0	85.0	85.0	93.6	110.6	110.6	110.6	85.0	85.0	119.1	119.1	119.1	119.1
61	366.9	65.8	77.4	112.2	112.2	65.8	65.8	174.1	162.5	96.7	65.8	65.8	65.8	297.9	65.8
62	102.7	32.6	48.9	32.6	32.6	32.6	41.3	32.6	32.6	38.0	32.6	108.7	32.6	97.8	97.8
63	99.8	8.0	18.0	24.0	18.0	8.0	25.9	11.0	11.0	30.9	18.0	27.9	18.0	66.9	8.0
64	88.9	54.3	60.5	54.3	54.3	54.3	62.3	54.3	54.3	54.3	54.3	63.1	54.3	63.1	63.1
65	168.6	16.9	42.1	59.0	53.9	16.9	59.0	74.2	70.8	16.9	16.9	55.6	16.9	146.7	16.9
7	230.3	29.9	82.9	99.0	87.5	92.1	128.9	92.1	87.5	29.9	29.9	62.2	39.1	161.2	29.9
68	86.2	77.6	77.6	77.6	77.6	77.6	77.6	77.6	77.6	86.2	77.6	86.2	86.2	86.2	86.2
69	96.2	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	45.2	26.0	57.7	57.7	79.8	79.8
70	124.7	24.9	24.9	24.9	24.9	24.9	24.9	67.4	64.9	34.9	31.2	46.2	46.2	99.8	58.6
73	92.4	83.1	83.1	83.1	83.1	83.1	83.1	83.1	83.1	93.4	83.1	93.4	93.4	93.4	93.4
74	[illegible]	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1
75	[illegible]	33.5	33.5	33.5	33.5	33.5	33.5	33.5	33.5	90.7	46.0	74.5	78.2	115.5	99.4
77	93.8	83.5	83.5	83.5	83.5	83.5	89.1	89.1	89.1	83.5	83.5	93.8	93.8	93.8	93.8
78	96.2	43.3	52.9	60.6	55.8	48.1	48.1	48.1	48.1	43.3	43.3	70.2	64.5	83.7	74.1
79	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6
80	146.9	130.7	130.7	130.7	130.7	130.7	130.7	130.7	130.7	138.1	130.7	136.6	136.[illegible]	146.9	146.9
82	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1
83	61.9	55.1	55.1	55.1	55.1	55.1	55.1	55.1	55.1	53.2	55.1	57.6	57.6	61.9	61.9
85	105.6	10.6	31.7	36.9	31.7	30.6	31.7	36.9	33.8	21.1	15.8	26.4	21.1	63.3	56.0
87	114.0	13.7	57.0	13.7	13.7	34.2	45.6	13.7	13.7	13.7	13.7	83.[illegible]	87.0	106.1	102.6
89	106.2	10.6	35.0	52.0	35.0	10.6	10.6	10.6	10.6	10.6	10.6	56.3	56.3	92.4	80.1
93	99.8	56.9	66.9	71.9	64.9	56.9	56.9	56.9	56.9	56.9	56.9	72.8	72.8	89.8	89.8
94	147.2	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	83.9	39.8	117.8	117.8	117.8	117.8
96	59.0	7.1	25.4	31.3	23.6	19.5	25.4	23.6	22.4	7.1	7.1	41.3	37.1	53.1	53.1
97	92.1	27.6	27.6	27.6	27.6	27.6	27.6	27.6	27.6	82.9	31.3	73.7	73.7	73.7	73.7
	106.4	16.0	37.2	16.0	16.0	16.0	39.4	16.0	16.0	16.0	16.0	16.0	26.5	16.0	16.0
100	102.1	71.4	71.4	71.4	71.4	71.4	71.4	71.4	71.4	88.8	73.5	102.1	102.1	102.1	102.1
102	70.4	49.3	49.3	49.3	49.3	49.3	49.3	49.3	49.3	56.3	58.4	52.8	52.8	63.3	59.8
TOTAL	9004.5	3203.3	3957.0	4230.7	3781.8	3456.8	3940.4	4122.0	3974.6	3997.0	3563.0	5520.4	5359.2	7427.1	6049.4
			GD3	GD20	GD7	E6	E20	E8	E9	S2	M20	207	212	232	233

FOLDOUT FRAME 2

FIGURE 3-30
VALUE OF RESEARCH ACHIEVABLE IN EACH FACILITY
Operational System No. 8–(M2)

VALUE OF NE. FACILITIES + EXISTING FACILITIES

3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
GD7	E6	F20	E8	E9	S2	M20	207	212	232	233	257	260	284	C/1	C/2	C/3	C/4	C/5
101.5	101.5	101.5	101.5	101.5	101.5	101.5	164.7	203.1	164.7	164.7	196.3	187.3	142.1	133.1	133.1	133.1	133.1	133.1
65.3	65.3	65.3	65.3	65.3	65.3	65.3	139.7	150.6	157.9	139.7	132.5	139.7	114.3	112.5	112.5	112.5	112.5	123.4
82.5	53.8	53.8	53.8	53.8	53.8	53.8	120.9	120.9	153.6	128.6	140.1	136.4	128.6	130.5	130.5	130.5	130.5	130.5
59.4	73.9	73.9	49.8	49.8	49.8	49.8	91.6	91.6	117.3	101.2	112.4	112.4	101.2	94.8	99.6	99.6	99.6	99.6
50.9	48.4	48.4	48.4	48.4	48.4	48.4	98.3	113.9	129.5	1[illegible].2	120.2	120.2	101.4	106.1	106.1	106.1	106.1	106.1
83.5	69.9	69.9	69.9	69.9	69.9	69.9	130.1	141.8	149.6	122.4	141.8	141.8	110.7	137.9	139.9	139.9	139.9	139.9
44.2	31.1	31.1	42.4	42.4	29.2	29.2	47.1	47.6	68.7	59.3	59.3	59.3	53.6	64.9	67.8	70.6	70.6	70.6
49.6	56.2	56.2	62.9	62.9	41.5	41.5	67.0	80.4	89.7	67.0	6[illegible].4	67.0	67.0	89.4	87.0	89.7	89.7	89.7
56.7	41.4	56.7	49.0	49.0	35.2	35.2	76.6	81.2	102.7	87.3	91.9	87.3	87.3	93.5	102.7	107.3	107.3	107.3
45.8	45.8	45.8	45.8	45.8	45.8	45.8	103.3	103.3	118.1	103.3	103.3	107.8	103.3	85.6	85.6	85.6	85.6	85.6
31.9	28.[illegible]	34.9	22.9	22.9	22.9	22.9	42.8	54.8	72.7	59.8	59.8	59.8	59.8	57.8	68.7	68.7	68.7	68.7
35.7	29.2	33.6	41.2	40.1	24.9	24.9	57.4	57.4	72.6	68.2	68.2	68.2	68.2	50.9	61.7	72.6	72.6	72.6
27.9	22.8	27.0	31.2	29.5	19.4	19.4	44.7	44.7	56.5	53.2	53.2	53.2	53.2	43.9	49.0	54.9	54.9	54.9
41.5	34.8	34.8	41.5	41.5	33.2	33.2	49.7	41.5	70.5	66.3	66.3	66.3	66.3	43.1	65.6	52.2	52.2	52.2
37.5	26.2	26.2	26.2	26.2	26.2	26.2	56.2	56.2	72.1	59.0	65.5	59.0	59.0	59.0	59.0	59.0	59.0	59.0
37.6	35.6	71.2	76.2	69.1	27.4	27.4	65.1	65.1	89.5	89.5	79.3	89.5	[illegible].5	60.0	67.1	86.4	86.4	86.4
[illegible]4.2	98.8	107.0	111.9	60.9	44.4	44.4	105.3	105.3	144.8	144.8	128.4	144.8	144.8	87.2	116.9	126.7	126.7	126.7
40.7	28.2	28.2	28.2	28.2	28.2	28.2	66.8	66.8	91.8	81.4	81.4	81.4	81.4	68.8	68.8	68.8	68.8	68.8
43.3	33.4	48.3	49.5	47.1	33.4	33.4	85.4	85.4	113.9	101.5	101.5	101.5	101.5	6[illegible].9	68.1	73.1	73.1	73.1
37.1	35.8	42.5	47.8	46.4	78.3	35.8	91.5	91.5	122.1	108.8	108.8	108.8	108.8	47.3	54.4	65.0	88.9	88.9
46.9	41.7	48.6	49.5	48.6	40.8	40.8	61.7	61.7	79.9	70.3	70.3	70.3	70.3	51.2	53.8	58.2	58.2	58.2
72.0	78.2	78.2	78.2	78.2	144.1	96.7	148.2	137.9	185.2	174.9	166.6	174.9	174.9	78.2	78.2	78.2	144.1	160.5
92.5	92.5	92.5	92.5	92.5	99.4	92.5	92.5	92.5	104.0	98.3	92.5	98.3	98.3	92.5	92.5	92.5	99.4	99.4
53.9	53.9	66.7	68.1	65.3	95.1	66.7	105.0	99.3	127.7	120.6	113.5	120.6	120.6	53.9	66.7	80.9	95.1	103.6
51.1	48.3	64.9	69.0	69.0	76.7	64.9	91.1	85.6	124.2	117.3	110.4	117.3	117.3	51.1	64.9	71.8	100.7	107.6
53.0	49.9	49.9	165.3	152.9	99.8	84.2	93.6	87.3	280.8	96.7	249.6	96.7	96.7	53.0	53.0	165.3	209.0	240.2
22.5	16.2	23.1	29.3	28.1	31.2	19.3	35.0	32.5	44.9	42.4	39.9	42.4	42.4	25.0	29.3	32.5	43.1	48.7
41.2	41.2	53.1	66.4	66.4	66.4	51.8	32.4	77.0	103.6	98.3	93.0	98.3	98.3	41.2	53.1	66.4	93.0	108.9
43.2	35.8	35.8	35.8	59.4	35.8	35.8	75.4	70.7	84.8	80.1	75.4	80.1	80.1	54.7	54.7	54.7	64.1	64.[illegible]
39.5	38.3	38.3	38.3	44.6	38.9	38.9	50.2	47.1	56.5	53.4	50.2	53.4	53.4	39.5	43.9	47.1	55.2	56.5
81.7	81.7	81.7	81.7	103.2	96.1	96.1	114.7	107.5	129.0	121.9	114.7	121.9	121.9	81.7	91.7	81.7	103.2	133.3
55.7	55.7	55.7	55.7	55.7	74.2	60.5	78.1	73.2	87.9	83.0	78.1	83.0	83.0	55.7	53.7	55.7	74.2	79.1
20.0	20.0	20.0	20.[illegible]	20.0	56.2	20.0	50.0	46.9	56.2	53.1	50.0	53.1	53.1	20.0	20.0	20.0	56.2	56.2
88.9	96.6	132.1	129.6	127.0	147.4	96.6	183.0	170.2	228.7	216.0	203.3	216.0	216.0	88.9	96.6	134.7	203.3	216.0
48.8	48.8	48.8	48.8	48.8	55.4	88.6	88.6	83.1	99.7	94.2	88.6	94.2	94.2	48.8	48.8	48.8	55.4	95.3
86.2	86.2	86.2	86.2	86.2	97.9	156.7	156.7	146.9	176.3	166.5	156.7	166.5	166.5	86.2	86.2	86.2	97.9	172.3
57.2	57.2	57.2	57.2	57.2	81.7	98.0	117.7	109.5	147.1	138.9	130.7	138.9	138.9	57.2	57.2	57.2	81.7	130.7
123.9	24.2	123.9	111.8	24.2	24.2	24.2	30.2	30.2	172.2	51.4	142.0	51.4	51.4	169.2	190.4	205.5	205.5	205.5
30.7	30.7	30.7	30.7	30.7	30.7	30.7	39.5	39.5	127.2	30.7	102.4	30.7	30.7	30.7	38.0	67.3	81.9	89.2
85.0	93.6	110.6	110.6	110.6	85.0	85.0	119.1	119.1	119.1	119.1	119.1	119.1	119.1	85.[illegible]	93.6	110.6	110.6	110.6
112.2	65.8	65.8	174.1	162.5	96.7	65.8	65.8	65.8	297.9	65.8	279.8	65.8	65.8	150.9	150.9	224.4	247.6	247.6
32.6	32.6	41.3	32.6	32.6	38.0	32.6	108.7	32.6	97.8	97.8	32.6	108.7	97.8	48.9	53.3	53.3	58.7	58.7
18.0	8.0	25.9	11.0	11.0	30.9	18.0	27.9	18.0	66.9	3.0	59.9	8.0	8.0	26.9	28.9	45.9	49.9	50.9
[illegible].3	54.3	62.3	54.3	54.3	54.3	54.3	63.1	54.3	63.1	63.1	58.7	63.1	63.1	60.5	68.5	68.5	68.5	68.5
55.9	16.9	59.0	74.2	70.8	16.9	16.9	55.6	16.9	146.7	16.9	134.9	16.9	16.9	67.4	80.9	96.1	96.1	96.1
87.5	92.1	128.9	92.1	87.5	29.9	29.9	62.2	39.1	161.2	29.9	138.2	29.9	29.9	105.9	122.0	145.1	145.1	145.1
77.6	77.6	77.6	77.6	77.6	86.2	77.6	86.2	86.2	86.2	86.2	86.2	86.2	86.2	77.6	77.6	77.6	86.2	86.2
16.4	16.4	16.4	16.4	16.4	45.2	26.0	57.7	57.7	79.8	79.8	87.5	87.5	79.8	16.4	16.4	16.4	45.2	52.9
24.9	24.9	24.9	67.4	64.9	34.9	31.2	46.2	46.2	9[illegible].8	58.6	99.8	58.6	58.6	24.9	24.9	67.4	74.8	77.3
83.1	83.1	83.1	83.1	83.1	93.4	83.1	93.4	93.4	93.4	93.4	93.4	93.4	93.4	83.1	83.1	83.1	93.4	93.4
76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.1	74.1	76.1	76.1	76.1	76.1
33.5	33.5	33.5	33.5	33.5	90.7	46.0	74.5	78.2	115.5	99.4	99.4	99.4	99.4	33.5	33.5	33.5	90.7	101.8
83.5	83.5	89.1	89.1	89.1	83.5	83.5	93.8	93.8	93.8	[illegible]	93.8	93.8	93.8	83.5	89.1	91.9	91.9	91.9
55.8	48.1	48.1	48.1	48.1	43.3	43.3	70.2	64.5	[illegible].7	74.1	83.[illegible]	83.7	57.7	72.2	72.2	72.2	72.2	72.2
71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6	71.6
130.7	130.7	130.7	130.7	130.7	138.1	130.7	136.6	136.6	146.9	146.9	146.9	146.9	146.9	130.7	130.7	130.7	138.1	138.1
114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1	114.1
55.1	55.1	55.1	55.1	55.1	58.2	5[illegible].1	57.6	57.6	61.9	61.9	61.9	61.9	61.9	55.1	55.1	55.1	58.2	58.2
31.7	10.6	31.7	36.9	33.[illegible]	21.1	[illegible]	26.4	21.1	63.3	56.0	42.2	56.0	56.0	42.2	49.6	61.2	64.4	77.1
13.7	34.2	45.6	13.7	13.[illegible]	13.7	[illegible]	[illegible]3.3	87.3	106.1	102.6	102.6	102.6	68.4	59.3	74.1	85.5	85.5	85.5
35.0	10.6	10.6	10.6	10.6	10.6	[illegible]	56.3	56.3	92.4	88.1	88.1	88.1	10.6	73.3	73.3	73.3	73.3	73.3
64.9	56.9	56.9	56.9	56.9	56.9	56.[illegible]	72.8	72.8	89.8	89.8	82.8	86.8	56.9	76.8	76.8	76.8	76.8	76.8
25.0	25.0	25.0	25.0	25.0	83.9	39.8	117.8	117.8	117.8	117.8	117.8	117.8	88.3	25.0	25.0	25.0	83.9	98.7
23.6	19.5	25.4	23.6	22.4	7.1	7.1	41.3	37.1	53.1	53.1	53.1	53.1	31.3	7.1	7.1	7.1	33.6	39.5
27.6	27.6	27.6	27.6	27.6	62.9	31.3	73.7	73.7	73.7	73.7	73.7	73.7	73.7	27.6	27.6	27.6	82.9	87.5
16.0	16.0	39.4	16.0	16.0	15.0	16.0	16.0	24.5	16.0	16.0	77.7	99.[illegible]	16.0	37.2	45.1	45.8	45.8	45.8
71.4	71.4	71.4	71.4	71.4	88.8	73.5	102.1	102.1	102.1	102.1	102.1	102.1	102.1	71.[illegible]	71.4	71.4	88.8	90.8
49.3	49.3	49.3	49.3	49.3	56.3	58.4	52.3	52.8	6[illegible].3	59.8	59.8	59.8	59.8	49.[illegible]	49.3	49.3	56.3	65.5
781.8	3456.8	3940.4	4122.0	3974.6	3997.0	3563.0	5520.4	5359.2	7427.1	6049.4	6844.9	6221.1	5753.2	4652.1	4931.2	5463.1	6227.5	6614.1
GD7	E6	E20	E8	E9	S2	M20	2	212	232	233	257	260	284	C/1	C/2	C/3	C/4	C/5

FIGURE 3-31
FACILITY RESEARCH VALUES – BASELINE FACILITIES
(Capability of Existing Plus New Facilities)

	OPERATIONAL SYSTEM			
	L2	C1	M1	M2
TOTAL	8905.1	8897.7	7947.1	9004.5
EXISTING	3295.0	4425.6	4646.0	3203.3
GD3	3949.7	4955.9	5261.2	3957.0
GD20	4306.3	5019.9	5254.0	4230.7
GD7	3844.0	4569.2	4786.8	3781.8
E6	3539.1	4941.7	5091.1	3456.8
E20	3898.7	5372.2	5547.4	3945.4
E8	4142.5	4971.2	5163.1	4122.0
E9	4035.6	5024.2	5203.8	3974.6
S2	4098.0	5153.8	5211.9	3997.0
M20	3653.3	4773.6	4936.2	3563.0
207	5599.5	6553.0	6562.9	5520.4
212	5547.1	6953.4	5911.4	5359.2
232	6563.5	6507.2	6494.2	7427.1
233	5922.3	6420.9	6417.5	6049.4
257	7256.5	6676.1	6621.0	6844.9
260	6055.9	6516.8	6493.9	6221.1
284	5662.3	6131.1	6126.6	5753.2
C/1	4689.9	5472.6	5661.7	4652.1
C/2	4941.6	6133.1	6304.9	4931.2
C/3	5457.1	6434.9	6545.2	5463.1
C/4	6218.8	7108.1	6994.8	6227.5
C/5	6593.9	7438.3	7155.9	6614.1

PERCENT ACHIEVED OF TOTAL RESEARCH INVOLVED

	OPERATIONAL SYSTEM			
	L2	C1	M1	M2
TOTAL	100.0	100.0	100.0	100.0
EXISTING	37.0	49.7	58.5	35.6
GD3	44.4	55.7	65.4	43.9
GD20	48.4	56.4	66.1	47.0
GD7	43.2	51.4	60.2	42.0
E6	39.7	55.5	64.1	38.4
E20	43.8	60.4	69.8	43.8
E8	46.5	55.9	65.0	45.8
E9	45.3	56.5	65.5	44.1
S2	46.0	57.9	65.6	44.4
M20	41.0	53.6	62.1	39.6
207	62.9	73.6	82.6	61.3
212	62.3	78.1	87.0	59.5
232	73.7	73.1	81.7	82.5
233	66.5	72.2	80.8	67.2
257	81.5	75.0	83.3	76.0
260	68.0	73.2	81.7	69.1
284	63.6	68.9	77.1	63.9
C/1	52.7	60.9	71.2	51.7
C/2	55.5	68.9	79.3	54.8
C/3	61.3	72.3	82.4	60.7
C/4	69.8	79.9	88.0	69.2
C/5	74.0	83.6	90.0	73.5

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6. GROUND RESEARCH FACILITY SYNTHESIS

The fifty-four ground research facilities postulated, and studied in Phase I were evaluated at the end of Phase I in terms of cost and research capability. Eleven ground research facilities were retained for refinement in Phase II, for parametric evaluation of the basic test leg and facility components (Figure 6-1). The design and operational features of the significant cost items were studied to identify a practical size and performance of the necessary equipment for each of the eleven ground research facilities.

FIGURE 6-1
PHASE II GROUND RESEARCH FACILITIES

	Phase I		Phase II
Gas Dynamic	17	Phase I Screening	3
Engine	11		4
Structural	9		3
Materials	4		1
Simulators	3		0
Fluid Systems	5		0
Subsystems	2		0
Avionics	2		0
Radiation	1		0
	54 Facilities		11 Facilities

In general, the cost of the test leg itself was small compared to the cost of the other facility components, represented by compressor plants, vacuum pumps, refrigeration systems, and prime movers. This fact results in the facility components contributing the most significant increments to the total cost of each facility while the conditions generated by the test leg contribute the most to the facility research value. Thus, unless the size of the test leg itself was varied, in most cases the variations in facility components significantly affected cost without materially affecting the facility research value. This necessitates close scrutiny of general engineering factors associated with the sizing and performance of the facility components. The eleven ground research facilities retained for refinement in Phase II are described in Figure 6-2.

FIGURE 6–2
PHASE II GROUND RESEARCH FACILITIES

Configuration Identification	Gas Dynamic			Propulsion			
	GD3	GD20	GD7	E6	E20	E8	E9
Test Time	20 sec (Minimum)	20 sec (Minimum)	1 to 4 sec	Continuous	Continuous	Continuous	Vitiated Air-Continuous, Clean Air – 60 sec
Mach Range	0.5 to 5.0	Leg 1–0.5 to 5.0 Leg 2–4.5 to 8.5	8 to 13	0 to 5.5 Direct-Connect	Leg 1–0 to 5.5 Direct Connect Leg 2–0 to 5.0 Free Jet	3 to 12 Modified Direct-Connect	3 to 9.5 Modified Direct-Connect
Maximum Reynolds No.	At least 1 5 of Flight R_e Throughout Range	1 5 Flight Re	1 5 Flight Re	Full Scale	Full Scale	1 3 to 1 6 Scale (One Module)	1 3 to 1 6 Scale (One Module)
Minimum Test Article Size	Length - 12.4 ft (3.8 m)	Leg 1 Length 12.4 ft (3.8 m) Leg 2 Length 9.3 ft (2.8 m)	Length 6.8 ft (2.06 m)	Engine Diameter 90 in. (229 cm)	Engine Diameter 90 in. (229 cm)	A_0 15 sq. ft. (1.39 m^2) (One Module)	A_0 15 sq. ft. (1.39 m^2) (One Module)
P_0 Range psia (N cm^2)	17 to 300 (11.7 to 207)	Leg 1 17 to 300 (11.7 to 207) Leg 2 50 to 3200 (34.5 to 2110)	1000 to 18,800 (690 to 12,960)	14.7 to 226 (10.1 to 156)	3 to 200 (2 to 140)	850 to 7000 (586 to 4826)	84 to 3110 (58 to 2144)
T_c Range	100 to 250°F (38 to 121°C)	Leg 1 100 to 250°F (38 to 121°C) Leg 2 150 to 800°C (66 to 426°C)	1260 to 2500°R (700 to 1389°K)	432 to 3200°R (240 to 1778°K)	432 to 1650°R (240 to 917°K)	3000 to 9500°R (1667 to 5278°K)	1090 to 5100°R (606 to 2833°K)

A_0 Captured Stream Tube

Phase II Ground Research Facilities

Configuration Identification	S–2 Structural			M–20 Materials Technology
	Full Scale	Major Section	Component	
Test Article Size – ft (m)	90 (27.4) High 125 (38.1) Wide 325 (99) Long	39 (11.9) High 70 (21.3) Wide 100 (30.5) Long	20 (6.1) High 20 (6.1) Wide 20 (6.1) Long	Facility contains all necessary equipment to conduct material research, determine material physical and thermal properties, develop manufacturing methods, and to conduct non–destructive evaluation.
Environments Simulated	Mechanical, Thermal Vibration, Acoustic, Altitude. Thermal Acoustic			
Degree of Simulation	All Parameters Simulated to Same Magnitude as Flight Trajectory			
Test Time	Time Variant to Correspond with Flight Trajectory or Static Test Times			

The design refinements and parametric evaluations performed on the eleven Phase II facilities are presented in Figure 6-3. As indicated in the figure, some parameters could be varied independently to establish trends while others were constrained by trajectory simulation requirements, material strength, or operational considerations. The wide spectrum of facilities studied precluded a universal application of rules to optimize the designs. Each class of facility has its own peculiar requirements and parameters which are arbitrarily variable. The most universal application of design guidelines and parametric variations occurred in the ancillary equipment; where the purpose of the equipment was related to its function and not necessarily to its application to a specific facility.

The facility related concepts studied are as listed.

- The degree of Reynolds number duplication, in terms of the maximum full scale requirement (gasdynamic)
- For a given degree of Reynolds number simulation, the effect of increasing test section size over a minimum size (gasdynamic)
- The degree of trajectory simulation necessary in the transonic region for free jet engine testing (engine)
- Scramjet module size requirements in terms of the full scale engine modules (engine)
- The required degree of trajectory simulation necessary, compared to facility material/cooling limitations (engine)
- The test article size necessary for structural research programs (structures)
- The degree of environmental simulation necessary for various structural research programs (structures)
- Techniques required to provide the conditions necessary to achieve various degrees of environmental simulation (structural)

The general engineering parameter variations are presented in Subsection 6.3. A complete description of the cost guidelines and basis is given in Subsection 6.1. The details of the design criteria, facility parametric evaluations, and controlling considerations are given for each group of facilities (gasdynamics, engine, structural and materials) in Subsections 6.3, 6.4, 6.5, and 6.6.

FIGURE 6-3
PHASE II REFINEMENT STUDIES, GROUND RESEARCH FACILITIES

Parameter	GD3	GD20	GD7	E6	E20	E8	E9	S2	M20
Test Time	Based on Analysis of Existing Facilities of Similar Type to Establish Acceptable Minimums			Based on Engine Operating Conditions Along Trajectory, and PFRT Requirements				Based on Flight Trajectory	Not Applicable
Mach Number	Each Individual Facility Based on Mechanical Operational Considerations			Based on Applicable Portion of Flight Trajectory				Not Applicable	Not Applicable
Reynolds Number	1 5 Full Scale Reynolds Number 1 2 Full Scale Reynolds Number			Full Scale Reynolds Number		Same as Module Scale		Not Applicable	Not Applicable
Test Article Size	1, 2.5 (1)	1, 2.5	1, 2.5	Full Scale Turbo-Machinery Engines		Scramjet Module Size A_0 15.45.90 Ft^2 (1.39.4.19.8.38m^2.		Complete Aircraft Major Section Component	Component Coupon
P_0 Range	1, 0.4 (1)	1, 0.4	1, 0.4	Based on Trajectory Simulation Requirements				Not Applicable	Not Applicable
T_0 Range	Based on Minimum Temperatures Necessary to Avoid Air Condensation			Based on Trajectory Simulation Requirements				Based on Trajectory and Skin Material	
Systems and Equipment Variations	Air Storage Volume, Pressure Requirements, Pump Up Time, Compressor Requirements Based on Pneumatic Losses		Air Storage Volume, Pressure Requirements	Compressor Requirements Based on Pneumatic Losses	Compressor Requirements vs Degree of Flight Duplication. Methods of Variation for Flexible Nozzle and Angle-of-Attack of Engine Inlet	Method of Providing Power Driving Force, Type of Prime Mover, Compressor Requirements	Augmentation of Blow Down Cycle with Continuous Flow Cycle. Synthesis of Carbon Combustion Techniques	Technique of Mechanical Load, Altitude Environment, Acoustic Techniques, Temperature-Load Rate Application, Dynamic Vibration Technique	Equipment to Accomplish to Varying Degrees the Applicable Research.

Notes:

(1) Indicates Multiplying Factors to be Applied to Baseline Definition

A_0; Stream Tube Capture Area

6.1 GENERAL COST METHODOLOGY

This section presents the guidelines and techniques used to prepare acquisition costs and operating costs for the baseline ground research facilities. To establish the costs for the parametric variations (alternates) in facility size or capability, scaling laws were developed which related the magnitude of the physical parameters describing the hardware to the facility size and performance (Subsection 6.1.14). All the ground research facilities were priced by determining the cost of individual components comprising the facility complex. The experience and judgement of vendors manufacturing and supplying the major components was extensively used to qualify and validate the generalized cost relationships used in Phase I. Figure 6-4 indicates the various sources of information used in developing the cost estimates for the different facility components. The general approach taken for cost estimation for each component is discussed in the appropriate subsection.

It must be recognized that each of the ground test facilities described herein, and their various alternates, represent, without exception, the largest facilities of their type ever seriously considered, and thus require ancillary systems and equipment considerably larger and higher in performance than any existing facilities. It should also be recognized that the depth of analytical treatment possible for the large number of facilities and their alternates in the short time allocated to this phase precludes a very detailed description of the facilities themselves or of their auxiliary systems. Only gross characteristics are described, and the cost estimates must reflect this fact. However, it is felt that the relative costs of the various facilities given are in proportion, having been estimated on a consistent basis. Likewise, the distribution of costs among the various components of a facility are considered relatively accurate, and provide a guide for Phase III, in which the major cost contributors are the components which will receive the greatest amount of critical analysis and more detailed cost estimation.

As definition of the components becomes more specific in Phase III, the component manufacturers should provide a credible base from which to refine facility costs. This refinement will be principally based on providing more economical arrangements of equipment to achieve the desired capability.

The following sections describe the general ground rules followed and the cost estimation techniques used in developing the acquisition costs of each facility (Section 6.1.1 thru 6.1.12), the costs associated with operating the facility (Section 6.1.13) and the scaling rules which were developed in order to estimate the impact of size and performance requirements on facility costs (Section 6.1.14).

6.1.1 GROUND RULES - The assumptions governing the estimation of acquisition costs are as follows:

a) All estimates were based on 1970 dollars using Means Industrial Index (Figure 6-5).

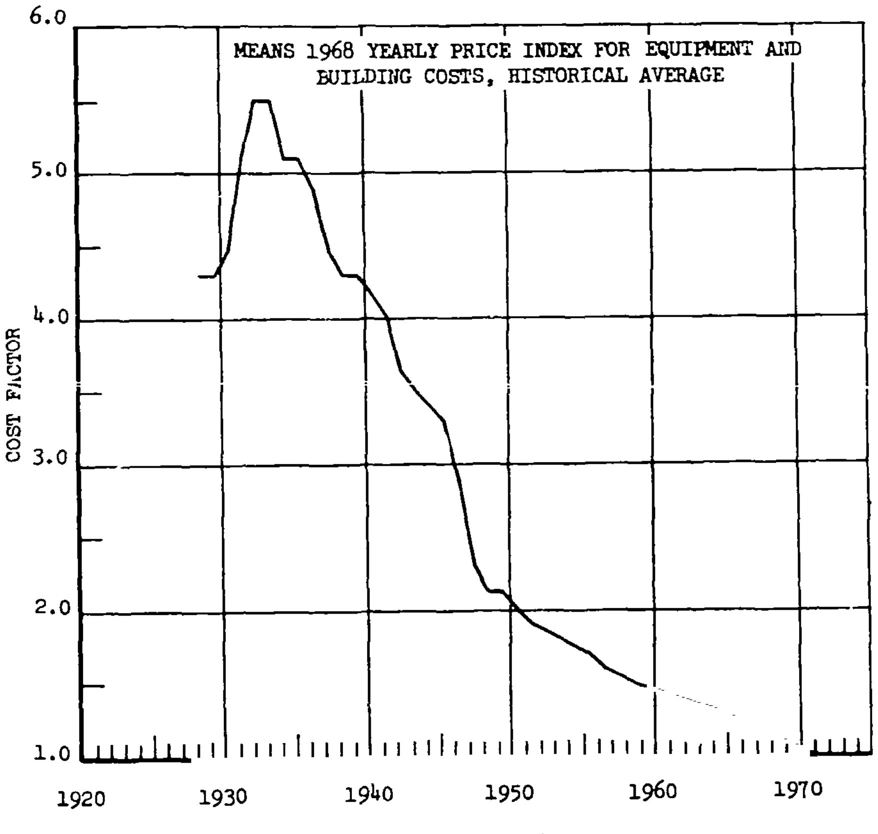
b) Cost of site acquisition was not included in the cost estimates. It is assumed that these facilities would be constructed on government owned property, and most probably at existing major test centers. Minimum costs are included in the building complex costs for site preparation, grading, access roads and sidewalks.

FIGURE 6-4
FACILITY COMPONENT – COST ESTIMATE SOURCES FOR GROUND RESEARCH FACILITIES

Buildings and Structural Shells	Compressor Plants	Steam Generators and Ejectors	Electric Motors	Gas Turbine Power Packages	Utility Power Costs	Vacuum Chambers	Acoustic Shrouds and Generators	Structural Heaters and Controls	Air Heaters, Continuous or Storage	Data Acquisition System	Instrumentation Systems	Cryogenic Supplies		Facility Component / Cost Estimating Base
●						●	●		●					Richardson Eng. Service Estimation Manual
●														MCAIR Reports
●						●	●	●	●	●	●			MCAIR Budgets
		●												MDAC-ED Reports
●										●	●			MDAC-ED Budgets
						●			●					Nooter Corporation
									●					Cabot Corporation
	●													Allis Chalmers
●						●			●					PDM Steel
												●		Air Reduction Co.
			●											Westinghouse
				●										General Electric
				●										Pratt & Whitney
									●					Combustion Engineering
	●	●												Ingersoll-Rand
		●												F.C. Brown & Co.
												●		Linde Div. Union Carbide
		●												NASA Reports
									●					Philadelphia Gear Co.
									●					Cornell Aero Lab.
									●					NASA Lewis
					●				●					AEDC
					●									Union Electric Co.
					●									Niagara Mohawk
				●										City Light and Power Jacksonville, Ill.

FIGURE 6-5
HISTORICAL COST FACTOR FOR EQUIPMENT AND BUILDING CONSTRUCTION ADJUSTED FOR A 1970 BASE YEAR

$$\text{Cost Factor for 1970 costs} = \frac{112}{\text{Price Index}}$$



Year	Index
1970	112
69	106
68	100
67	95
66	92
65	88
64	86
63	84
62	82
61	80
1960	79
59	77
58	75
57	73
56	70
55	66
54	64
53	63
52	61
51	59
1950	56
49	53
48	53
47	48
46	39
45	34
44	33
43	32
42	31
41	28

Year	Index
1940	27
39	26
38	26
37	25
36	23
35	22
34	22
33	20
32	20
31	22
1930	25
29	26
28	26

c) Each facility has been independently estimated, with no consideration as to integration with other proposed facilities or with existing facilities. Considering the dominating costs of the facility components, rather than the test leg itself, integration into existing facilities could offer substantial savings in ancilliary equipment costs. Integration possibilities will be considered for the facilities carried forward into Phase III.

d) It was not possible to estimate individually the cost of each facility structure and component for all the variations upon the several baseline definitions. The baseline definitions were cost estimated and these costs were scaled to determine costs of similar, but larger or higher performance equipment. The scaling laws used are developed in Section 6.1.14.

6.1.2 BUILDINGS AND STRUCTURAL SHELLS - Cost estimates for structural elements of the various facilities were developed using procedures outline in Commercial-Industrial Estimating and Engineering Standards, 1969 edition, prepared by International Estimating Services, and published by Richardson Engineering Services, Inc., Downey, California.

The costs of the test leg structural components of the gasdynamic and engine research facilities were estimated by estimating the volume, tonnage, and type of material required, using as a source the facility sketches and descriptions which were developed during this phase. The forming, fabrication, and erection costs were then estimated using the procedures in Richardson's Manual. Special features, such as flexible plate nozzles, required the provision of additional costs for machining, actuators, and control systems. Foundations for these components were priced to include excavation to bedrock a nominal 20 feet (6 m) below grade.

Buildings which were estimated include laboratory, office, and control areas for the flow facilities and the materials facility. Areas of these buildings were estimated based on test area size and costs were developed, using Richardson's Manual, on a per area basis. These buildings were assumed to have a six inch (15 cm) steel reinforced concrete foundation.

Exterior walls for high bay industrial areas are pre-enameled sandwich panels with 1.5 inch (3.81 cm) insulation. Office areas are enclosed by curtain walls with continuous windows. Roofs are of a built-up type on a metal roof deck support. Lighting is provided at 100-foot candles (1070 lumen/m^2). Convenience, power, ventilation, comfort conditioning, plumbing, etc., are provided proportional to building envelope size.

The structural test facility building is assumed to have the same sort of construction, with the exception that floors subjected to structural load bearing tests are at least 3 feet (.91 m) thick with 1-7/8 inch (4.76 cm) steel reinforcing rods 6 inches (15 cm) each way on center, and rest either on bedrock or pilings.

6.1.3 COMPRESSOR PLANTS - The air system costs were estimated from the major equipment and associated operating factors, which constitute the total system. The gasdynamic and engine test facility air systems comprise a compressor plant, air storage tank and distribution lines. A nominal stored mass was described in terms of different storage pressures and volumes, and used as a basis for determining the compressor requirements at different pump-up times. The necessary power to drive the compressors was then known as a function of stored mass, pump-up time, and storage pressure. This information was then scaled to provide cost estimates for the applicable systems. These are presented in Figure 6-6.

The air storage pressure vessel requirements were developed to the ASME Code for unfired spherical shell vessels under internal pressure, Paragraph UG-27. The tonnage of steel required to provide storage tanks and distribution piping systems was estimated and priced by the component method for fabrication and erection using the procedures in Richardsons. These costs were then extended to the air system requirements of each flow facility.

Synchronous electric motors with wound rotor starters are used to drive the compressors. The power required as a function of output pressure and inlet volume flow was calculated using the following formula, for isothermal compression with 75% efficiency.

$$\text{Required power} = 0.000161\, V_a\, T_a \ln \frac{P_2}{P_a} \qquad \text{(hp)} \qquad 6.1\text{-}1$$

P_a = Atmospheric pressure

P_2 = Compressor discharge pressure

V_a = Inlet volume flow (scfm)

This equation is plotted in Figure 6-6a along with relationships for the more exact multistage polytropic compression process. It can be seen that the 75% efficient isothermal process gives more conservative power estimates than the polytropic multistage process. An interesting conclusion which can be drawn from this figure, and which is substantiated in actual compressor plant designs, is that the power (and thereby over-all plant cost) is linearly proportional to the inlet volume flow rate, whereas the pressure has a major effect only in the low pressure range.

The dollar per brake horsepower unit costs for the compressors are given in Figure 6-7. Cooling water for the compressor was determined at 1.67 gpm/bhp (1.41×10^{-4} m^3/kW-sec) and the cooling water pump horsepower was determined at 10 gpm/bhp (8.44×10^{-4} m^3/sec-kW). These factors were added to the basic compressor plant determined from Figures 6-6a and 6-6b. During Phase III. these factors will be refined, as for low pressure cooling systems the water cooling pump requirements could be substantially reduced. A nearly horizontal cooling system with low velocity cooling water could be provided for as little power at 1.0 gpm/hp ($8.44 \times 10^{-3} \times 10^{-3}$ m^3/sec-kW) in some instances.

FIGURE 6–6a
COMPRESSOR HORSEPOWER PER UNIT VOLUME FLOW

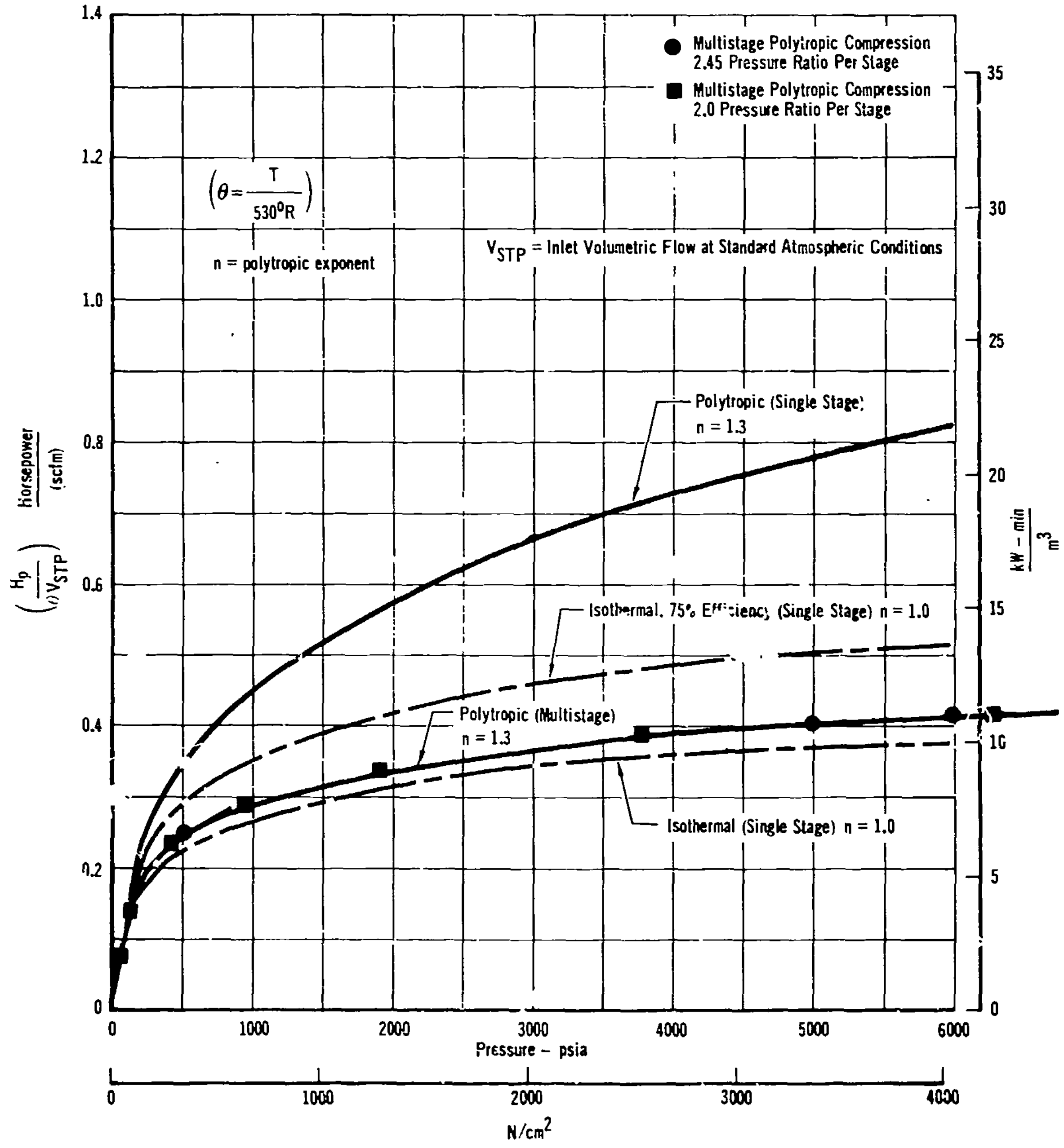


FIGURE 6-5b
COMPRESSED AIR SYSTEM COSTS

English Units

Tank Pressure psig	Tank Storage $ft^3 \times 10^3$	Pump-Up Time – Minutes				Storage Steel		Distribution System Compressor To Storage		Remarks
		20		60						
		Free Air scfm $\times 10^6$	Brake hp $\times 10^4$	Free Air scfm $\times 10^6$	Brake hp $\times 10^4$	Tons $\times 10^3$	Cost $\times 10^6$ (Dollars)	Tons	Cost $\times 10^3$ (Dollars)	
500	1790	1.16	35.0	0.385	11.63	22.250	17.634	175	135.12	1. Distribution System Compressor to Storage Priced at: (a) $700.00 Ton Installed (b) Controls 20% of (a) 2. Storage Tanks and Supports Priced at: (a) Tanks – $800.06 Ton Installed (b) Supports – $600.00 Ton Installed
1,000	550	1.16	41.8	0.385	13.9	13.676	10.816	251	194.04	
1,500	330	1.16	45.9	0.385	15.23	12.272	9.724	116	89.87	
2,000	235	1.16	48.8	0.385	16.2	11.648	9.229	198	152.96	
2,500	183	1.16	51.0	0.385	16.9	11.44	9.064	243	188.29	
3,000	153	1.16	52.7	0.385	17.5	11.128	8.817	221	172.29	
3,500	130	1.16	54.4	0.385	18.0	11.232	8.9	260	200.95	
4,000	115	1.16	55.6	0.385	18.5	11.544	9.147	101	87.55	
4,500	104	1.16	56.9	0.385	18.85	11.856	9.394	132	102.21	
5,000	95	1.16	57.8	0.385	19.2	12.116	9.6	160	124.59	

S.I. Units

Tank Pressure N/cm^2	Tank Volume $m^3 \times 10^3$	Pump-Up Time – Minutes				Storage Steel		Distribution System Compressor to Storage		Remarks
		20		60						
		Free Air $m^3/min \times 10^3$	Power $kW \times 10^4$	Free Air $m^3/min \times 10^3$	Power $kW \times 10^4$	kg $\times 10^6$	Cost $\times 10^6$ (Dollars)	kg $\times 10^3$	Cost $\times 10^3$ (Dollars)	
345	50.7	32.8	26.1	10.9	8.68	20.2	17.634	175	135.12	1. Distribution System Compressor to Storage Priced at: (a) $0.77 kg installed (b) Controls 20% of (a) 2. Storage Tanks and Supports Priced at: (a) Tanks – $ .99 kg installed (b) Supports – $ .66 kg installed
690	15.6	32.8	31.2	10.9	10.4	12.4	10.816	251	194.04	
1,033	9.35	32.8	34.2	10.9	11.4	11.1	9.724	116	89.87	
1,379	6.65	32.8	36.4	10.9	12.1	10.6	9.229	198	152.96	
1,723	5.18	32.8	38.1	10.9	12.6	10.4	9.064	243	188.29	
2,068	4.35	32.8	39.3	10.9	13.1	10.1	8.817	221	172.29	
2,412	3.68	32.8	40.6	10.9	13.4	10.2	8.9	260	200.95	
2,757	3.26	32.8	41.5	0.9	13.8	10.5	9.147	101	87.55	
3,100	2.94	32.8	42.4	10.9	14.1	10.7	9.394	132	102.21	
3,450	2.68	32.8	43.1	10.9		[illegible]	9.60	160	124.59	

FIGURE 6-7
COMPRESSED AIR SYSTEM COMPRESSOR STATION UNIT ACQUISITION COST

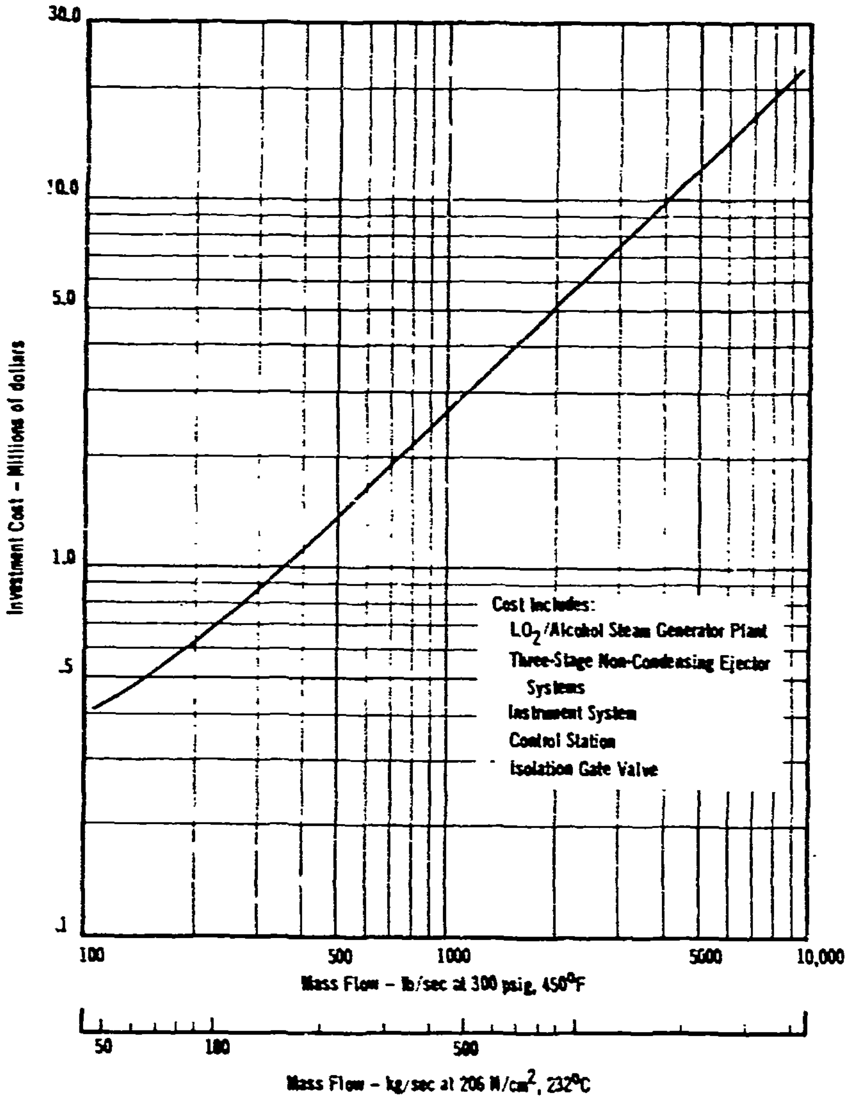
DRIVER CONNECTION	ELECTRICAL SYNCHRONOUS MOTOR, GEARS		DUAL-FUEL TURBINE ENGINE, GEARS & PNEUMATIC COUPLING	
ITEM OF COST	LABOR	MATERIAL	LABOR	MATERIAL
Equipment Less Prime Unit	4.50	30.00	9.25	35.00
Piping	15.00	22.75	18.00	42.75
Building & Painting	6.75	7.50	6.75	7.50
Steelwork	3.00	6.00	3.00	6.75
Subtotal $/bhp	29.25	66.25	32.75	92.00
Prime Unit	75.00		85.00	
Prime-Unit Freight	4.50		6.00	
Total Unit Cost-$/bhp	$175.00/bhp		$220.00/bhp	

NOTE: Above unit prices <u>do not</u> include storage tanks, tank supports or manifolding and distribution piping.

$1/bhp = $1.34/kW

6.1.4 STEAM GENERATORS AND EJECTORS - Chemical LO_2/Alcohol Rocket and conventional boiler steam generation systems were investigated for application to the steam ejector requirements of S2. This facility requires very large evacuation rates and very low chamber pressures when simulating climb trajectories. In addition, the ejector utilization rate would most probably be low, in terms of annual usage. These operational characteristics highly favor the chemical steam generation systems over conventional boilers, since chemical steam generation is characterized by low acquisition cost and high operation costs in comparison to boilers. A chemical steam ejector system was estimated by F. C. Brown Co, for the S2 baseline facility. This estimate, together with previous estimates for other similar systems, provided sufficient data from which to develop Figure 6-8 for chemical steam generators.

FIGURE 6-8
LO_2/ALCOHOL ALTITUDE SIMULATION SYSTEM
ACQUISITION COSTS



6.1.5 PRIME MOVER COSTS - Costs of prime movers used in this phase are based on the use of synchronous electric motors with wound rotor starter motors. Figure 6-9 shows the costs of these motors as a function of shaft horsepower and, for reference, shows the corresponding costs for gas turbine engines. Figure 6-10 shows the costs of some existing gas turbine power units as a function of power. Although straight electric motors were used for cost estimates in this phase, these curves indicate that there are alternate methods which should be considered in detail for specific applications in order to minimize acquisition and operating costs. An illustration of some possibilities is shown in Figure 6-11, which compares acquisition and operating costs for three methods of providing constant speed power. The first method is a gas turbine directly driving the load. This method has the highest acquisition and lowest operating cost. The third method is a gas turbine driving a synchronous motor, where the motor and its controls are owned by the operator and the gas turbine acquisition and maintenance costs are amortized over a 15 year period assuming 12 hour utilization per day and are included in the operating costs. The second method is a synchronous motor with utility provided power. This has the same acquisition cost as the third method but lower operating costs, with the provision that these costs were based on the rates charged at AEDC (See Section 6.1.6). For ordinary commercial rates, the costs could easily exceed those of method three.

These cost comparisons are rather simplified and are for constant speed drives only. Other methods are available, such as direct water turbine drive, and a myriad of methods are available for variable speed drives such as are needed for the multi-compression heater engine research facility (E8). In Phase III, a study will be made of various drive methods, and a general outline of available energy sources, including those used for high, short term peaking loads, will be provided.

6.1.6 UTILITY PROVIDED POWER - Power costs were further refined during Phase II. It has proven very difficult to predict the exact cost of electrical energy until the loads are better determined and the geographical area for the facilities is ascertained. By analyzing the AEDC power billing from the TVA, it was determined that the average cost of power is approximately $.00615 per kW-hour. This is made up of about 50% in transmission and generation charges and 50% in demand charges. The demand charges range between $.15 and $.90 per kW demand per month depending on the time of day. AEDC billing appears to be based on about 22% load during peak, 44% load during intermediate, and 100% load during off-peak periods. Most commercial companies employ a much higher demand charge; i.e., MDC demand billing for Tract II is $1.99 per kW demand per month. The power company demand rate is $1.99 per kW for peak periods and $.995 per kW for off-peak periods. MDC currently averages $.0088 per kW-hr. In the absence of any specific site selections for the ground facilities, and without knowledge of probable demand charges, a cost of $.008 per kW-hr has been assumed for all utility-provided electric power for the estimation of facility operating costs.

6.1.7 VACUUM CHAMBERS - The vacuum requirements for S2 are provided for by building a structure with sufficient framing to allow the attachment of a totally welded cold rolled, mild steel skin. Full opening, track mounted, electrically operated doors are provided at one end of the building. Those steel members attaching the side walls to the floor shall be milled on their connecting surfaces to allow the insertion of an inflatable seal. Those steel members providing contact between the doors and the building structure shall be milled to hold an inflatable seal and the doors shall be provided with a sufficient number of screw clamps to maintain the seal.

FIGURE 6–9
ELECTRIC MOTOR PRIME MOVER ACQUISITION COST

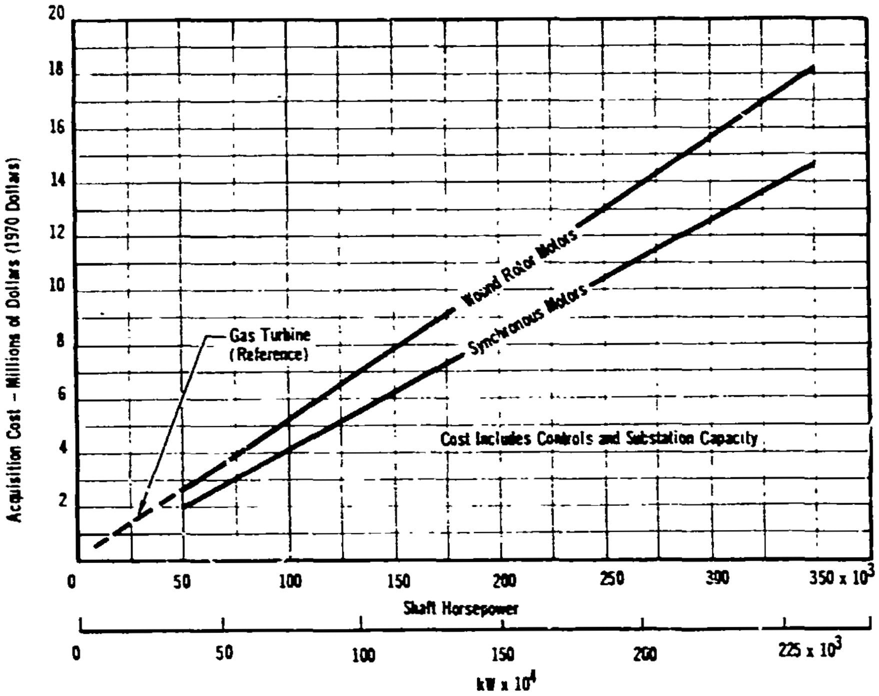


FIGURE 6–10
GAS TURBINE PRIME MOVER ACQUISITION COST

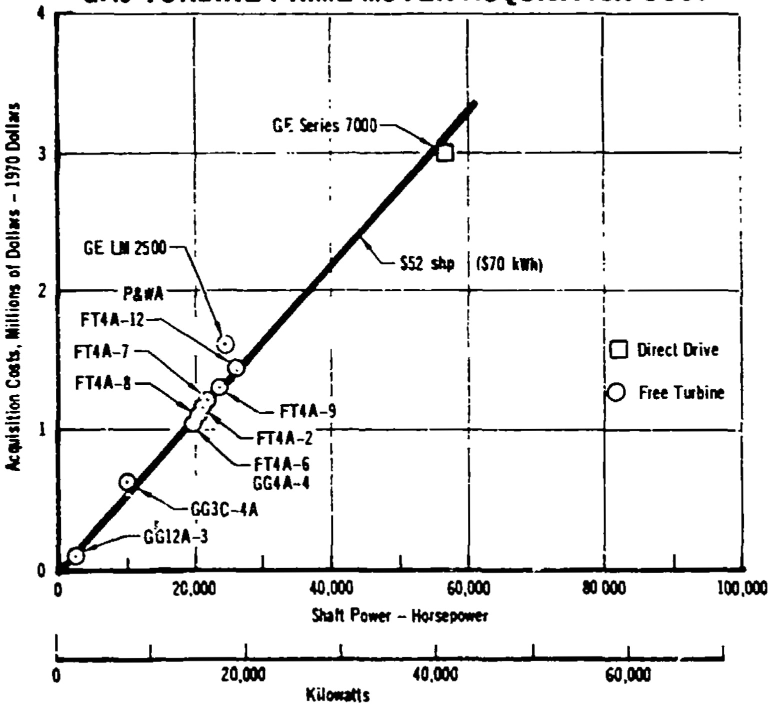
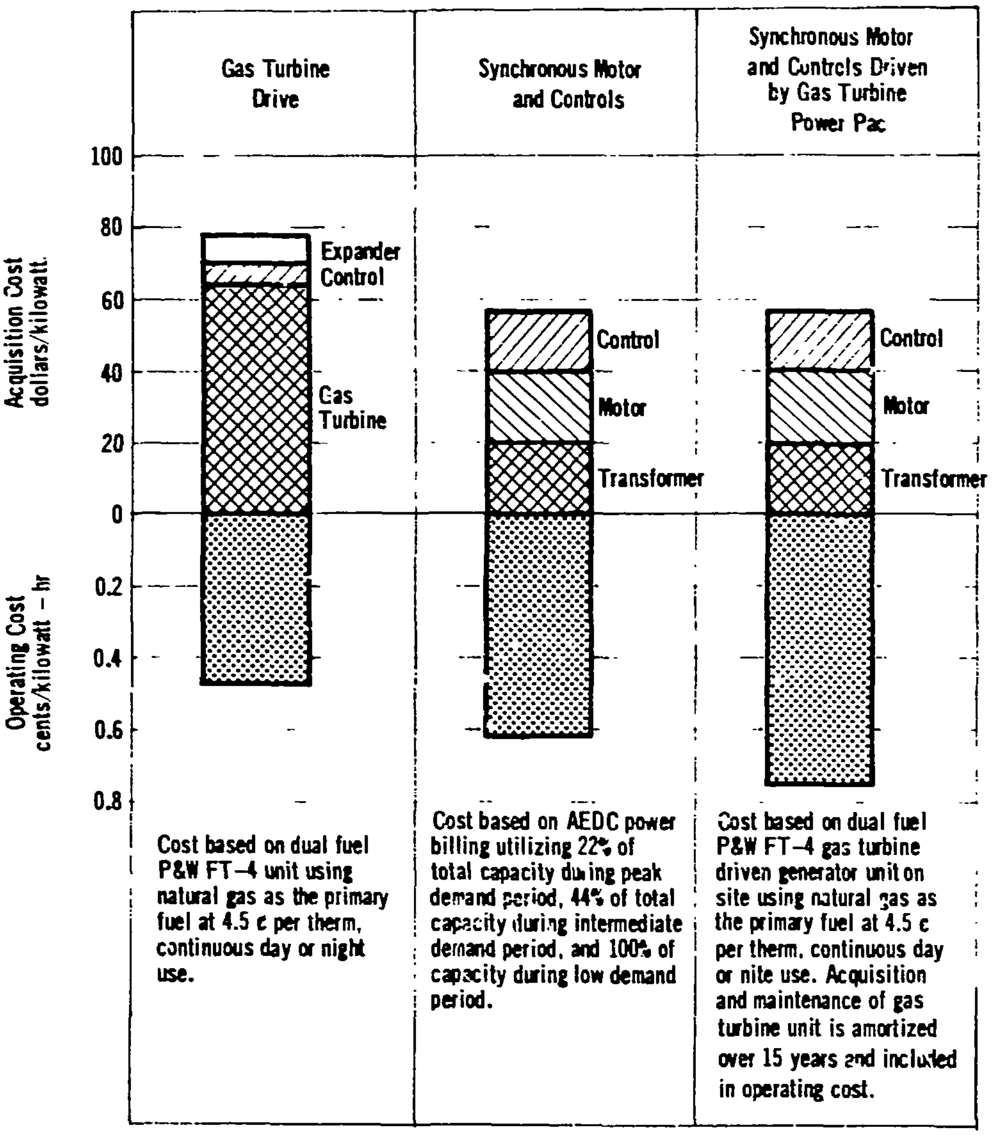


FIGURE 6–11
COMPARATIVE COSTS FOR PRIME MOVERS, CONSTANT SPEED DRIVES



Cost based on dual fuel P&W FT–4 unit using natural gas as the primary fuel at 4.5 ¢ per therm, continuous day or night use.

Cost based on AEDC power billing utilizing 22% of total capacity during peak demand period, 44% of total capacity during intermediate demand period, and 100% of capacity during low demand period.

Cost based on dual fuel P&W FT–4 gas turbine driven generator unit on site using natural gas as the primary fuel at 4.5 ¢ per therm, continuous day or nite use. Acquisition and maintenance of gas turbine unit is amortized over 15 years and included in operating cost.

Chamber evacuation to one torr ($133 N/m^2$) in a very short time period is accomplished by use of steam ejectors operated in conjunction with a LO2-alcohol steam generator. Ejectors are so staged as to provide for minimum operation to maintain the vacuum after initial pump down. The chamber was priced by determining the tonnage, fabrication, and erection costs by the method described in Section 6.1.4.

The environmental chamber for M-20 was priced using a curve relating acquisition costs of existing environmental chambers to their diameters (Figure 6-12). The spread of data in the figure is accounted for by the wide range of test capabilities represented by these facilities, and by their variations in chamber shape, orientation, and amounts of cryogenic storage volume. The mean line indicated in Figure 6-12 was the relationship chosen for estimating the M-20 environmental chamber.

6.1.8 ACOUSTIC SHROUDS AND GENERATORS - Costing the acoustic shroud involved estimating the steel required to develop a self-supporting shroud along with the fabrication and erection costs primarily from experience. The acoustic watt generators were priced at fifty cents for each acoustic watt output. Some insight into acoustic vibration testing was gained from discussion with MDC Laboratory personnel and NASA Technical Memorandum NASA TMX-58017, "Concept, Design, and Performance of the MSC Spacecraft Acoustic Laboratory".

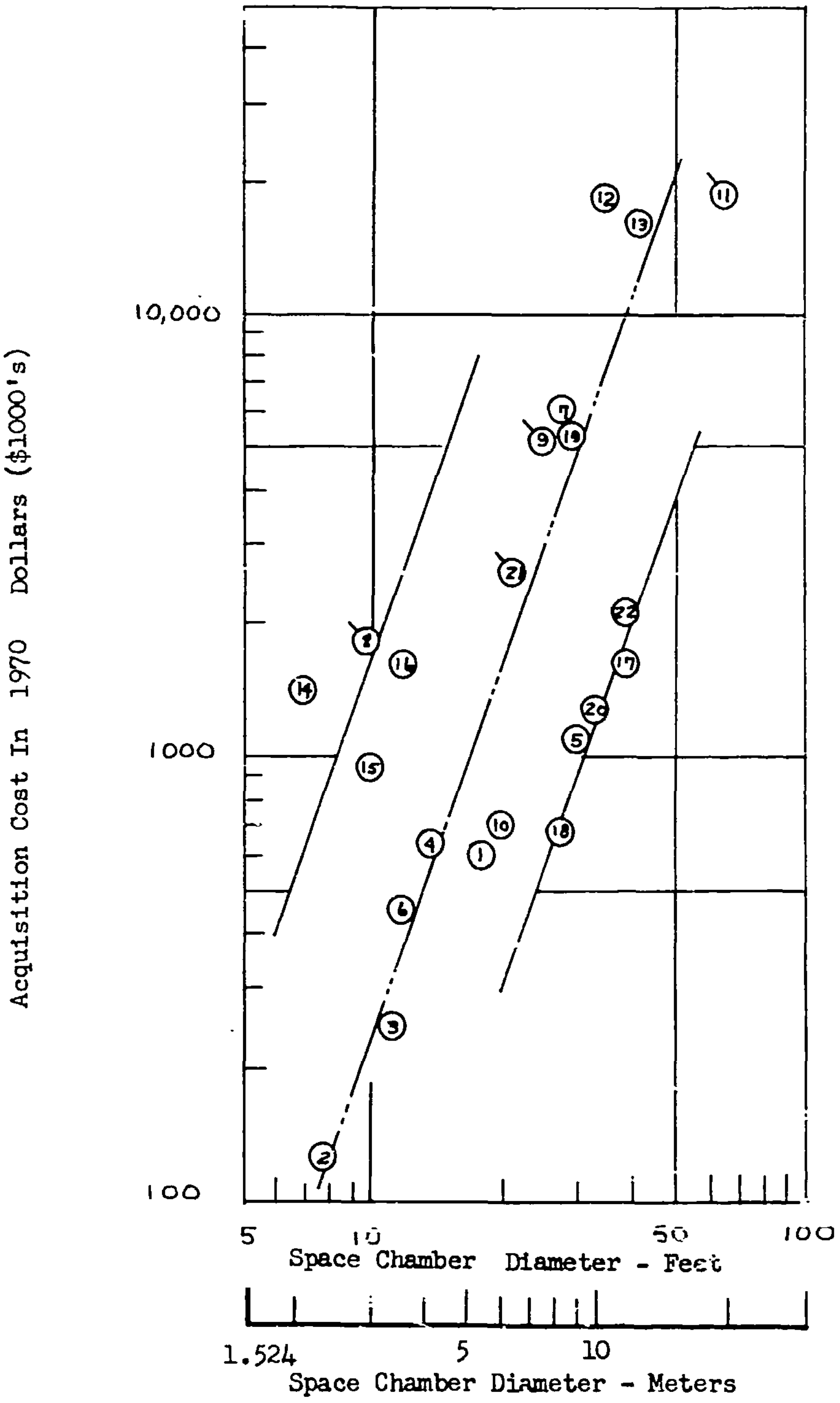
6.1.9 STRUCTURAL HEATERS AND THERMAL CONTROL - The heaters are of either the quartz lamp or graphite resistance type. A cost curve (Figure 6-13) was developed from an analysis of heaters required to produce a given heat flux per square foot of area and was used to establish quartz heater cost. Graphite heaters were priced at \$12,000 for 120 Btu/ft^2 sec through 450 Btu/ft^2 sec (1370 kW/m^2 through 5120 kW/m^2). Thermal control consists of a programming capability and a temperature recording/controlling capability using 250 kW ignitron units. Costs of thermal controllers are taken at \$5000 per channel, based on actual costs of recent MDC purchases. Total radiant heater system costs are the sum of the heater and control channel costs.

6.1.10 AIR HEATERS, CONTINUOUS AND STORAGE - The various heaters in the flow facilities are, unlike the radiant heaters used in the structural facility, not comprised of numerous individual heaters of current technology level size and power. They are, in general, very large and powerful units which will certainly require intensive design effort to ensure their desired performance and reliability. At this stage of the study, only gross characteristics of the various heaters are known, such as maximum power, mass flow, and temperature, so some general rules-of-the-thumb were developed in order to estimate the cost of the many heaters required. These are discussed for the various heater types.

a) Electric Heaters - These heaters, examples of which are required on GD7, GD15, E6, E20, and the air preheater of E9 were cost estimated on the basis of the actual costs of several recent MDC resistance heater purchases. A value of \$32 per kilowatt was used, this cost including the entire heater and its control system.

b) Gas-fired Heater - A heater of this type is used on GD3 in order to avoid air liquefaction at its higher Mach numbers. This heater cost was estimated based on a recent purchase of a similar, but smaller, heater from Combustion Engineering Company. The cost was scaled proportional to the heating rate required.

FIGURE 6-12
SPACE CHAMBER ACQUISITION COST AS RELATED TO SPACE CHAMBER DIAMETER



McDonnell-St.Louis
1. 18 ft Chamber
2. 8 ft Chamber
3. 11 ft Chamber
4. 14 ft Chamber
5. 30 ft Chamber

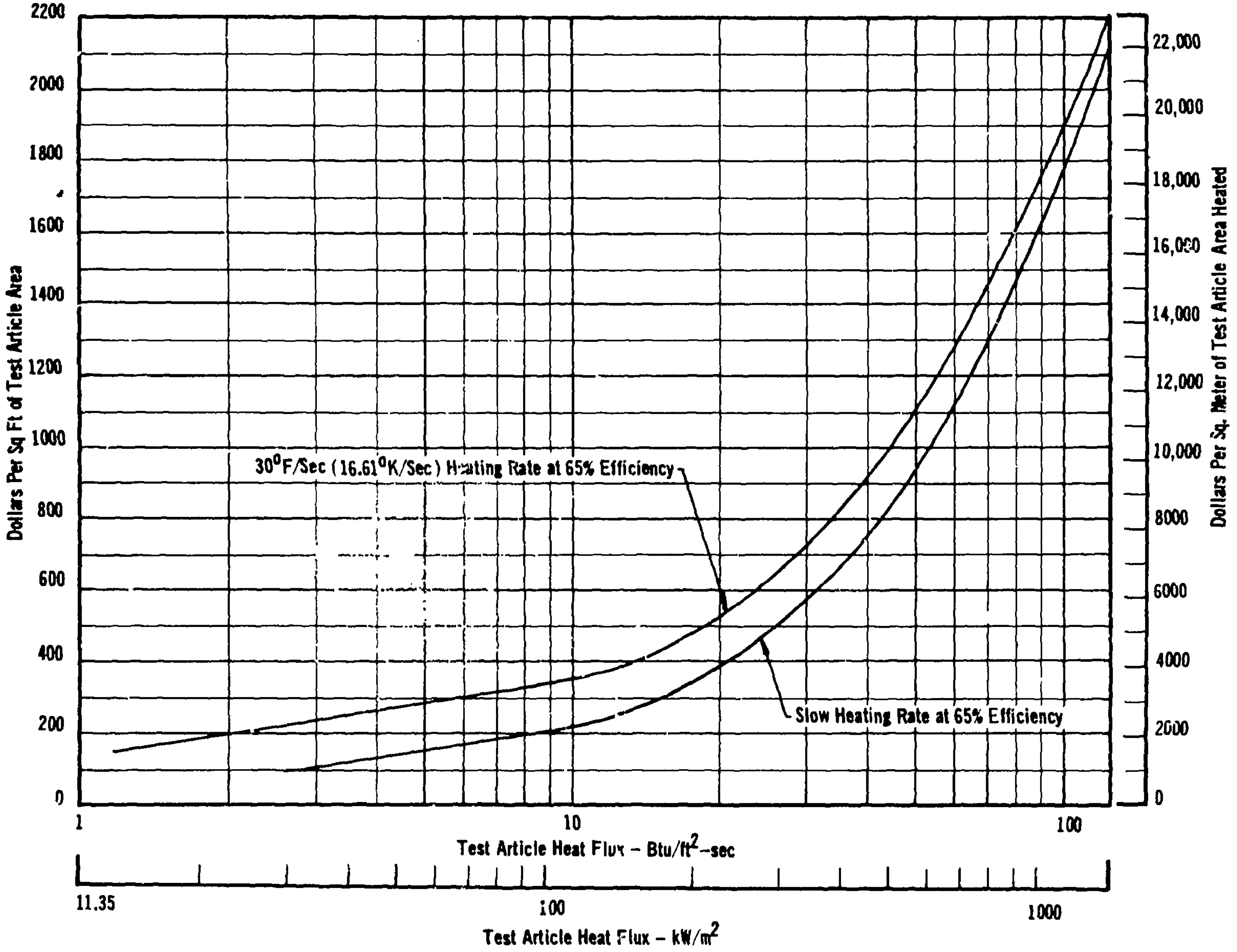
NASA-Goddard
6. Thermal/Vacuum Chamber
7. Space Environ. Sim.

NASA-JPL
8. 10 ft Space Sim.
9. 25 ft Space Sim.

NASA-MSC
10. 20 ft Chamber
11. SESC Chamber A
12. SESC Chamber B

AEDC
13. Aerospace Environ. Chamber (Mark 1)
14. Aerospace Research Chamber (7V)
15. Aerospace Research Chamber (8V)
16. Aerospace Research Chamber (12V)
17. GE/Valley Forge
18. STL
19. Martin/Denver
20. Xerox/Electro-Optical Systems Div.
21. TRW
22. Philco-Ford/WDL

FIGURE 6-1[illegible]
QUARTZ HEATER ACQUISITION COST AS RELATED TO TEST ARTICLE HEAT FLUX REQUIREMENTS



c) Pebble Bed Storage Heater (E9) - In this case, the zirconia refractory heater was essentially identical in size and pressure rating to a proposed heater at AEDC. The estimated cost of the AEDC heater was used directly.

d) Multirecompression Heater (E8) - This heater is actually a mechanical device which both heats and compresses the air passing through it. No examples of any size have been constructed, so scaling in any manner is not possible. In this case, a rough estimate of the material and fabrication costs was obtained, using the very conceptual MRCH sketches as a basis. Consultation with personnel at Philadelphia Gear Company aided in estimating the cost of the rotors in particular.

e) Carbon-monoxide Combustor (E9) - Again, no scaling from existing similar combustors was possible in this case, so material and fabrication costs were estimated directly from the Phase II conceptual sketch (Figure 6-73) and using the general principles discussed in Section 6.1.2.

f) Graphite resistance heater (E9 Alt.) - The cost of this heater was scaled from data provided by NASA LeRC on their Plumbrook Facility, which incorporates a graphite induction heater.

6.1.11 <u>DATA ACQUISITION COSTS</u> - Data acquisition equipment is defined as that equipment required to record, store, compute, and playback data collected during facility operation. For the flow facilities it was based on an estimate of required channels and costs extrapolated from existing facilities. For the non-flow facilities it was based on the number of control channels necessary and the number of environmental parameters being simulated, as determined from the facility component breakdowns. Source information from recent MCAIR purchases indicate a nominal cost of $1000 per data acquisition channel.

6.1.12 <u>INSTRUMENTATION COSTS</u> - The instrumentation comprises thermocouples, strain gauges, pressure transducers, flow meters, accelerometers, microphones, and any other devices which are required to sense physical quantities required for facility control and test data. MCAIR and MDAC-ED budgets were again used for source data, and a cost of $1000 per instrumentation channel was used.

6.1.13 OPERATING COSTS - Operating costs for each facility were developed on an occupancy-hour basis. Occupancy hours are defined as the total time a test occupies a facility, or portion of a facility, and includes set-up, calibration, testing, and test removal times.

Different rationales are required to calculate operating costs for the flow and non-flow facilities. In a flow facility, only one test occupies the facility at a given time, and all applicable charges incurred by the test are applied directly to it. For non-flow facilities, several or many tests can be going on simultaneously. The various test articles can vary widely in size and in the amount and type of test environments being used. It is impossible, therefore, to calculate a single number which is applicable to any and all tests being run in a non-flow facility without knowing test article type, size, type of environment(s) to be used, amount of power required, and the number of personnel, direct and indirect, charging their time to the test. The approach taken here is to calculate the average cost of operating the entire facility, assuming 2000 hours of available occupancy time per year. In order to calculate the cost of a given, identified test, an estimate of the proportion of the various services required should be made and ratioed to the total capability cost.

Operating costs for both facility categories include the cost of power, consumables, maintenance parts and supplies, and facility staffing. Amortization costs of the facilities are not included, it being assumed that acquisition of the facilities will be provided for by special appropriations, while operating costs are charged to an annual operations budget for the test center.

(a) Non-Flow Facility Operating Costs - The various items comprising the total operating cost of the non-flow facilities are explained below:

- Cost of building operation and maintenance is taken to be 10% of the building acquisition cost per year. This factor is based on analysis of similar costs from MCAIR budgets.

- Cost of environmental chamber operations and maintenance is taken to be 3% of the chamber acquisition cost per year, and is based on average MDC budgets for this type of equipment.

- Cost of radiant heater maintenance is dependent of the range of heating rates, since heater replacement rate is proportional to the heating rate.

  For rates less than 110 Btu/ft^2 sec (1250 kW/m^2), complete replacement of all heaters every 10 years is assumed.

  For rates greater than 110 Btu/ft^2 sec (1250 kW/m^2), complete replacement of all heaters every year is assumed.

  These heater replacement costs are based on experience in the MCAIR radiant heat facility.

- Cost of control equipment, data acquisition, and instrumentation repair and maintenance is proportional to the number of data channels and is based on the labor charge (at \$10 per hour) of one man servicing 150 channels. This cost is based on operating experience in the MCAIR engineering laboratories.

- Cost of miscellaneous services and utilities maintenance is taken to be 16% of their acquisition cost per year. This figure is representative of the experience of the MCAIR engineering labs.

- Cost of substation operation and maintenance is taken to be 3% of the substation acquisition cost per year and is based on average industrial substation replacement rates.

- Electrical power cost is based on \$.008 per kWhr (see Section 6.1.6), utilizing, on the average, 33% of the maximum installed power.

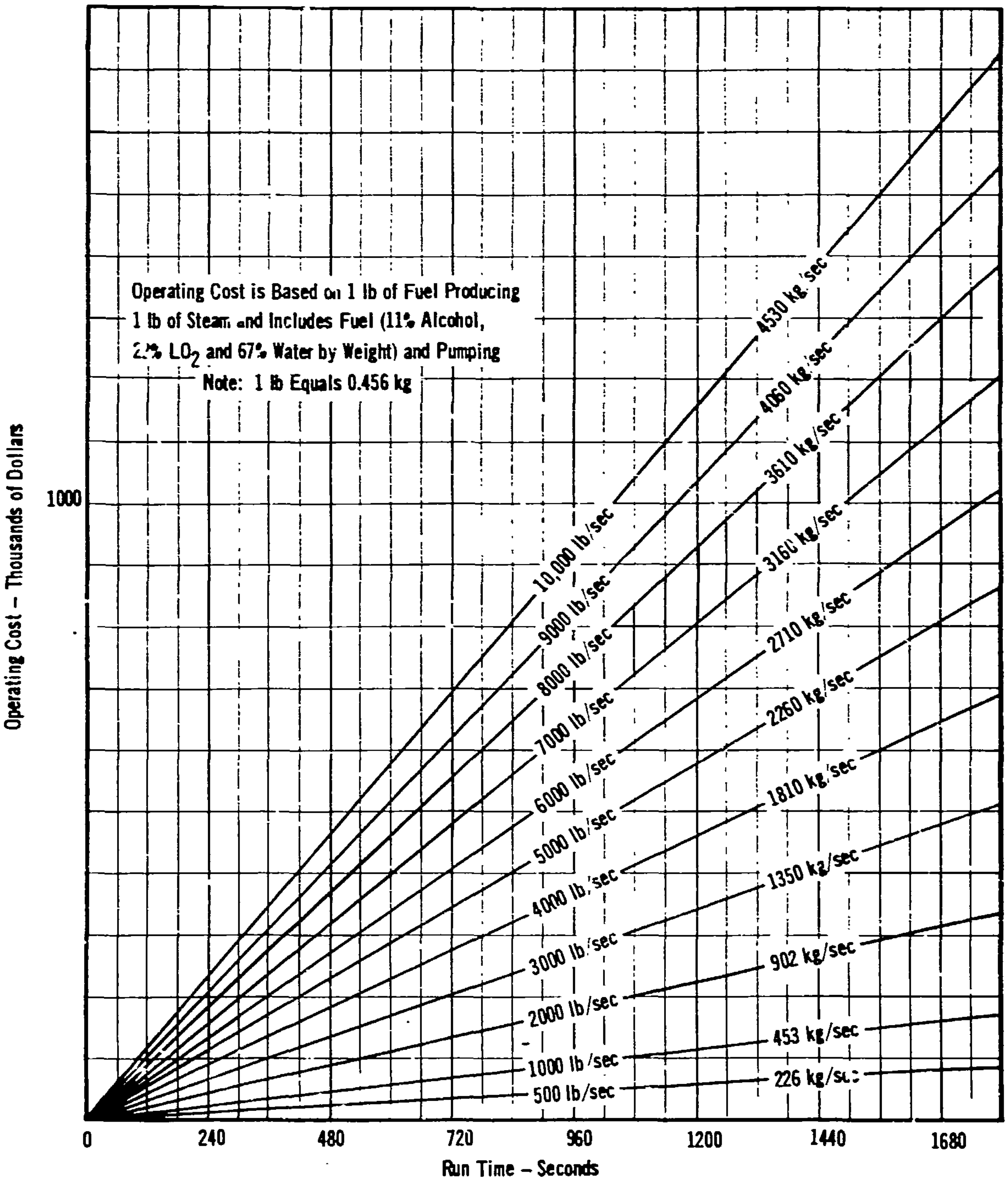
- Cost of steam ejector operation is proportional to the pumping rate (and thus climb trajectory simulated) of the vacuum chamber, and is made up of the cost of LO_2, alcohol, and water for steam generation. For this cost model, it is assumed that the vacuum chamber is occupied one-third of the available time (or 667 hours per year). During this time, the chamber is under actual vacuum conditions 10% of the time, the remainder of the time being spent in test installation, instrumentation, calibration, and test article removal. Thus, 67 hours per year are spent under vacuum conditions. A typical one-hour run has been assumed, consisting of a 4-minute climb to altitude and 56 minutes holding at altitude, where the steam consumption is 10% of the maximum rate in order to overcome the chamber leak rate. This run model is used, in conjunction with Figure 6-14, which shows operating cost as a function of run time and steam rate, to calculate the total ejector operating cost per year or per 2000 total facility available occupancy-hours.

(b) Flow Facility Operating Costs - As discussed above, operating costs of flow facilities can be calculated directly on an occupancy-hour basis, since only one test at a time is performed, and all systems and components comprising the facility are utilized. A run model is necessary, as for the steam ejectors, for all cost factors which are incurred as a function of actual run times and test conditions. Assumptions made for the flow facility operating costs are explained below:

- Repair and maintenance costs were calculated on a basis of 3% of the total facility acquisition cost per year or per 2000 available occupancy-hours. This is a judgement factor which was used because of the difficulty of obtaining industry data on the wide range of facility types represented in this phase, and because of the novelty of several of the facility concepts where no such data is available.

- Labor or staffing costs were calculated by assuming a staffing level for each facility and an average rate of \$10/hour to allow for some overhead functions.

FIGURE 6-14
OPERATING COST
LO_2/Alcohol Altitude Simulation System



Operating Cost is Based on 1 lb of Fuel Producing 1 lb of Steam and Includes Fuel (11% Alcohol, 22% LO_2 and 67% Water by Weight) and Pumping

Note: 1 lb Equals 0.456 kg

- Run time related cost factors were calculated assuming that facility systems were operating 90% of the total occupancy time and 10% of the time was spent in installation, calibration, model changes, and test removal. It was further assumed that average power or consumption rates throughout a typical run were 70% of the total available. Cost factors for power and consumables assumed were:

  Utility-provided electric power - $.008 per kilowatt-hour (Section 6.1.6)

  Gas turbine power - $.0035 per horsepower-hour ($.0047 per kW; Section 6.1.3)

  Liquid nitrogen[1] = $.06 per lb ($.132 per kg) with a utilization factor of 1.5

  Liquid oxygen[1] = $.0061 per lb ($.0134 per kg) with a utilization factor of 1.54

  Carbon supply[2] (for CO reactor, E9) = $.07 per lb ($.154 per kg).

6.1.14 SCALING - For the parametric studies of Phase II, two alternate facility design concepts (discussed in Section 6.2.7) were selected. In estimating the facility acquisition costs for the gas dynamic facilities, it was found impossible to do a detailed component breakdown and cost estimate for each of the facilities, which total nine, counting all baselines and alternates. Instead, a fairly detailed cost breakdown was estimated for the three baseline facilities, according to the guidelines developed in the other subsections of 6.2. These costs were then scaled up for the alternate facilities according to the guidelines developed in this section.

The differences between the baseline facilities and their alternates lie in two physical factors; size and stagnation pressure level. There are no differences in Mach number or stagnation temperature. The two scaling factors, then, are:

$$\text{Stagnation Pressure Ratio} = \frac{p_{o\,\text{ALTERNATE}}}{p_{o\,\text{BASELINE}}} = \gamma \qquad 6.1\text{-}2$$

$$\text{Size Ratio} = \sqrt{\frac{C_{\text{ALTERNATE}}}{C_{\text{BASELINE}}}} = \lambda \qquad 6.1\text{-}3$$

where C = Test Section Area

These factors, evaluated for the alternate facilities as defined are:

Facility	γ	λ
Baseline	1.0	1.0
Alternate 1	0.4	2.5
Alternate 2	1.0	2.5

Cost scaling for the defined alternate gasdynamic facilities will be developed for these specific values of γ and λ.

[1] Linde Div., Union Carbide and Air Reduction Co.

[2] Cabot Corporation

o <u>Pressure Shells with Positive Internal Pressure</u> - Cost estimates for structural components have been calculated as a function of component weight, so the cost scaling ratio (CSR) is equal to the ratio of the alternate and baseline component weight.

$$\text{CSR} = \frac{W_{ALT}}{W_{BASELINE}}$$

The weight of a component is proportional to the volume of material, which is a function of thickness, length, and diameter.

For Cylinder

$$w = kLDt$$

where: L is a typical length
D is a typical diameter
t is material thickness

So: $$\text{CSR} = \frac{L_{ALT}\ D_{ALT}\ t_{ALT}}{L_{BL}\ D_{BL}\ t_{BL}} = \lambda^2 \frac{t_{ALT}}{t_{BASELINE}}$$

The thickness ratio is found by assuming that equal stress levels are desired in both alternates and baseline facilities, and, using the Hoop Stress Law:

$$\frac{t_{ALT}}{t_{BL}} = \left(\frac{P_{ALT}}{P_{BL}}\right)\left(\frac{D_{ALT}}{D_{BL}}\right) = \left(\frac{P_{o\,ALT}}{P_{o\,BL}}\right)\left(\frac{D_{ALT}}{D_{BL}}\right) = \gamma\lambda$$

Then: $\boxed{\text{CSR} = \gamma\lambda^3}$ General Rule 6.1-4

$\text{CSR}_1 = 6.25$

$\text{CSR}_2 = 15.6$

These values have been used to scale all pressure shells which carry positive internal pressure.

o <u>Pressure Shells with Negative Internal Pressure</u>

$$\text{CSR} = \frac{W_{ALT}}{W_{BL}} = \lambda^2 \frac{t_{ALT}}{t_{BL}}$$

In this case all structures are sized for a maximum pressure differential of one atmosphere, so using the Hoop Stress Law:

$$\frac{t_{ALT}}{t_{BL}} = \frac{D_{ALT}}{D_{BL}} = \lambda$$

$\boxed{\text{CSR} = \lambda^3}$ General Rule 6.1-5

$\text{CSR}_1 = \text{CSR}_2 = 15.6$

This value has been used to scale all pressure structures which carry negative internal pressure.

o Storage Spheres

$$\mathrm{CSR} = \frac{W_{ALT}}{W_{BL}}$$

In this case the volume of the sphere is proportional to the facility weight flow, since run time is held constant.

$$\text{Volume} = V = k\,\dot{w} = k\,P_o\,d_*^2$$

So:

$$\frac{V_{ALT}}{V_{BL}} = \lambda^2\gamma = \frac{D_{s\,ALT}^3}{D_{s\,BL}^3}$$

$$\frac{D_{s\,ALT}}{D_{s\,BL}} = (\gamma\lambda^2)^{1/3}$$

d_* = NOZZLE THROAT DIA.

Weight of the sphere is a function of surface area and thickness:

$$W = k D_s^2 t$$

$$\mathrm{CSR} = (\gamma\lambda^2)^{2/3}\,\frac{t_{ALT}}{t_{BL}}$$

As for other vacuum structures,

$$\frac{t_{ALT}}{t_{BL}} = \frac{D_{s\,ALT}}{D_{s\,BL}} = (\gamma\lambda^2)^{1/3}$$

So: $\boxed{\mathrm{CSR} = \gamma\lambda^2}$ General Rule 6.1-6

$\mathrm{CSR}_1 = 2.5$

$\mathrm{CSR}_2 = 6.25$

These values were used for scaling the cost of the vacuum sphere for GD7.

o Heaters - Cost estimates for heaters have been calculated as a function of heater power, so the CSR for heaters is equal to the ratio of the alternate and baseline power required.

$$\mathrm{CSR} = \frac{\text{POWER ALTERNATE}}{\text{POWER BASELINE}}$$

Power required is proportional to facility weight flow

$$\text{POWER} = k\,\dot{w} = k\,P_o\,d_*^2$$

So: $\boxed{\mathrm{CSR} = \gamma\lambda^2}$ General Rule 6.1-7

$\mathrm{CSR}_1 = 2.5$

$\mathrm{CSR}_2 = 6.25$

These values were used to scale heater costs for GD3 and GD20. The gas piston driver of GD7 was scaled as a pressure vessel.

6.2 GAS DYNAMIC RESEARCH FACILITIES

The Gas Dynamic Research Facilities are provided for aeronautical research in the areas of aerodynamic and thermodynamic configuration development, inlets and exhaust nozzles, structures, and operations. As conceived for this study, the baseline facilities provide approximately 5 times the Reynolds number capability of the best existing intermittent facilities and up to 10 times the capability of major existing continuous facilities.

The concepts presented are based on specific equipment performance capabilities representative of current technology, but are of an absolute size exceeding present installations. This should provide facilities which are able to provide a near term increase in research capability. The performance requirements of the Gas Dynamic Facilities were based on an analysis of the nine potential operational systems. The size of the facilities is not completely arbitrary; but is based on analysis of model materials and balances, so as to describe a minimum size facility to achieve a given Reynolds number.

6.2.1 DESIGN CRITERIA - The role of the wind tunnel is primarily that of a Reynolds number/Mach number simulator. For that reason, it was decided to supplement the engine research facilities with aerodynamic nozzles for research which required aerodynamic flow and pressure-temperature-velocity duplication. Of necessity, the engine facilities had to provide flight duplicated conditions, and repeating this capability for the gas dynamic facilities appeared redundant. Therefore, the gas dynamic facilities are designed to operate at a minimum temperature, just sufficient to avoid air condensation in the test section, and at sufficient pressure to attain the desired unit Reynolds number in the test section.

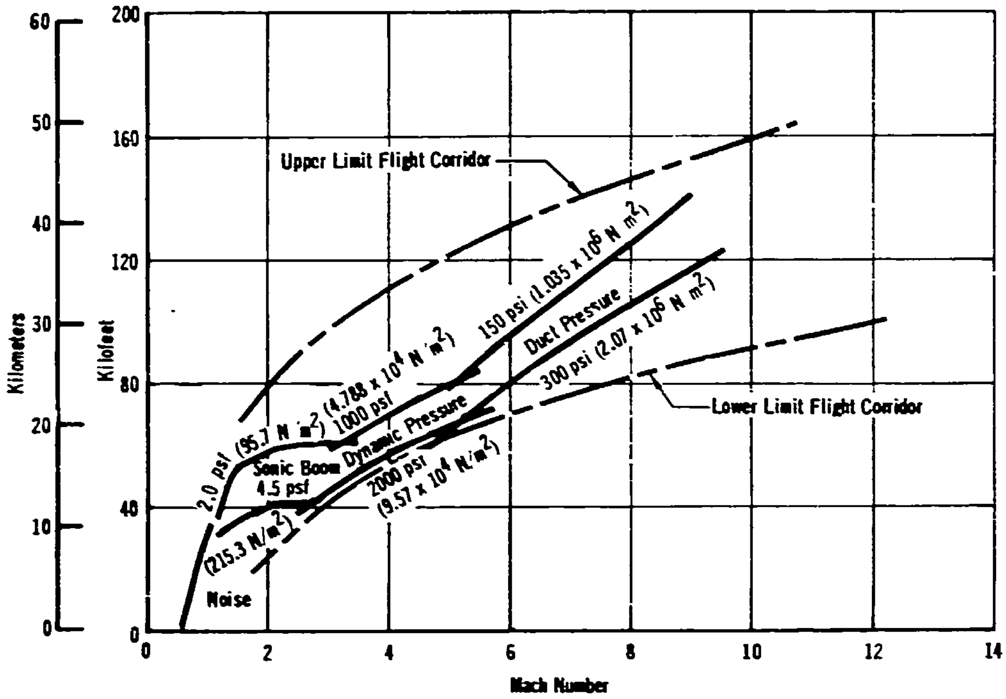
In order to determine the Reynolds number/Mach number envelope required by the potential operational hypersonic aircraft, an analysis of the flight corridor (Figure 6-15) and the potential operational aircraft (Volume VI) was made, and is presented in Volume II. In order to translate this into vehicle Reynolds number, the sizing criteria developed in Volume II is used to relate the length of the model to the square root of the test sectional area; that is

$$\sqrt{C} = \frac{L}{1.3} \qquad 6.2\text{-}1$$

These results are presented in Figure 6-16 and are compared to the capability of existing facilities using the same model-to-tunnel size criteria.

Examining Figure 6-16, the Reynolds number capability represented by one-fifth of the maximum full scale Reynolds number is about a three-fold increase in existing capability, and also represents a reasonable increment in facility size, structural requirements, and hardware performance. Discussions with Aerophysics Branch personnel, NASA Langley, concerning the prediction of full scale skin friction drag from subscale tests for low aspect ratio, highly swept configurations indicated that if Reynolds number levels approached one-fifth full scale values, extrapolation to full scale could be done with a minimum of error. If one-fifth the maximum Reynolds number could be achieved, corresponding to a maximum dynamic pressure of 2000 psf (95,700 N/m^2), then for all other areas of the flight envelope, greater

FIGURE 6-15
FLIGHT CORRIDOR BASED ON POTENTIAL OPERATIONAL HYPERSONIC AIRCRAFT



than one-fifth full scale Reynolds number is attainable, minimizing the extrapolation necessary to full scale values. This is especially true in the area of hypersonic cruise at 500 to 700 psf (24,000 to 33,500 N/m^2) dynamic pressure, where Reynolds numbers of 60 to 100% of the full scale values can be achieved, minimizing the risk of extrapolation errors in a very crucial region. It appears then, that a Reynolds number capability for the gasdynamic research facilities of one-fifth the maximum full scale values would provide a reasonable baseline facility definition.

As stated initially, the gas dynamic facilities were to be Reynolds number/Mach number simulators, not flight condition duplicators. Figure 6-17 illustrates this point, by comparing the conditions required for flight duplication and those necessary for Reynolds number simulation in a minimum sized wind tunnel.

The conditions for the gasdynamic research facilities listed in Figure 6-17 are based on model strength and balance load carrying capacity. These are independent of the size of the facility or model, and therefore, represent the maximum dynamic pressure conditions consistent with the model strength and balance capabilities for models of the potential operational hypersonic aircraft. Since the Reynolds number per unit length is then fixed for each Mach number, the tunnel size must be large enough to accommodate a model of sufficient size to achieve the desired Reynolds number, that is, the product of the unit Reynolds number times model length.

The process of identifying the reservoir conditions and wind tunnel size is characterized in Figure 6-18. The two basic judgements made in the selection of the gas dynamic facilities were the degree of Reynolds number simulation as a baseline value and the Mach number range for each facility.

FIGURE 6-16
REYNOLDS NUMBER CAPABILITIES OF EXISTING FACILITIES COMPARED TO REQUIREMENTS

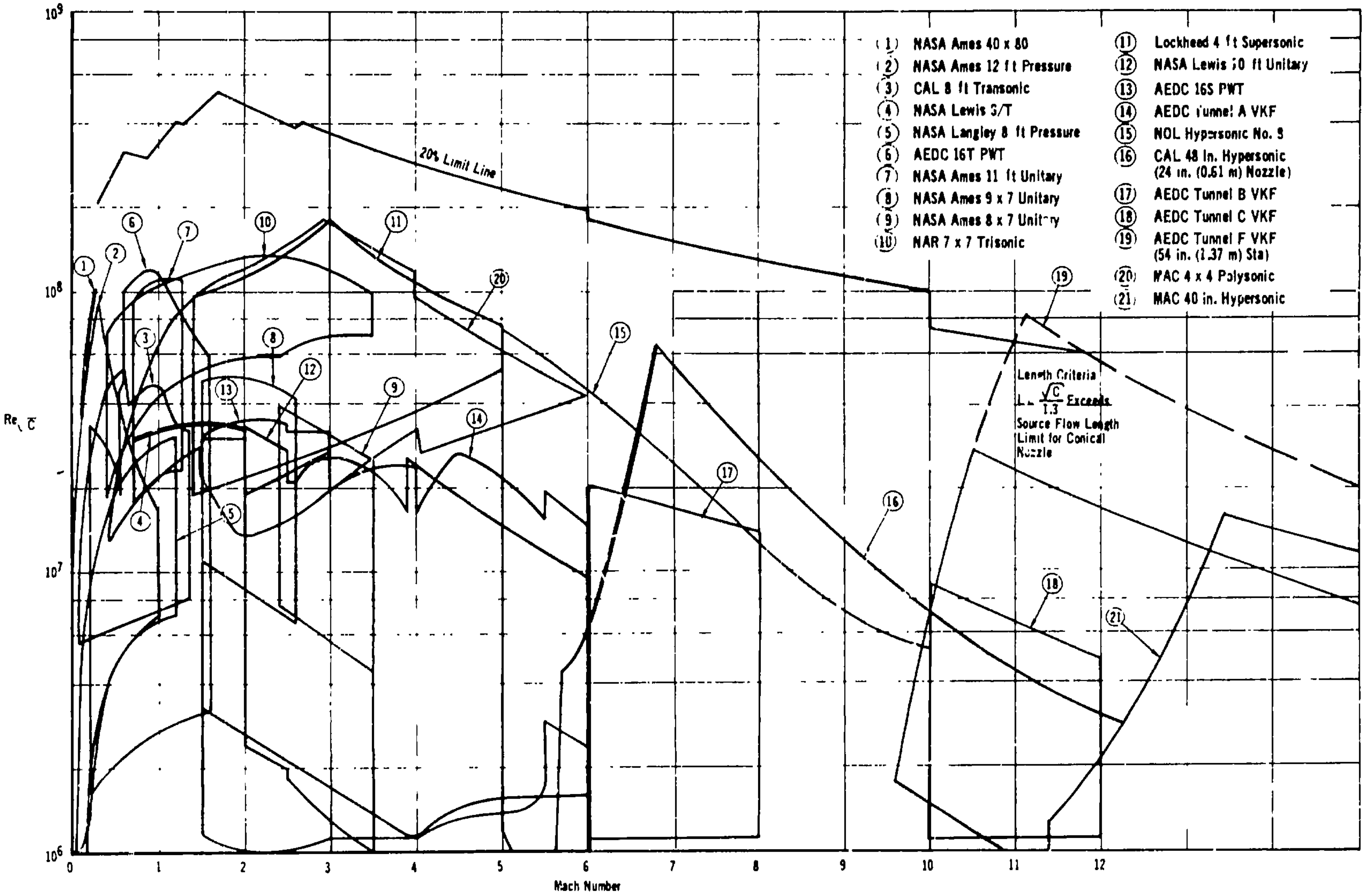
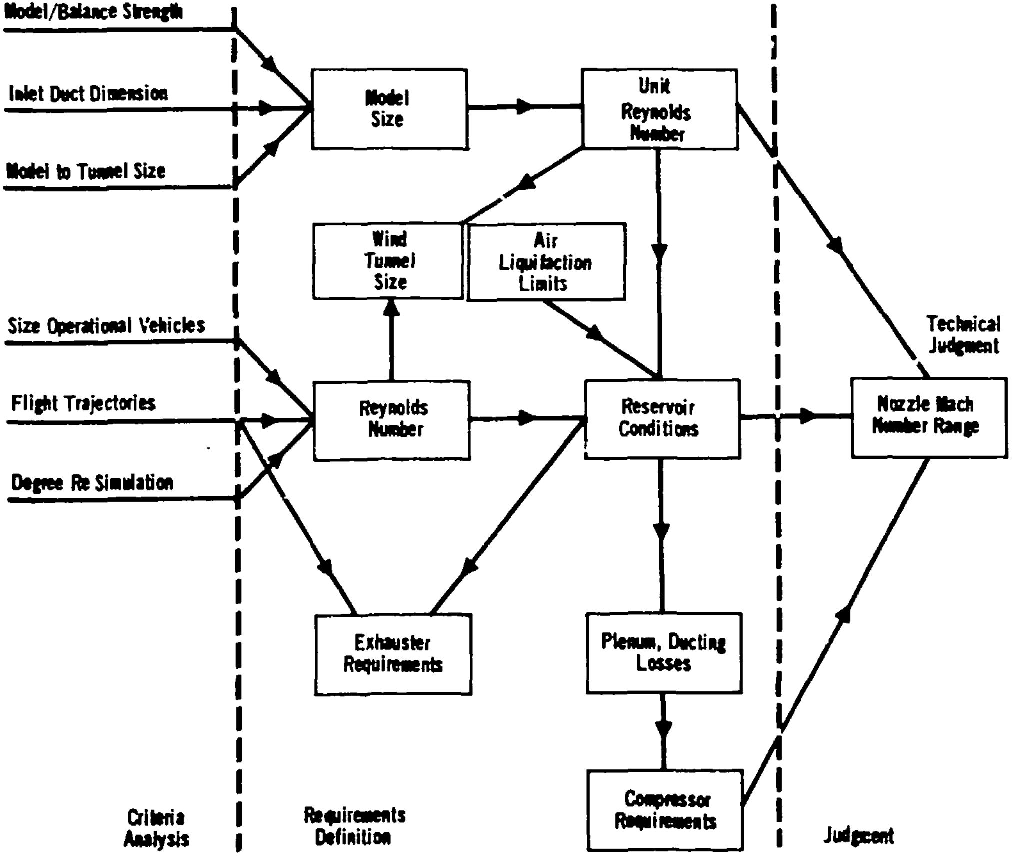


FIGURE 6–17
DEGREE OF FLIGHT SIMULATION FOR GASDYNAMIC FACILITIES

	MACH NO.	UNIT REYNOLDS NUMBER x 10^{-6} 1/ft (1/m)	PRESSURE ALTITUDE kft (km)	VELOCITY ft/sec (m/sec)	STATIC PRESSURE psia (N/cm^2)	STATIC TEMPERATURE °R (°K)	ISENTROPIC STAGNATION TEMPERATURE °R (°K)	ISENTROPIC STAGNATION PRESSURE psia (N/cm^2)
FLIGHT	1.67	6.59(21.6)	20(6.1)	1730(530)	6.75(4.64)	460(256)	700(389)	35(17.1)
WIND TUNNEL	1.67	38.8(127.0)	-20(-6.1)	1530(468)	29.7(20.4)	360(200)	560(305)	140(68.5)
FLIGHT	5.0	2.92(9.59)	66(21)	4840(1480)	.785(.540)	390(216)	2300(1280)	315(218)
WIND TUNNEL	5.0	15.0(49.2)	73.2(22.3)	2480(755)	.555(.382)	102(56.6)	610(339)	294(202)
FLIGHT	8.0	1.65(5.42)	86(26.2)	7850(2390)	.31(.213)	400(221)	4600(2560)	4000(2560)
WIND TUNNEL	8.0	13.7(45.0)	83(25.3)	3660(1120)	.34(.234)	87(48.4)	1200(666)	3210(2210)
FLIGHT	13.0	7.25(23.8)	108(32.8)	13,000(3960)	.112(.077)	415(230)	9700(5380)	100,000(68,900)
WIND TUNNEL	13.0	92.2(310.0)	120(36.6)	5600(1705)	.068(.047)	77(42.8)	2500(1390)	18,800(12,900)

FIGURE 6-18
GAS DYNAMIC FACILITY SYNTHESIS



6.2.2 MODEL SIZE/REYNOLDS NUMBER CAPABILITY - Determination of the level of Reynolds number simulation does not necessarily determine the size of the facility. The Reynolds number based on the model length is:

$$Re_L = \frac{1.78 \times 10^6 \, q_\infty \left(1 + \frac{202}{T_\infty}\right) L}{T_\infty \, M_\infty} \qquad 6.2\text{-}2$$

where: q_∞ = test section dynamic pressure (psf)
L = model length (ft)
T_∞ = test section static temperature (°R)
M_∞ = test section Mach number.

The test section Mach number and desired Reynolds number are known from the aircraft size and flight envelope (reference the development in Volume II). The dynamic pressure required may appear to be freely variable over a wide range, however, it is not. As will be developed in this section, the strength of wind tunnel models and the load carrying capacity of force and moment balances provides an upper limit to the magnitude of the dynamic pressure a given configuration can sustain, independent of its size. Given this value, and knowing the nozzle Mach number, the test section static pressure is then known. For this combination of Mach number and test section static pressure, there is a minimum temperature which describes the onset of condensation of the gaseous constituents of air. Therefore, through isentropic expansion relationships, the minimum stagnation temperature and maximum stagnation pressure are defined.

The only remaining variable is the length of the model. Therefore, since all the other parameters in this equation are based on non-dimensional characteristics of the wind tunnel model, its absolute length must be sufficient to achieve the desired Reynolds number, based on the maximum load carrying capability of the model structure and the force and moment balance. A gasdynamic facility based on this definition is therefore the minimum sized facility which achieves a given Reynolds number without failing either the model or balance.

A complete derivation of the strength limits for wind tunnel models is given in Volume II and is summarized here.

The maximum dynamic pressure based on the spanwise wing bending strength, with 80% of the wing cross section area load carrying is:

$$\frac{q_\infty C_L}{\sigma} = \frac{850 \left[\frac{\frac{t}{c}}{AR}\right]^2}{\left(1 + \frac{C_T}{C_R}\right)^2 \left(1 + 2\frac{C_T}{C_R}\right)} \qquad 6.2\text{-}3$$

$(\frac{t}{c})$ = wing root, thickness to chord ratio

AR = wing aspect ratio

C_T/C_R = wing, tip to root, chord ratio

q_∞ = test section dynamic pressure (psf)

σ = wing material working stress level (psi)

C_L = maximum lift coefficient encountered in conduct of wind tunnel tests.

Inspection of equation 6.2-3 reveals that the absolute size of the wind tunnel model does not affect its load carrying capability; the wing strength is in terms of a non-dimensional grouping of geometric parameters.

The maximum dynamic pressure based on the chordwise bending strength of a delta wing, with a fuselage balance cavity is:

$$\frac{q_\infty C_L}{\sigma} = \frac{120 \left(\frac{h}{L}\right)^2}{AR \left(\frac{L}{b}\right)} \left[1 - 0.545\left(\frac{h}{b}\right)^2\right] \qquad 6.2\text{-}4$$

(applicable to all-body and blended body configurations where (h/L) is approximately equal to the (t/c) of the wing at the fuselage centerline)

h = fuselage height at centerline
L = length of wing, or fuselage
b = wing span
AR = wing aspect ratio.

In order to determine the maximum dynamic pressure that a given configuration can sustain, the working stress levels of the wing material are necessary. For this study, they are:

Conventional Alloy Steels	25,000 to 35,000 psi (17,000 to 24,000 N/cm^2)
Armco 17-4PH, 15-5PH	55,000 psi (38,000 N/cm^2)
Vascomax 300CVM	83,000 psi (57,000 N/cm^2)
1975-1980 Steels	125,000 psi (85,000 N/cm^2)

These represent levels which have safety factors reflecting requirements consistent with general wind tunnel practice, and fatigue limits for a long life model.

The balances used to measure the model forces and moments are also subject to strength limitations. The data presented in Volume II was obtained from various wind tunnel reports and the Task Corporation, for multi-component balances.

These balances are typical of those used in intermittent blow down, and continuous wind tunnels. The natural frequency of the balance is not a dominating feature of these classes of wind tunnels, as the run time is far greater than the period characteristics of the balance natural frequency. This is not true however for impulse tunnels with run times on the order of one second and shorter. To achieve a balance/sting combination whose first bending mode period is less than one tenth the run time, some of the maximum load carrying capability must be sacrificed to minimize elongation and increase stiffness. For GD7 then, the load carrying capability of the balances will be somewhat less than those for GD3 and GD20, in order to maintain high enough natural frequencies in the bending modes.

The maximum dynamic pressure based on balance load carrying capability is:

$$\frac{q_\infty C_L}{C_1} = 66 \left(\frac{h}{b}\right)^2 AR \qquad 6.2\text{-}5$$

h = fuselage height in the area of the balance cavity
b = wing span
AR = wing aspect ratio
C_1 = balance total normal force capability per diameter squared.

From data presented in Reference 6, the balance capability can be summarized as:

	C_1
o present balances, mean level	~ 500 lb/in^2 (345 N/cm^2)
o present balances, maximum capability	890 to 1000 lb/in^2 (613 to 690 N/cm^2)
o projected capability, from Task Corporation	1600 to 1780 lb/in^2 (1100-1230 N/cm^2)

For the evaluations used in this report, 900 lb/in^2 (620 N/cm^2) was used as a reasonable maximum. McDonnell Aircraft has operated present balances at load levels over 1000 lb/in^2 (690 N/cm^2), but useful life of the balances was shortened, compared to previous lower capacity balances.

Equations 6.2-3, 6.2-4, and 6.2-5 are graphically presented in Figure 6-19. The materials and balance limitations, and the symbols for different aircraft configurations plotted on the graphs for reference are given in Figure 6-19a. The spanwise wing bending strength (Equation 6.2-3) is presented in Figure 6-19b.

The chordwise bending strength (Equation 6.2-4) is presented in Figure 6-19c. This equation is valid for the all-body configurations and shows only minor variations in the allowable dynamic pressure level.

The balance capability limitations (Equation 6.2-5) are presented in Figure 6-19d. Although the range of allowable dynamic pressure is about ten to one, it is much smaller than the range for spanwise bending. The largest variation occurs in the all-body configuration primarily because of the variations in (L/b). The allowable dynamic pressure for the all-body configurations is similar in magnitude to that for subsonic transport configurations.

These three criteria are evaluated for the configurations, materials strength, limits and balance capabilities listed in Figure 6-19a, as presented in Figure 6-19e. In general the spanwise bending strength limits the dynamic pressure level for high aspect ratio transports, although an unfavorable combination of a very high strength steel (300CVM) model and a low capability balance would prevent utilizing the full potential of the model. For the lower aspect ratio aircraft however, it is the balance which clearly limits the allowable dynamic pressure. This balance determined dynamic pressure limit is much less than the allowable limit based on model strength.

These limits represent the maximum for each criterion. Many design practices, like two piece wing designs, can substantially reduce the spanwise bending dynamic pressure limit.

FIGURE 6-19a
MODEL STRENGTH AND BALANCE CAPACITY LIMITATIONS

Symbol	Airplane
●	DC 9
■	DC 8
●	DC 10
▲	Elliptical All Body
◗	Elliptical All Body
☗	All Body
◣	All Body
⬟	F-4B
♦	B-52

Material Working Stress Limits for Wind Tunnel Models

Material	(σ) Stress Level
Present Steels	35,000 psi (24,000 N/cm^2)
17-4PH	55,000 psi (38,000 N/cm^2)
300 CVM	83,000 psi (57,000 N/cm^2)
Future (1975-1980)	125,000 psi (85,000 N/cm^2)

TP8257-110

Balance Load Carrying Capability, Normal Force/Diameter^2

Time Period	Load Capacity (C_1)
Present Mean	500 psi ± 10% (340 N/cm^2)
Present Maximum	900 psi ± 10% (610 N/cm^2)
Projected Future Capability (1971-1975)	1690 psi ± 5% (1150 N/cm^2)

FIGURE 6–19b

MAXIMUM DYNAMIC PRESSURE LIMITS BASED ON MODEL STRENGTH AND BALANCE CAPACITY LIMITATIONS

(Wing Bending Strengtn in Spanwise Direction)

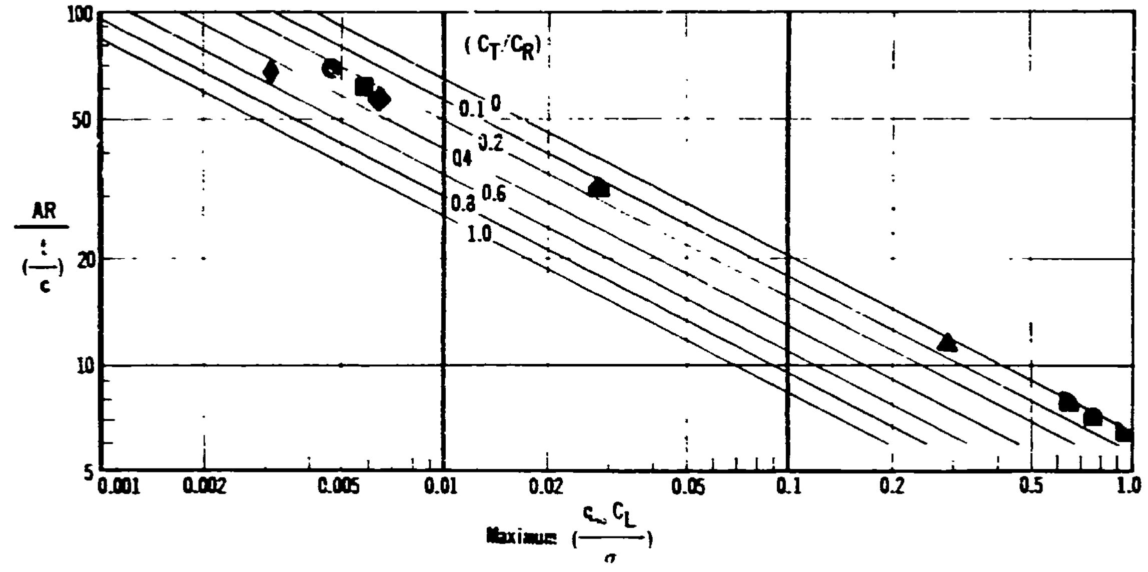


FIGURE 6-19c

MAXIMUM DYNAMIC PRESSURE LIMITS BASED ON MODEL STRENGTH AND BALANCE CAPACITY LIMITATIONS

(Wing Bending Strength, Chordwise Direction)

For Delta Planform

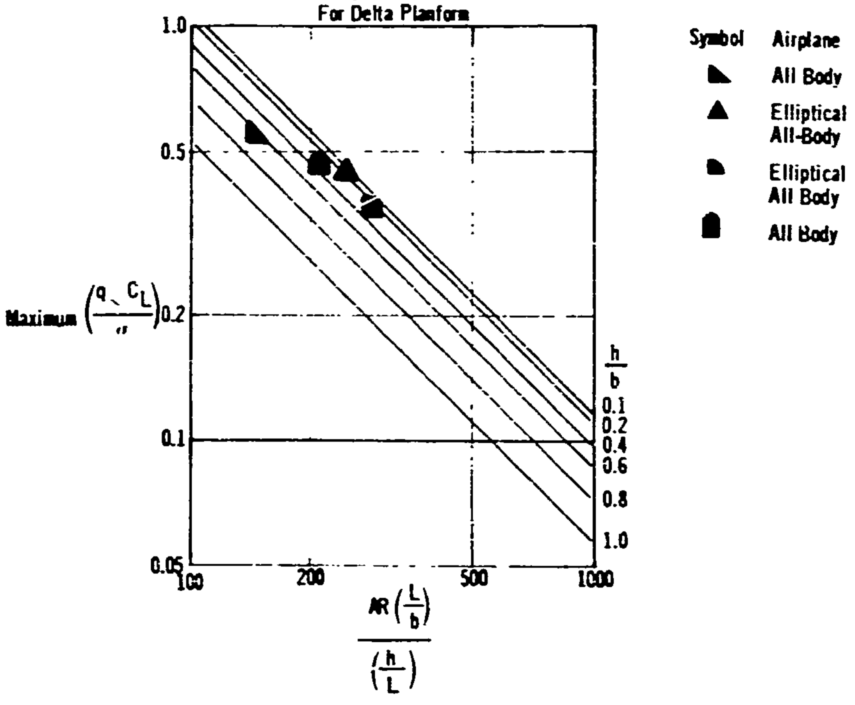


FIGURE 6-19d
MAXIMUM DYNAMIC PRESSURE LIMITS BASED ON MODEL STRENGTH AND BALANCE CAPACITY LIMITATIONS
(Balance Capacity)

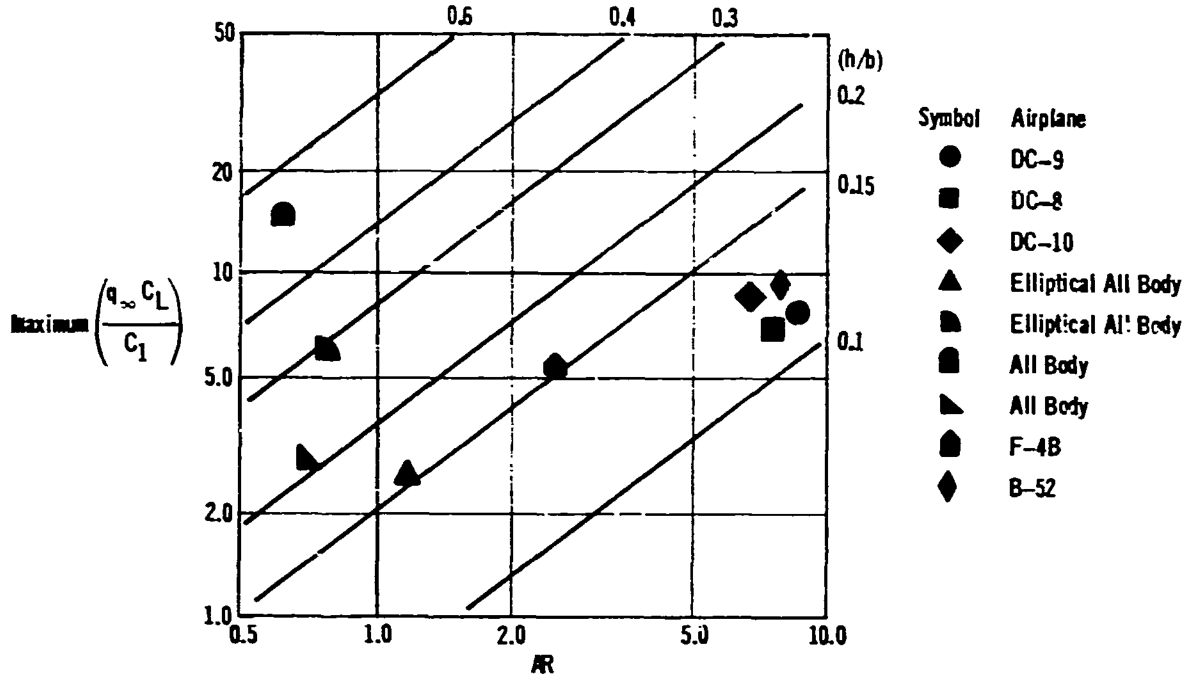


FIGURE 6-19e
MODEL STRENGTH AND BALANCE CAPACITY LIMITATIONS
(Summary)

Aircraft	$q_\infty C_L$ psi Spanwise Bending		$q_\infty C_L$ psi Chordwise Bending		$q_\infty C_L$ psi Balance Limit	
	17-4PH	300 CVM	17-4PH	300 CVM	Present Mean	Present Maximum
F-4B	11,300 (565)	17,700 (850)			[illegible]	[illegible]
DC 10	[illegible]	5,900 [illegible]			4,400 (211)	7,750 (371)
DC 8	[illegible]	4,900 [illegible]			3,000 (143)	5,400 (254)
DC 9	[illegible]	3,900 [illegible]			3,490 (167)	6,260 (300)
Elliptical Allbody		244,000 (11,700)	24,700 (1,180)	37,100 (1,770)	[illegible]	[illegible]
			20 200 (961)	30,700 (1,460)	[illegible]	[illegible]
All Body			25,800 (1,230)	38,500 (1,850)	[illegible]	[illegible]
			30,500 (1,450)	45,900 (2,180)	[illegible]	[illegible]

Shaded values indicate minimum values of dynamic pressure values.
Values for N/cm² in parentheses.

The model dynamic pressure limits can now be expressed in terms of the required wind tunnel size to achieve a given Reynolds number level.

$$\frac{R_e\sqrt{C}}{10^9} = 1.78 \times 10^{-3} \; (q_\infty C_L) \; \frac{\left(1+\frac{202}{T_\infty}\right)}{T_\infty} \; \frac{\sqrt{C}}{M_\infty C_L}$$

(Viscosity term based on Sutherland's equation from NASA Report R50, 1958.)

C = wind tunnel test section cross sectional area (ft^2)

q_∞ = test section dynamic pressure (psf)

T_∞ = test section static temperature (°R)

M_∞ = test section Mach number

C_L = maximum model lift coefficient

R_e = Reynolds number.

This can be translated into the size of the wind tunnel necessary to achieve a given Reynolds number level, assuming

$$L_{MODEL} = \frac{\sqrt{C}}{1.3}$$

as developed in Volume II.

Thus:

$$\sqrt{C} = \frac{731}{(q_\infty C_L)} \left[\frac{T_\infty}{\left(1+\frac{202}{T_\infty}\right)}\right] \left[\frac{R_{e_L}}{10^9}\right] (M_\infty C_L) \qquad 6.2\text{-}7$$

$q_\infty C_L$ from equations 6.2-3, 6.2-4, or 6.2-5.

$\dfrac{T_\infty}{\left(1+\frac{202}{T_\infty}\right)}$ from air condensation consideration. (Figure 6-20b)

R_{e_L}, M_∞ from flight envelope, vehicle size

$C_{L_{MAX}}$ from vehicle configuration, angle of attack. (Figure 6-20a)

Thus, the wind tunnel size to achieve a given Reynolds number is uniquely described by the aircraft flight envelope, size, and configuration, and the physical limitations of the facility hardware and materials.

The dynamic pressure limits given in equations 6.2-3, 6.2-4, and 6.2-5 are based on steady state running loads at the maximum lift coefficient. The starting load for blow-down wind tunnels, with the model in the test section at zero angle

FIGURE 6-20a
MAXIMUM LIFT COEFFICIENTS FOR HIGHLY SWEPT, LOW ASPECT RATIO WINGS AS A FUNCTION OF MACH NUMBER

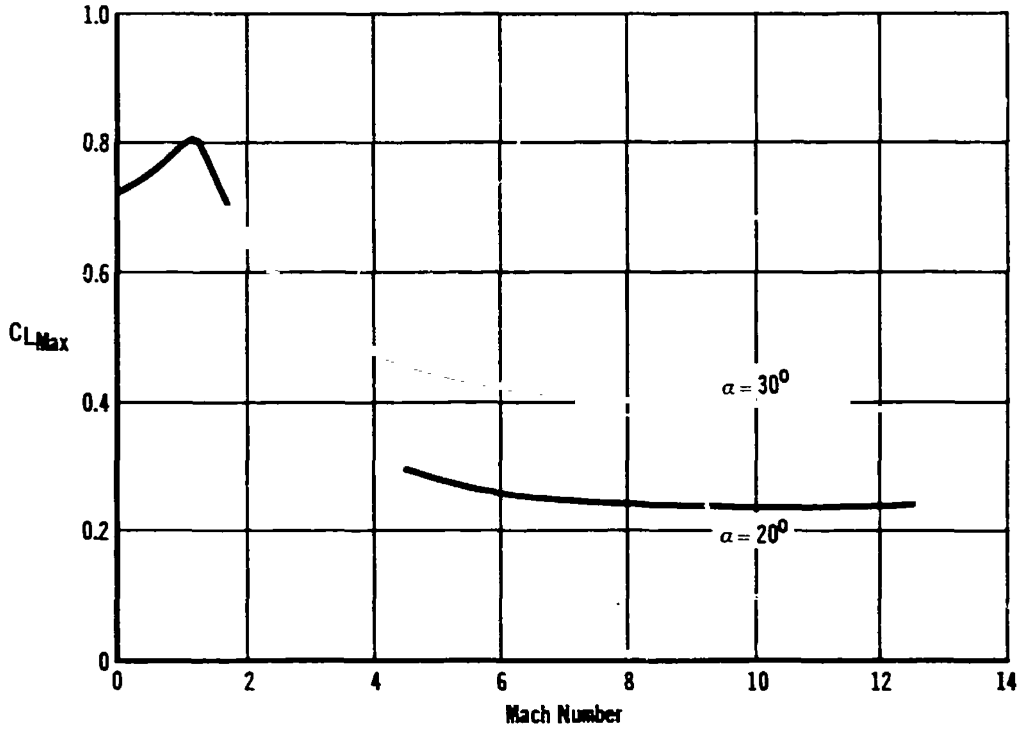
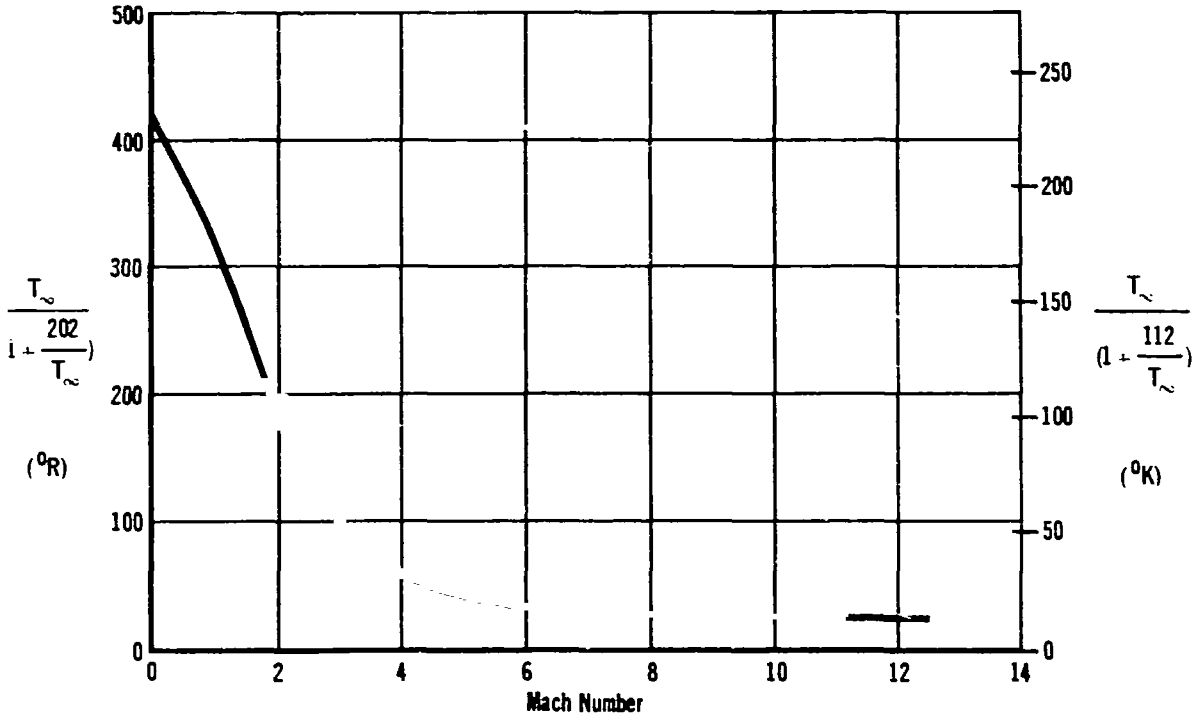


FIGURE 6-20b
TATIC TEMPERATURE FUNCTION FROM REYNOLDS NUMBER EQUATION vs MACH NUMBER



of attack, can exceed the maximum running loads by several times. Based on the McDonnell Aircraft Company Polysonic Wind Tunnel and the Hypersonic Impulse Tunnel testing experience, the starting loads for GD20 and GD7 were estimated, and used in the evaluation of the maximum dynamic pressures allowable. For the model removed from the test section during the starting process, then injected into the test section, the initial loads seldom exceed the maximum running loads. However, current blowdown wind tunnels of the type represented by GD20 do not use model injection schemes, which for the loads involved would require considerable development. The maximum value of the product of $q_\infty C_L\sqrt{C}$, considering allowances for tunnel starting loads, is shown as a function of Mach number for the chosen test Reynolds number of 1/5 of the flight full scale values in Figure 6-21.

In Phase I the facilities were not sufficiently defined to adequately determine the exact temperature limits so that a constant temperature was used for the test section temperature. Although this was not realistic over the entire Mach number range, it did provide a reasonable limit on which to base the test section size. When other criteria concerning the size of the model and test section were evaluated, the original estimate of wind tunnel size was still valid.

In addition to the Reynolds number requirement, there are model size limitations based on model detail. The following ground rules were established:

- desired minimum model scale is 2%
- desired minimum duct diameter for turbomachinery engine duct is 2 inches (5.08 cm) diameter
- desired minimum cowl height for scramjet engines is 1 inch (2.54 cm).

FIGURE 6-21
MAXIMUM VALUE OF $q_\infty C_L\sqrt{C}$ AS A FUNCTION O MACH NUMBER CONSIDERING STARTING LOADS

	M_∞	$\frac{Re_{\sqrt{c}}}{10^9}\frac{1}{5}$	$C_{L_{MAX}}$ (FIGURE 6-19a)	$\frac{q\ START}{q\ RUN}$	C_1 (FROM EQUA. 6.2-5)	$q_\infty C_L\sqrt{C}$ psf -$\sqrt{ft}$
POTENTIAL OPERATIONAL HYPERSONIC AIRCRAFT	.3	.21	.73	1.0	900	10,400
	.6	.32	.75	↑	↑	30,000
	.9	.30	.76			39,600
	1.2	.41	.82			67,900
	1.3	.39	.81			67,200
	1.7	.52	.71			81,300
	2.6	.38	.62	↓		44,000
	2.7	.40	.61	1.0		44,400
	4	.29	.50	.63	↓	29,800
	5	.23	.45	.43	900	26,800
	5	.23	.45	.43	500	48,300
	6	.20	.42	.33	↑	50,500
	6	.18	.42	.33		46,800
	7	.15	.41	.30		45,000
	8	.13	.40	.28		45,000
	9	.11	.40	.26		43,800
	10	.10	.40	.24		47,000
	10	.073	.40	.24		34,300
	11	.066	.39	.22		34,300
	12	.060	.39	.20	↓	35,300
	13	.057	.38	.20	500	35,300
SUBSONIC TRANSPORTS	.3	.21	3.0	1.0	900	41,900
	.6	.32	.92	1.0	900	36,200
	.9	.30	.70	1.0	900	35,400

The turbomachinery duct size was considered a minimum to achieve the proper number of steady state and time variant pressure measurements to describe the compressor or combustor recovery pressure distribution. Preferably, the duct diameter should be larger in diameter for best time variant measurements but this was considered an acceptable minimum. For these criteria, and the potential operational aircraft described in Volume VI, the required model scale and test section size is given in Figure 6-22a. For reference, three of the flight research facilities are presented. The engine designations can be found in Volume V. The details of arriving at these scale factors are given in the accompanying Figure 6-22b. For the scramjet engines, the ratio of the geometric free stream capture area to the cowl area is 5.65.

The minimum test section size required to achieve one-fifth of the maximum Reynolds number required by the potential operational hypersonic aircraft is presented in Figure 6-23, as a function of Mach number. Three values of the dynamic pressure/lift coefficient product are given, representing a nominal range of all-body type configurations (taken from Figure 6-19d). The minimum wind tunnel sizes indicated from the model/balance strength analysis generally are of the same magnitude as those indicated from the engine duct size analysis (Figure 6-22). Although the Phase I analysis was less detailed, the results were consistent with these results. The test section sizes for the gasdynamic facilities will remain the same as that selected in Volume II. That is:

GD3 $\sqrt{C}$ = 16 ft (4.9 m) $0 < M_\infty < 5$

GD15 12 ft (3.6 m) $4.5 < M_\infty < 8.5$

GD7 8.9 ft (2.7 m) $8 < M_\infty < 13$

For comparison the minimum test section size required to achieve one-fifth full scale Reynolds numbers based on length for subsonic transports is shown in Figure 6-23. This represents about twice the magnitude of the Reynolds number stated in Reference 17 as necessary for wind tunnels, when considering very large transports. The criteria stated in Reference 17 for subsonic transports is:

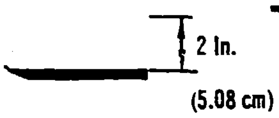
$$R_{e_{\bar{c}}} \geq 10 \times 10^6$$

As shown in Figure 6-23, the requirements for subsonic transports are of the same magnitude as for the potential operational hypersonic aircraft.

The dynamic pressure/lift coefficient products used in Figure 6-23 to determine the minimum sized test section for the potential operational hypersonic aircraft, and for the subsonic transports (3500 psf - 16.5 N/cm^2) generally exceed current practice in wind tunnel testing, although consistent with the strength analyses. Some technique development will probably be required to attain the maximum values determined from the strength analysis in actual operations for this reason.

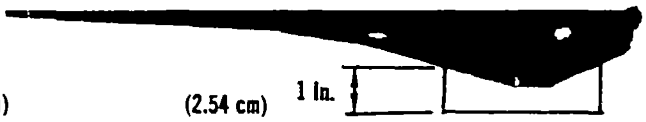
FIGURE 6-22a
MODEL SIZING CRITERIA

Duct Dia.



**Minimum Model Inlet
Duct Size For
Turbojets/Turboramjets/Ramjets**

Cowl Height



**Minimum Model Inlet Size For
Scramjets**

- **Minimum Scale Factor 2%**

Operational Aircraft	Mach Number Range	Engine (See Figure 2-13) Volume V	$\sqrt{C}$ ft (m)	% Scale
L1	0.3 to 6	④	12 (3.6)	3.3
L2	0.3 to 3.5 3.5 to 12	2.5 x ① ⑥	6.1 (1.8) 16 (4.9)	2 4.2
L3	0.3 to 12	Rocket	5.5 (1.7)	2
L4	3.0 to 12	⑧	12.5 (3.8)	5.7
C1	0.3 to 6	④	14 (4.3)	3.3
C2	0.3 to 3.5 3.5 to 10	1.25 x ① ⑧	8.5 (3.5) 13.7 (4.2)	2.7 5.7
M1	0.3 to 4.5	④	4.0 (1.2)	3.3
M2	8 to 12	⑧	11 (3.3)	5.7
M3	8 to 12	⑨	10 (3.0)	7.9
Flight Research Facility				
-207A	0.3 to 7	RJ-207	5.6 (1.7)	6.3
-212A	0.3 to 7	RJ-212	4.4 (1.3)	5.0
-257B	3.5 to 12	⑤	11.0 (3.3)	7.0

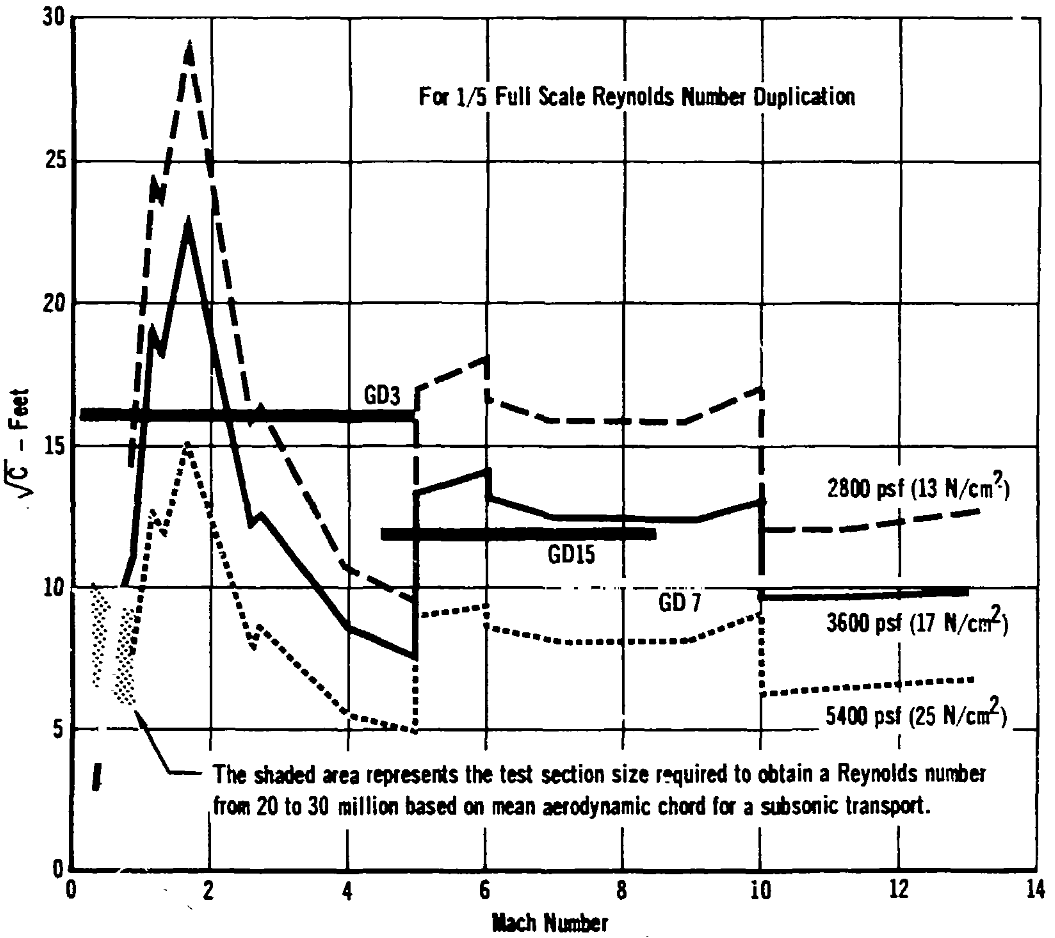
FIGURE 6-22b MODEL SIZING CRITERIA, ENGINE SIZE

For Engine Specific Performance, See Volume V

Engine As Given Figure 2-13, Volume V	Duct Diameter in (m)	% Scale for 2 Inch (5.08 cm) Model Duct Size
Turbojet (1)	79 (2)	2.5%
Turbojet (2)	47 (1.2)	4.3%
Turboramjet (3)	71 (1.8)	2.8%
Turboramjet (4)	60 (1.8)	3.3%
Turbofan (5)	96 (2.4)	2.1%

	Free Stream Capture Area ft^2 (m^2)	Number of Modules	Module Size at Cowl ft (m)	% Scale for 1 Inch (2.54 cm) Model Cowl Height
Acceleration Convertible Scramjet	80 (8.3)	3	1.25 x 3.76 (.382 x 1.15)	6.75
Acceleration Convertible Scramjet (6)	480 (43.5)	7	1.54 x 3.96 (.60 x 1.23)	5.4
Acceleration Scramjet (8)	270 (25.0	5	1.15 x 4.14 (.94 x 1.21)	7.2
Cruise Scramjet (9) and (10)	140 (13.0)	4	.829 x 3.72 (.506 x 1.13)	10.0
Ramjet Engine from Flight Research Vehicle - 207A	16 (1.5)	1	1.33 x 6.9 (.41 x 2.1)	6.3
-212A	21 (1.9)	1	1.66 x 7.2	5.0
Ramjet Engine (7)	15 (1.4)	1	1.5 x 5 (.46 x 1.65)	5.5

FIGURE 6-23
GAS DYNAMIC FACILITY SIZE REQUIREMENTS BASED ON MODEL/BALANCE STRENGTH



6.2.3 TEMPERATURE CONTROL REQUIREMENTS - In the operation of a continuous or intermittent wind tunnel, the pressure and temperature must be maintained within certain limits if the Reynolds number is to be maintained relatively constant in the test section. For slender hypersonic configurations the skin friction dominates the total drag, and a 10% Reynolds number variation could mean up to a 5% variation in the drag (for those portions of the models in laminar flow). Any variations greater than this would mean each drag point would have to be corrected, to reflect its value at the nominal Reynolds number. It was decided to place a maximum value of 10% total variation in the Reynolds number during a run. If the control uncertainties associated with the Mach number control (nozzle contour position accuracy) and the pressure control are considered relatively constant, then that portion of the total error attributed to temperature control is about 7%.

The expression for Reynolds number is:

$$R_e = \frac{\rho_\infty V_\infty L}{\mu_\infty} = \frac{\rho_\infty M_\infty a_\infty L}{\mu_\infty} = \frac{P_\infty M_\infty}{\mu_\infty}\sqrt{\frac{\gamma}{RT_\infty}}\; L$$

When pressure and Mach number are held constant, the temperature ratio in terms of an allowable Reynolds number ratio is:

$$\frac{T_{\infty 2}}{T_{\infty 1}} = \left(\frac{\mu_1}{\mu_2}\right)^2 \left(\frac{R_{e_1}}{R_{e_2}}\right)^2 \qquad 6.2\text{-}7$$

Substitution of a suitable viscosity law allows solution of equation 6.2-7 for the temperature ratio which will produce a certain Reynolds number ratio. One such viscosity law is the power law,

$$\frac{\mu_1}{\mu_2} = \left(\frac{T_{\infty 1}}{T_{\infty 2}}\right)^{.76}$$

Using this relationship, equation 6.2-7 becomes

$$\frac{T_{\infty 2}}{T_{\infty 1}} = \left(\frac{R_{e_2}}{R_{e_1}}\right)^{-.79} \qquad 6.2\text{-}8$$

A more accurate viscosity relationship is Sutherland's equation,

$$\frac{\mu_1}{\mu_2} = \left(\frac{T_{\infty 2} + 198.6}{T_{\infty 1} + 198.6}\right)\left(\frac{T_1}{T_2}\right)^{3/2}$$

Using Sutherland's law for viscosity, equation 6.2-7 becomes

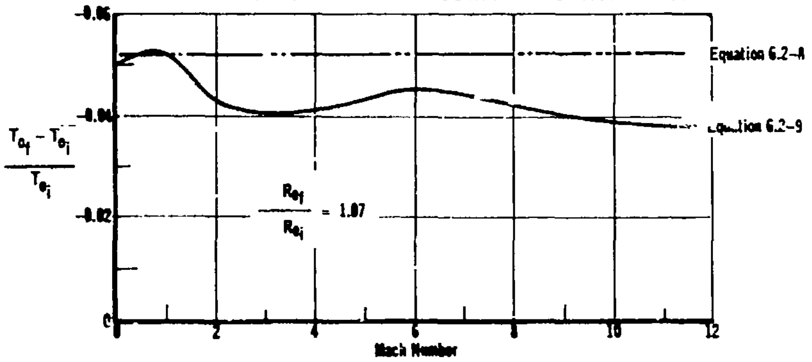
$$\frac{T_{\infty 2}}{T_{\infty 1}} = \left[-\frac{T_{\infty 1}}{397} + \sqrt{\left(\frac{T_{\infty 1}}{397}\right)^2 + \frac{R_{e_2}}{R_{e_1}}\left(\frac{T_{\infty 1}}{198.6}\right)\left(1 + \frac{198.6}{T_{\infty 1}}\right)}\,\right]^{-1} \qquad 6.2\text{-}9$$

Solution of either equation 6.2-8 or 6.2-9 for a desired maximum Reynolds number change during a facility run of 7% gives the allowable temperature change during a run. By equation 6.2-8, the per cent temperature change is constant with Mach number and is ± 5.2%. Since the initial static temperature is one of the variables in equation 6.2-9, assumed values of initial stagnation temperature must be used and the initial static temperature then calculated. Assumed values and results are shown below.

M_∞	To		$\frac{\Delta To}{To_i}$	ΔT	
	(°R)	(°K)		(°R)	(°K)
0	560	(311)	.0503	± 28	(15.5)
1	560	(311)	.0526	± 29	(16.1)
2	560	(311)	.0423	± 24	(13.3)
4	600	(333)	.0416	± 25	(13.9)
6	830	(461)	.0457	± 38	(21.1)
8	1300	(722)	.0423	± 55	(30.5)
10	1900	(1055)	.0484	± 73	(40.5)
12	2500	(1390)	.0392	± 98	(54.5)

The permissible stagnation temperature change for a maximum Reynolds number change of 7% is shown in Figure 6-24, plotted versus Mach number. Near Mach number 1 the approximate equation agrees well with the more exact equation, but at higher Mach number it overestimates the allowable temperature deviation. These results can then be used to determine heater requirements, storage volumes, and wind tunnel size necessary for a desired degree of Reynolds number simulation in other sections of this report. In general, for the limits set for this report, about a ± 4% variation in stagnation temperature would be the maximum permissible to maintain Reynolds number control.

FIGURE 6-24
TEMPERATURE VARIATIONS PERMISSIBLE BASED ON A DESIRED REYNOLDS NUMBER VARIATION



6.2.4 PNEUMATIC LOSSES - In order to establish compressor pressure requirements and the size of supply pipes for the flow facilities, estimates of system pressure drops were required.

o Stilling Chamber Pressure Drop - An idealized geometric concept was chosen to represent the stilling chamber design for all the flow facilities, and the pressure drop characteristics of this concept were calculated as a function of pipe-to-stilling chamber area ratio and inlet Mach number. A sketch of the assumed geometry is shown in Figure 6-25 and the results of the calculations are shown in Figure 6-26. Figure 6-25 defines the geometry and stations used in all the analyses of the air supply systems discussed in Section 6.2.

The method of calculating the pressure drops of each component was based on the loss coefficient or K-factor, wherein the pressure drop through a flow passage is expressed as a function of the entering dynamic pressure, such as:

$$\Delta P_{T_{1,2}} = K q_1 \qquad 6.2\text{-}10$$

Physical descriptions of the stilling chamber components and their loss coefficients follow.

Diffuser: A 90° included angle cone. K = 1.03

Flow Disperser: A 120° included angle, 40% porous cone. (Porosity chosen to keep the Mach number through the holes < .3), K = 3.0

Two Turbulence Screens: Porosity = .5, K = 1.6 (each)

Heater or Honeycomb: K = 1.0

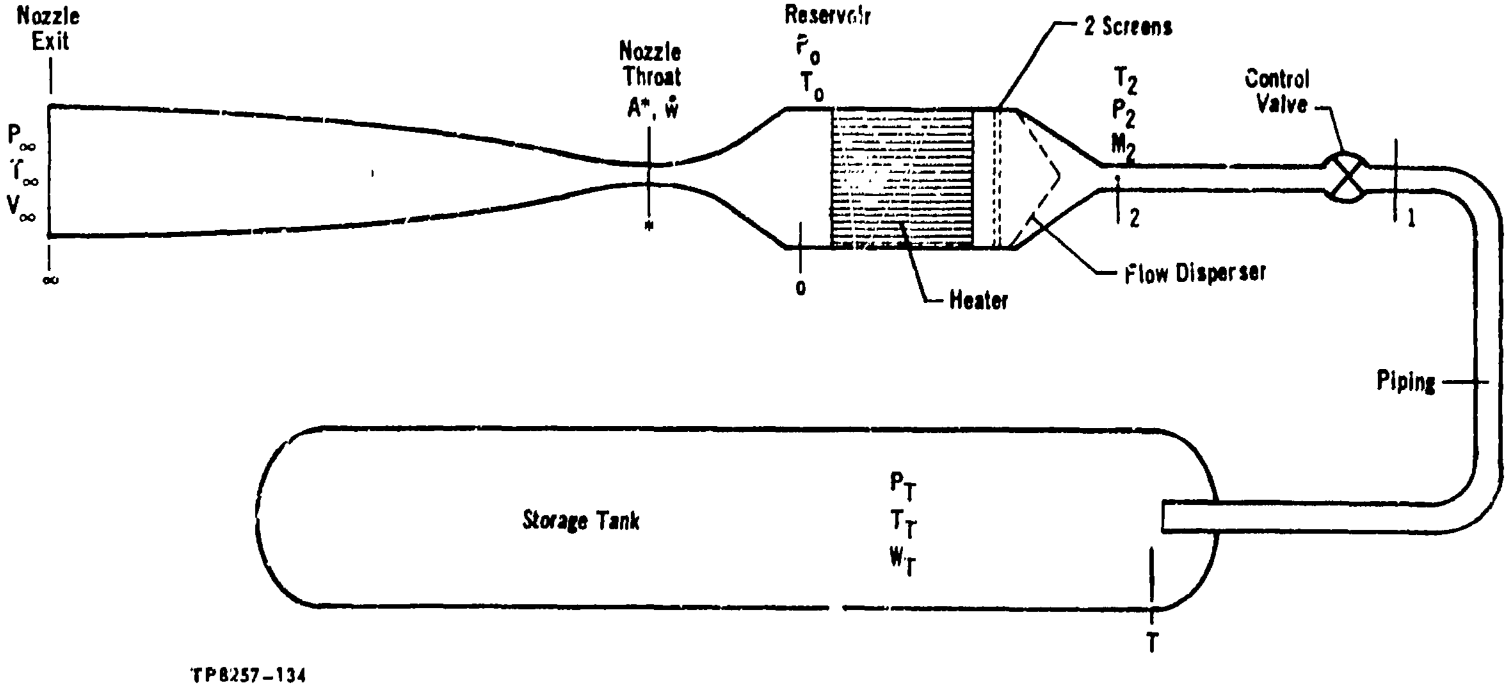
(K values obtained from Crane Technical Bulletin No. 410 and data provided by J. A. Gunn, E. M. Kraft, and M. W. Poole of ARO, Inc.).

Pressure drop calculations for each of the flow facility stilling chambers were performed using the data from Figure 6-26, for the specific ratio chosen for each facility.

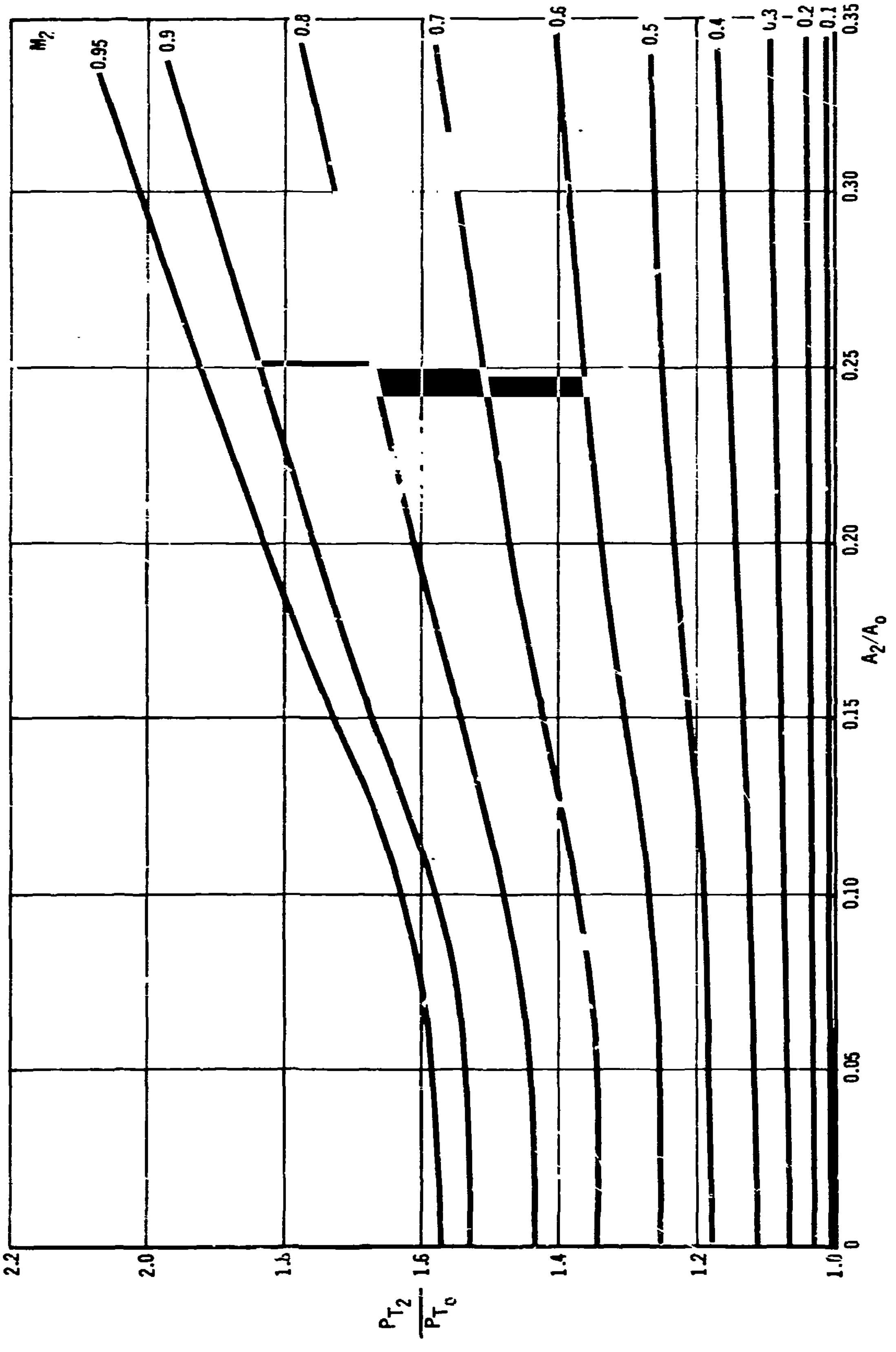
o Supply Pipe Frictional Losses - The frictional pressure drop from storage tanks or compressor to the stilling chamber was calculated by assuming adiabatic flow with friction (Fanno flow). An equivalent frictional length of 1000 ft (305 m) was assumed for all facilities to account for the actual length and for the various elbows, tees, etc., which would be present in the real pipeline. The pipe diameter was assumed constant and was sized to give an exit Mach number (M_2) = 0.7 at the maximum $\dot{w}/P_o$ flow condition.

Having decided upon the dimensions of the stilling chamber and supply pipe, pressure drop calculations were made for a number of flow conditions which established the minimum upstream conditions required at the storage tank or compressor outlet. In actual practice throttling valves will be used when convenient to match the facility requirements with the compressor characteristics.

FIGURE 6-25
WIND TUNNEL SCHEMATIC LAYOUT FOR DETERMINING STORAGE VOLUME, TEMPERATURE CONTROL, AND COMPRESSOR PLANT REQUIREMENTS



PRESSURE DROP IN STILLING CHAMBER AS A FUNCTION OF SUPPLY PIPE/CHAMBER AREA RATIO AND INLET MACH NUMBER



6.2.5 AIR DISTRIBUTION SYSTEM - In establishing the supply pipe sizes for the blowdown facilities GD3 and GD20, the procedure described in 6.2.4 was followed with the exception that the blowdown pipe size was established assuming choked conditions at the maximum $\dot{w}/P_0$ flow condition at the pipe exit. In theory, one pipe could be specified which would carry the facility weight flow. Three constraints operate in actuality to prevent using this simple one-pipe system.

o Stress Considerations - The assumption has been made, based on information from Nooter Corp., St. Louis (a structural steel fabrication firm specializing in large rolled and seam welded cylinders, tanks, etc.) that the fabrication limit of cold rolled 1020 type steel is about 4 inches (10.1 cm) thick. This limitation, used in conjunction with the ASME formula for unfired pressure vessels,

$$t = \frac{pr}{\sigma E - 0.6p} \qquad 6.2\text{-}11$$

where: t = material thickness in inches
p = internal pressure in psi
σ = allowable stress in psi (17,500 psi) (12,100 N/cm^2)
r = internal radius
E = efficiency.

Or the simpler hoop stress equation,

$$t = \frac{pr}{\sigma} \qquad 6.2\text{-}12$$

results in a basic limitation in structure diameter as a function of internal pressure. This limitation is shown graphically in Figure 6-27, and applies to all pipe systems. Certain special structures, such as very high pressure air storage tanks or stilling chambers, will be built using high strength steels or lamination techniques, and will not adhere to this limitation. The square symbols on this figure show that choosing a single supply pipe for the baseline and both alternate hypersonic legs of GD20 and for alternate 2 of GD3 would result in higher than permissible stresses. The round symbols show the result of choosing multiple pipes. Ten pipes are used for each case except alternate 2 of the GD20 hypersonic leg, which uses 32 pipes.

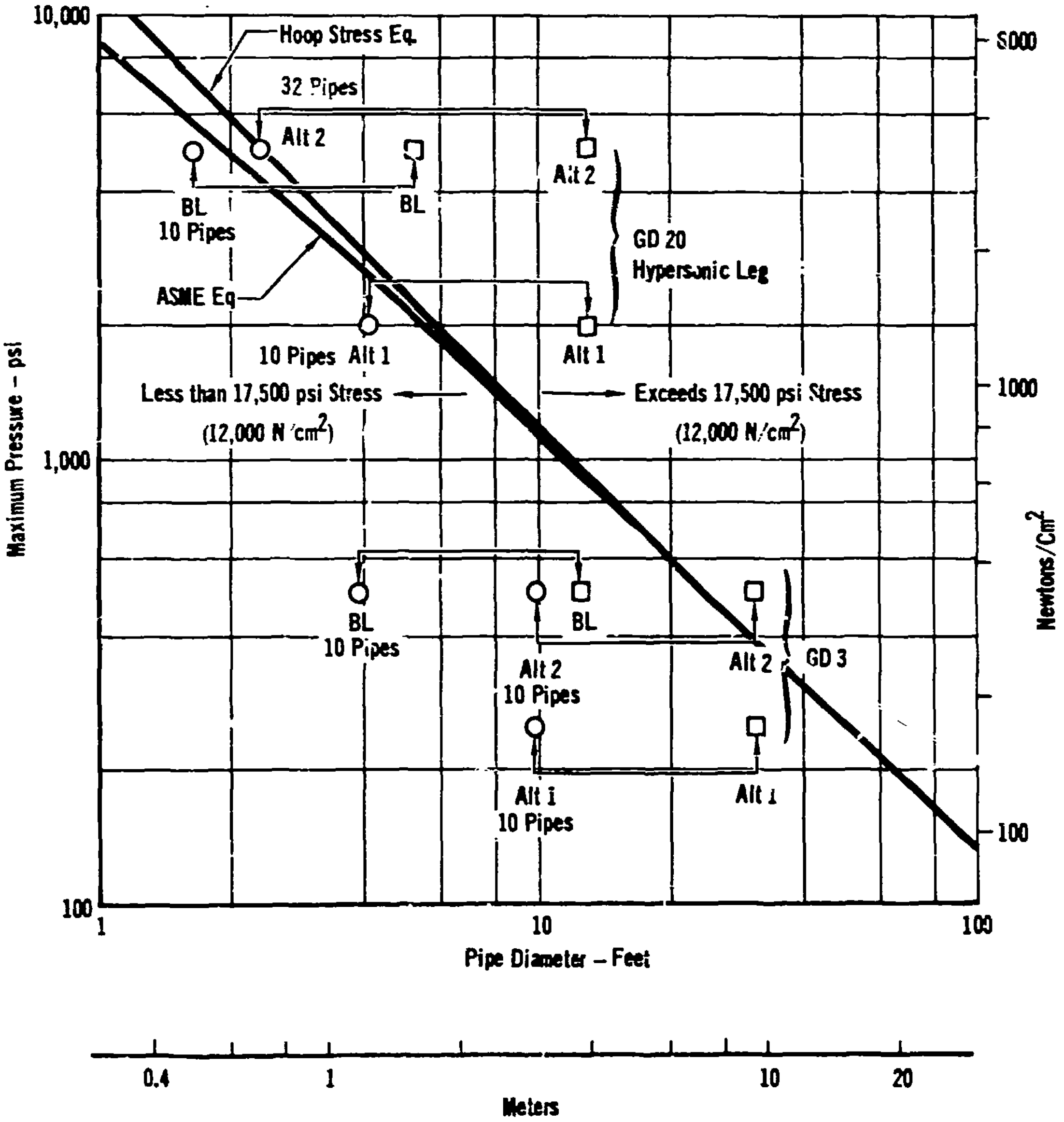
o Valve Design - The isolation valves on the upstream end of the supply line and the throttling valves on the downstream end must not only withstand the maximum tank storage pressure, but must seal tightly against it. The working pressure and diameter of the single pipe arrangements are so far beyond the state-of-the-art that no valve manufacturer was willing to discuss their design or manufacture. GD3, alternate 2, needs 500 psi (345 N/cm^2) working pressure and a 31 ft (9.5 m) diameter valve. Even the expedient of going to 10 pipes produces very stringent valve requirements, and higher numbers of pipes may be needed, if valves within current projected capability are considered.

Valves were sized for the maximum mass flow case, with the control valve assumed to be fully open. Under these conditions, the valve flow was assumed to be choked, and the pressure drop negligible (nearly true for a ball or sleeve type valve). The required valve area is then (reference Figure 6-25 for station nomenclature).

FIGURE 6-27
PIPE MAXIMUM PRESSURE AS A FUNCTION OF DIAMETER, ASSUMING MAXIMUM WALL THICKNESS OF 4 INCHES (10 cm)

□ Shows facility blowdown line pressures and diameters for a single pipe.

○ Shows facility blowdown line pressures and diameters for the multiple pipes chosen.



$$A_{valve} = \frac{\dot{w}_{max}\, Z\sqrt{T_2}}{124\, n_v\, P_2} \qquad (ft^2) \qquad 6.2\text{-}13$$

$\dot{w}_{max}$ = maximum mass flow (lbm/sec)

T_2 = supply temperature, upstream of heater at $\dot{w}_{max}$ conditions (°R)

P_2 = supply pressure, upstream of flow diverter at $\dot{w}_{max}$ conditions (psia)

Z = compressibility factor

n_v = number of valves.

o Flow Control Rangeability - The blowdown test facilities have minimum weight flows less than one tenth the maximum mass flow rate. A single large valve throttling to very small flows is subject to control system "hunting", severe flow separations with attendant noise and flow quality problems, and accelerated wear on valve trim. Provision of a number of smaller valves alleviates all these problems, since in the case of the minimum flow rate, 8 or 9 valves can be completely closed and one or two valves can be operating nearly open, in their most effective control range. For a practical limit to maintain flow quality and minimize turbulence level in the test section, a mass flow range for a single valve of eight to one should be considered a maximum.

Any one of the previous three criteria listed can necessitate a multiple valve/piping system. It is not necessary to establish exactly how many are required for the Phase II analysis, but only that they will be required and the governing factors have been identified. With fewer facilities to study in Phase III, and more specific requirements, a more definitive limit can probably be obtained from the valve manufacturers. Considering the magnitude of the size and performance increment of the study facilities, the valve certainly should not be a high risk item in attaining the overall performance, and therefore, will be based on present or limited projections of current technology, requiring minimum development. A review of the factors associated with valve rangeability and control can be found in References (1) through (4).

Multiple valves and supply pipes require the recombining of several individual flows into the single flow stream entering the facility flow generating nozzle. The mixing of several, sometimes asymmetrical inlet flows, into a single uniform stream is not without problems and localized flow nonuniformities can easily be present over some portions of the entire operational envelope. A subscale development program such as conducted by the Arnold Engineering Development Center (AEDC) for the APTU facility to determine mixer techniques and geometry can minimize the problems encountered in bringing a major facility to full operational capability. For all of the gasdynamic facilities, it should be assumed that a subscale mixer de[illegible] program would be desirable to confirm satisfactory performance over the [illegible] of facility mass flows.

[illegible] REQUIREMENTS - These requirements are most pertinent to the blow- [illegible] operate completely on stored air; but the principles apply [illegible] in general. There are theoretically almost infinite combina- [illegible] and pressures that are possible, however, in practice practical limits can be imposed on the definition to restrict the number of possible combinations. The reason that air storage requirements need more attention is that in the process of supplying air to the facility, the pressure as well as the temperature of the supply gas fall as mass is removed from the fixed volume storage. The minimum usable supply pressure is related to the pressure ratio across the nozzle/diffuser system required to maintain flow. The allowable change in supply temperature is related to the allowable variation of Reynolds number in the test section. The maximum initial pressure in the storage tanks is a function of the volume of the storage system, and the total mass removed from the tanks during a run. These interrelated effects can be evaluated if the mass removed from the tanks, the minimum pressure required to maintain flow in the test section, and the permissible temperature drop in the tank temperature are specified. The first two factors are a function of the Mach number/Reynolds number point desired for a given size facility. The third is a function of the permissible Reynolds number variation that occurs during the run (as defined in 6.2.3). The purpose of the air storage system is then not simply to store air, and its specification is not arbitrary.

The storage requirements were evaluated for the maximum mass flow case, with the control valve fully open at the end of the specified run, and the tank pressure at that point equal to the desired reservoir pressure plus the line losses as given in Figure 6-26.

The mass flow through the wind tunnel nozzle throat is:

$$\dot{w} = 76.9 \frac{Po}{\sqrt{T_o}} A^* \qquad \text{(lbm/sec)} \qquad 6.2\text{-}14$$

Po = reservoir pressure (psia)
T_o = reservoir temperature (°R)
A^* = throat area (ft^2)

The mass of gas stored in the tank is

$$w = 2.7 \frac{P_T V}{T_T} \qquad \text{(lbm)} \qquad 6.2\text{-}15$$

P_T = tank pressure (psia)
T_T = tank temperature (°R)
V = tank volume (ft^3)

The mass of gas in the tank in terms of the initial conditions and those at some later time are:

$$w = 2.7\ (B)\ (T_T)^{\frac{1}{n-1}}\ V = 2.7\ (B)^{\frac{n-1}{n}}\ (P_T)^{\frac{1}{n}}\ V \qquad 6.2\text{-}16$$

$$B = \frac{P_{T_i}}{(T_{T_i})^{\frac{n}{n-1}}}$$

Terms are as described for Equation 6.2-15 with the addition:

n = polytropic constant describing the frictionless, non-adiabatic expansion of the gas in the tanks, where $n < \gamma$ for an expansion with heat added (from tank walls).

$_i$ = conditions corresponding to initial conditions prior to a blowdown.

The mass flow from the tanks is then described from differentiating Equation 6.2-16 with respect to time, by:

$$\dot{w} = V\frac{d\rho}{dt} = \frac{2.7\ B\ V}{(n-1)}\ (T_T)^{\frac{2-n}{n-1}}\left(\frac{dT_T}{dt}\right) \qquad 6.2\text{-}17$$

Since the mass flow out of the tank equals the mass flow through the nozzle, then:

$$76.9\ \frac{P_o}{\sqrt{T_o}}\ A^*\ dt = 2.7\ \frac{B\ V}{(n-1)}\ (T_T)^{\frac{2-n}{n-1}}\ dT_T = \dot{w} \qquad 6.2\text{-}18$$

Three possible solutions were studied which depended on the physical arrangement of the facility elements given in Figure 6-25. These three cases were as follows:

Case I, Constant Nozzle Mass Flow - A heater is provided in the reservoir so that T_o is a constant for the duration of the run. It is assumed that valve control is maintained so that P_o is constant. That is:

$$P_{T_{final}} > P_o + \text{Losses}$$

The tank volume specified by integrating Equation 6.2-18 for the following conditions

$$T_C = \text{Constant} \neq f(T_T)$$

$$P_o = \text{Constant} \neq f(P_T)$$

is:

$$V = 28.5\left(\frac{P_o}{P_{T_i}}\right)\left(\frac{T_{T_i}}{\sqrt{T_o}}\right)\frac{A^*\ t_{run}}{\left(1-(1-\frac{\Delta T}{T_{T_i}})^{\frac{1}{n-1}}\right)}\quad (\text{ft}^3) \qquad 6.2\text{-}19$$

The parameters are the same as described for Equations 6.2-14 and 6.2-15, with the addition

t_{run} = facility run time (sec)

ΔT = permissible tank temperature drop (°R)

Using the relationship:

$$\frac{\Delta T}{T_{T_i}} = 1-\left(\frac{P_f}{P_i}\right)^{\frac{n-1}{n}} \qquad 6.2\text{-}20$$

the denominator of Equation 6.1-10 can be expressed as:

$$1-\left(1-\frac{\Delta T}{T_{T_i}}\right)^{\frac{1}{n-1}} = 1-\left(\frac{P_f}{P_i}\right)^{\frac{1}{n}} \qquad 6.2\text{-}21$$

For this case, the value of n is less than gamma, and is a function of the final to initial tank pressure ratio: as given below from High Speed Wind Tunnel Testing, by Pope and Goin:

P_f/P_i	.4	.5	.6	.7	.8	.9
n	1.170	1.130	1.100	1.072	1.048	1.022
$\Delta T/T_{T_i}$	.1246	.0766	.0454	.0237	.0105	.0023

Case II, Variable Nozzle Mass Flow - No heater is provided in the reservoir or tank so that T_o is a function of T_T. It is assumed valve control is maintained so P_o is constant, that is:

$$P_{T_f} > P_o + \text{Losses}$$

The tank volume specified by integrating Equation 6.2-18 for the following conditions:

$$T_o \; \alpha \; T_T$$

$$P_o = \text{Constant} \neq f(P_T)$$

is:

$$V = 28.5 \left(\frac{n+1}{2}\right) \left(\frac{P_o}{P_{T_i}}\right) \frac{T_{T_i}}{\sqrt{kT_{T_i}}} \; \frac{A^* \, t_{run}}{\left[1-\left(1-\frac{\Delta T}{T_{T_i}}\right)^{\frac{n+1}{2(n-1)}}\right]} \qquad 6.2\text{-}22$$

This rationale assumes that the reservoir temperature (T_o) is essentially equal to the storage tank temperature (T_T) except for minor thermal changes caused by flowing through the piping to the reservoir. Thus:

$$T_o = kT_T$$

where k is a correction constant for thermal heat additions or loss.

The parameters are the same as for Equation 6.2-19. The denominator of Equation 6.2-22 can be expressed as:

$$1-\left(1-\frac{\Delta T}{T_{T_i}}\right)^{\frac{n+1}{2(n-1)}} = 1-\left(\frac{P_f}{P_o}\right)^{\frac{n+1}{2n}} \qquad 6.2\text{-}23$$

For this case, the value of n is the same as for Case I.

Case III, Variable Nozzle Mass Flow - A thermal matrix is provided in the storage tank to make the expansion process more isothermal, T_o is a function of T_T. It is assumed valve control is maintained so that P_o is constant, that is:

$$P_{T_f} > P_o + \text{Losses}$$

The tank volume specified by integrating Equation 6.1-9 for the following conditions:

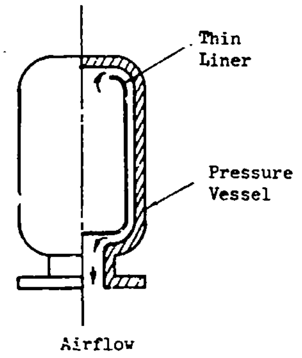
$$T_o = kT_T$$

$$P_o = \text{Constant} \neq P_T$$

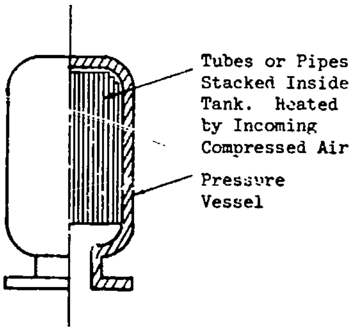
is the same as for Case II. However, because of the thermal matrix, n is a different function of the final to initial tank pressure ratios as given below, as estimated from Pope and Goin:

P_f/P_i	.3	.4	.5	.6
n	1.051	1.041	1.032	1.023
$\Delta T/T_{T_i}$	.0567	.0354	.0213	.0114

The exact geometry of the matrix heater need not be determined for this simplified analysis, but it could represent a number of concepts as sketched below:



Liner forces outgoing air to flow adjacent to tank wall, producing a more constant exit temperature
(Vessel wall as thermal matrix)



Tubes add large surface area for heat transfer and thermal storage to control temperature drops
(Pipes or tubes added as thermal matrix to pressure vessel)

Again the rationale is the same as for the storage tank with no thermal matrix. The reservoir gas temperature will be almost equal to the tank temperature, except for minor fluctuations. The rate of change of tank temperature with change in tank pressure has been reduced by the selection of a value of the polytropic constant closer to unity.

These three solutions can be expressed in terms of the initial stored mass in the tank compared to the mass removed during a run. These are:

Case I

$$\frac{\dot{w}\, t_{run}}{w_i} = 1-\left(1-\frac{\Delta T}{T_{T_i}}\right)^{\frac{1}{n-1}} \qquad 6.2\text{-}24$$

Using the temperature limits derived in Section 6.2.3, then:

$\frac{P_f}{P_i} \simeq 0.475$ $\Delta T = 50°R\ (27.8°K)$

$n \simeq 1.145$ $T_{T_i} = 530°R\ (294°K)$

$\frac{\Delta T}{T_{T_i}} = 0.094$

then:

$$\boxed{w_i = 1.994\, \dot{w}\, t_{run}} \quad (\text{lbm}) \qquad 6.2\text{-}25$$

Case II

$$\frac{\dot{w}\, t_{run}}{w_i} = 1-\left(1-\frac{\Delta T}{T_{T_i}}\right)^{\frac{n+1}{2(n-1)}} \qquad 6.2\text{-}26$$

Using the temperature limits derived in Section 6.2.3, then:

$\frac{P_f}{P_i} \simeq 0.60$

$n \simeq 1.10$

$\frac{\Delta T}{T_{T_i}} = 0.042$

Then:

$$\boxed{w_i = 2.626\, \dot{w}_i\, t_{run}} \quad (\text{lb}) \qquad 6.2\text{-}27$$

Case III

$$\frac{\dot{w}_i \, t_{run}}{w_i} = 1-\left(1-\frac{\Delta T}{T_{T_i}}\right)^{\frac{n+1}{2(n-1)}}$$

Using the temperature limits derived in Section 6.2.3, then:

$$\frac{P_f}{P_i} \doteq 0.35$$

$$n \doteq 1.046$$

$$\frac{\Delta T}{T_{T_i}} = 0.042$$

then:

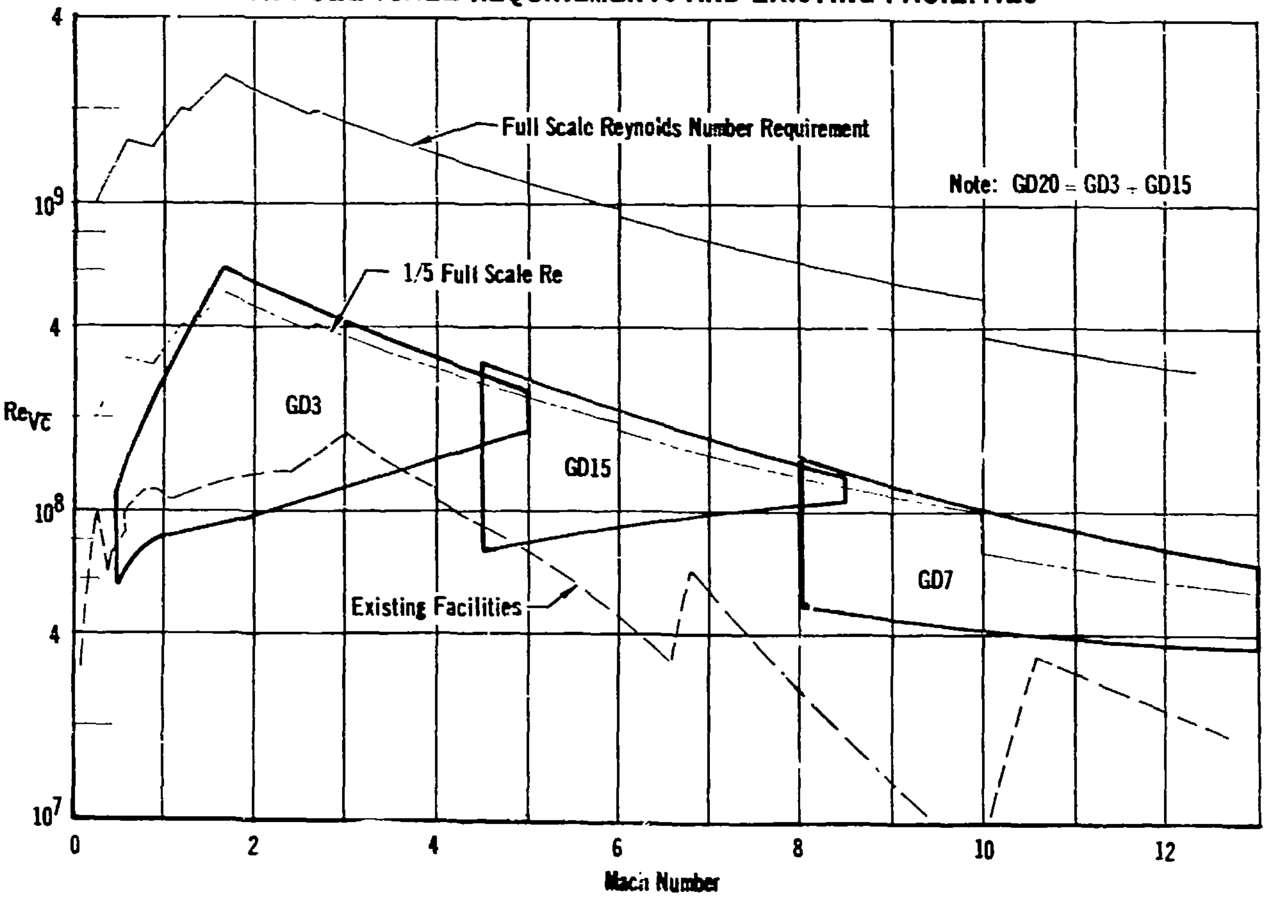
$$\boxed{w_i = 1.599 \, \dot{w}_i \, t_{run}} \qquad 6.2\text{-}28$$

For each case, there is a unique solution of storage volume and pressure. Each particular application of a storage system must be analyzed to determine which provides the most practical system costs to achieve the desired performance. For stagnation temperatures which are too high, the concept of a thermal matrix in the storage tank incurs an unacceptable cost increment, because the pressure vessel becomes a hot walled structure. In that case the reservoir heater becomes the most attractive alternate. Even though the storage volume is larger, the lower storage pressure required for Case II (no heater) make this alternate feasible for some low pressure applications.

6.2.7 GAS DYNAMIC PARAMETRIC VARIATIONS - The parametric variations possible with the gas dynamic facilities, at the level of detail consistent with Phase II, is rather limited. The entire test leg contour, which generates the desired conditions in the test section, is a function only of the Mach number to be generated. Variations in construction or actuation require a level of detail exceeding the specification possible in Phase II, considering the number of facilities under study. Attempting any but general evaluation of the peripheral equipment such as compressors, exhausters, and cooling requirements again cannot be accomplished (in any degree of detail) in the time allocated for Phase II.

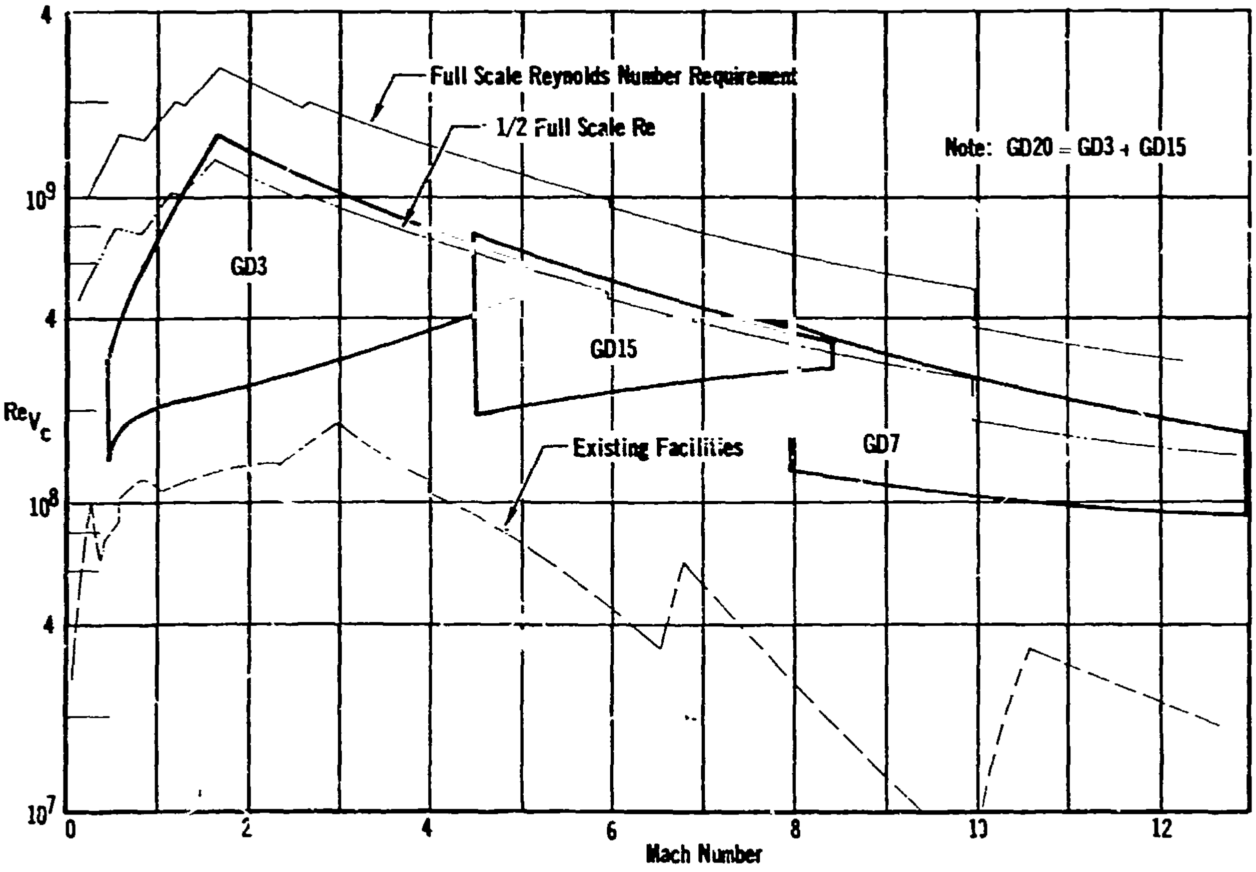
Using Figure 6-16 as a reference, the capabilities of the minimum sized one-fifth maximum full scale Reynolds number simulation facilities are shown in Figure 6-28. These are the baseline facilities for Phase III. The first alternate chosen was to retain the same performance level, but increasing the test section size by 2.5 times, and decreasing the baseline reservoir pressure to 40% of its value for the baseline facilities. This provides a measure of absolute size on research capability and cost.

FIGURE 6-28
COMPARISON OF BASELINE GAS DYNAMIC FACILITIES
WITH FULL SCALE REQUIREMENTS AND EXISTING FACILITIES



Alternate 2 was chosen to evaluate minimum sized one-half full scale Reynolds number simulation facilities, as shown in Figure 6-29. These operate at exactly the same reservoir conditions as the baseline facilities, but are 2.5 times larger and have 2.5 times the Reynolds number capability of the baseline facilities. The factors affected most by these parametric variations are the costs of equipment which is required to make the test section operate. In this area, the degree of detail and variations possible preclude sophisticated evaluation until Phase III reduces the number of facility variations to a manageable number.

FIGURE 6-29
COMPARISON OF ALTERNATE 2 GAS DYNAMIC FACILITIES WITH FULL SCALE REQUIREMENTS AND EXISTING FACILITIES



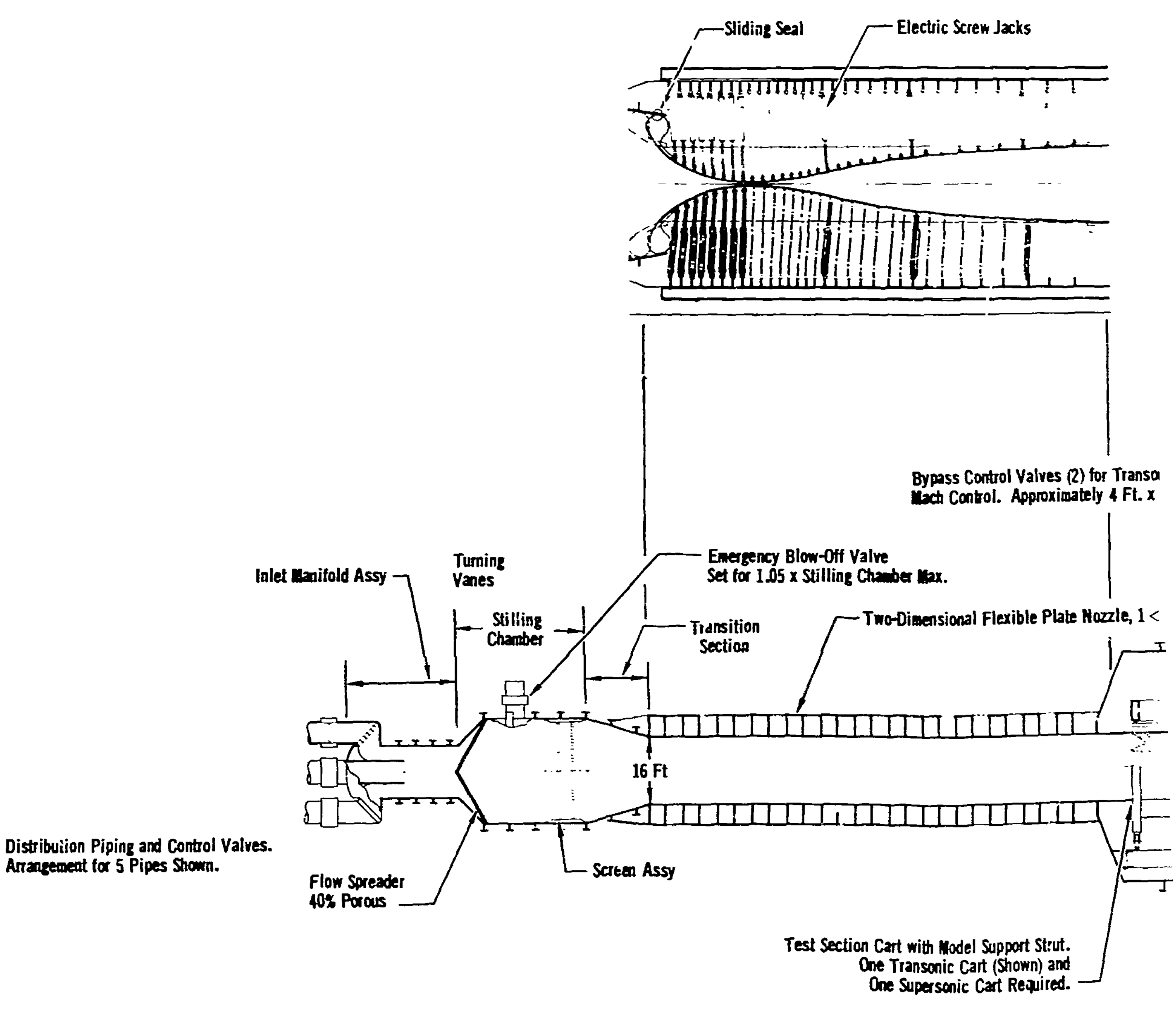
6.2.8 TRANSONIC/SUPERSONIC BLOWDOWN WIND TUNNEL (GD3) - This facility is a blowdown-to-atmosphere wind tunnel operating in the Mach number range 0.5 to 5.0. Details of the tunnel test leg are shown in Figure 6-30, while a schematic drawing of the complete facility is shown in Figure 6-31. The test section dimensions of the baseline facility give it the capability to test at Reynolds numbers up to 1/5 the maximum flight Reynolds numbers of the study operational vehicles, throughout the entire facility Mach number range. This capability is approximately 2.5 to 3 times that of the best existing blowdown facilities and from 2.5 to 10 times that of the existing continuous facilities.

The Mach number range of GD3 was chosen based on considerations of stagnation pressure and temperature. Since a maximum Reynolds number of one-fifth the flight value was decided upon (see criteria, Section 6.2.1) as being desirable to fulfill a majority of the aerodynamic research tasks, the tunnel was specified to operate at stagnation temperatures just sufficient to avoid air liquefaction at the test Mach number. By limiting the maximum Mach number to 5.0, it is practical to provide the maximum stagnation temperature which is approximately 250°F (121°C) by means of a gas heater which heats air just after leaving the compressor, storing this hot air in the regular air tanks. This is a simple and economical method, and the heater is only used when high Mach numbers are being run. Choice of higher Mach numbers for the facility leads rapidly to the need for much higher temperatures and the use of in-line tunnel heaters, which are much more costly when being used, and which create unnecessary pressure drop in the stilling chamber when not being used. Stagnation pressure influences the choice of maximum Mach number because of the rapid increase in required maximum stagnation pressure with Mach number. A maximum Mach number of 5 was chosen for two reasons. Operation at Mach number 5 to an atmospheric exhaust was consistent with the maximum tank pressure required to supply the necessary air for the maximum mass flow case at Mach number 1.7. Because of the greatly reduced mass flow at Mach number 5, an acceptable run time could be achieved, permitting a minimum tank pressure decrease during the run. This results in an overall cost savings in the compressor, air storage tanks, blowdown lines, and stilling chamber design.

The test section size of GD3, which is 16 x 16 ft (4.9 x 4.9 m) for the baseline definition, is a result of the development in Section 6.2.2, where minimum test section size as a function of Mach number is derived in terms of model/balance strength and Reynolds number criteria. The specific dimension of 16 ft was chosen because of the existence of the 16T and 16S propulsion wind tunnels at AEDC, which are the largest continuous tunnels in the U.S. covering this same Mach number range. In a wind tunnel of this size, test installation time can become a very considerable and costly item. The test section cart system, as used by the 16T and 16S tunnels, ensures that the wind tunnel is not tied up for test installations, this work being done in a special building. The same concept is proposed for GD3, in fact it is essential to the GD3 specifications in order that its potential test utility be realized. Choice of the 16 foot dimension gives the possibility of integrating GD3 with the AEDC facilities. Integration could result in large savings in costs by possible sharing of transfer cars, model assembly building, the test section carts (with some modification of the model support system because of the higher dynamic pressure of GD3), compressor and electric substation capability already present at AEDC, computers and instrumentation, and operating personnel. The extent of practical integration possibilities and resultant cost saving is one probable task for Phase III.

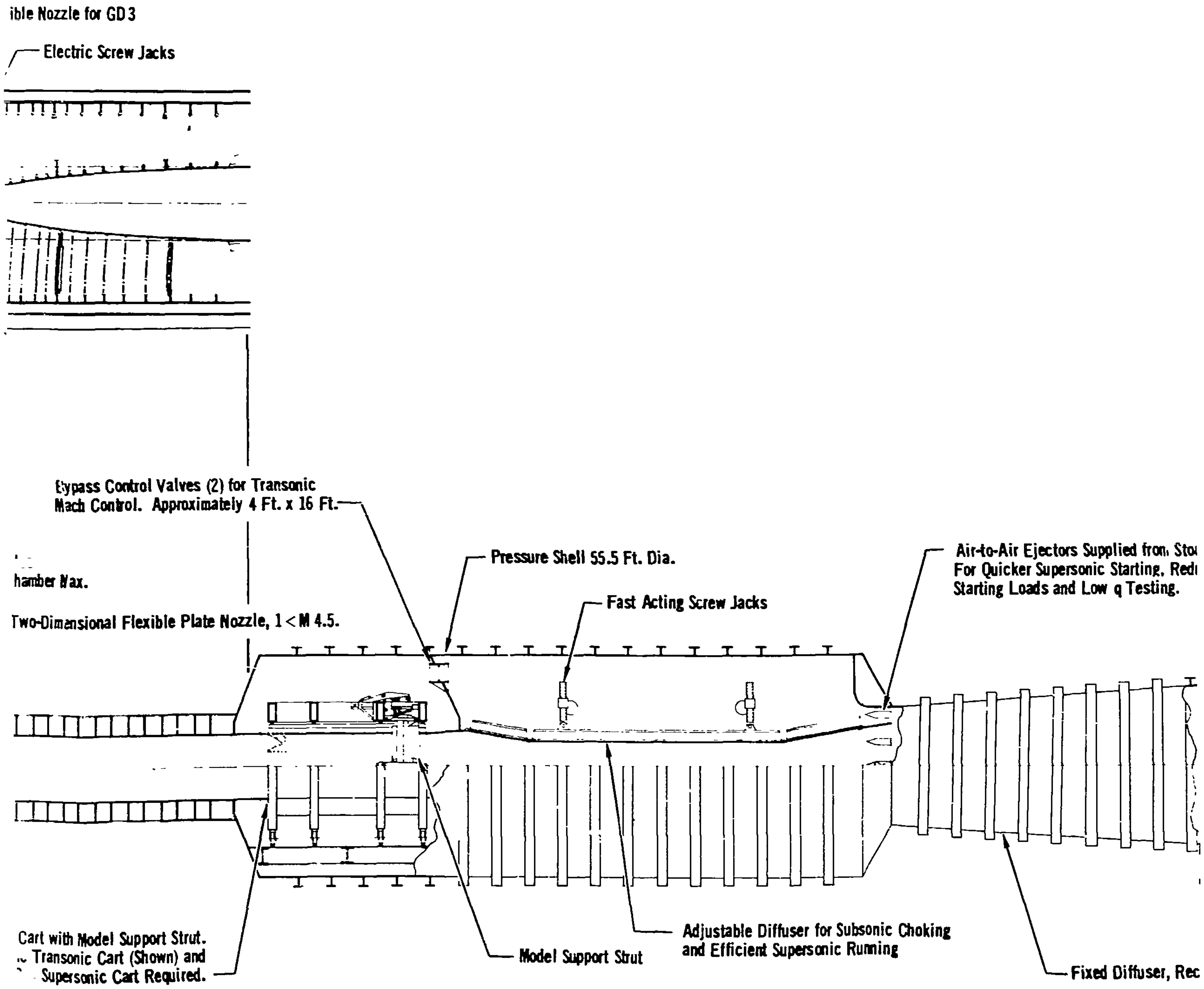
FOLDOUT FRAME 1

FIGURE 6-30
GF 3, TRISONIC BLOWDOWN FACILITY

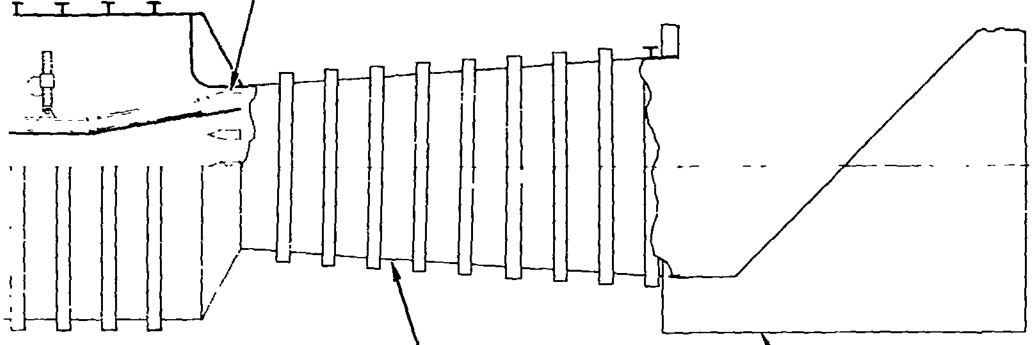


FOLDOUT FRAME 2

FOLDO



FOLDOUT FRAME 3



Air-to-Air Ejectors Supplied from Storage System. For Quicker Supersonic Starting, Reduction of Starting Loads and Low q Testing.

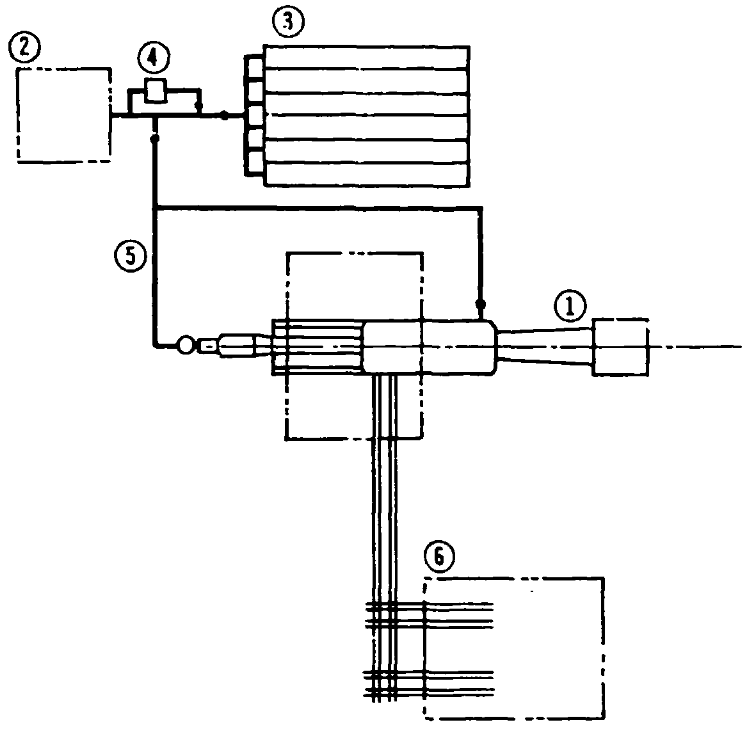
Jacks

Diffuser for Subsonic Choking
fficient Supersonic Running

Fixed Diffuser, Rectangular Cross-Section

Muffler Assy. Outlet is 60 Ft x 60 Ft. Reinforced Concrete Construction.

FIGURE 6-31
SCHEMATIC LAYOUT OF GD3 HIGH REYNOLDS NUMBER TRISONIC WIND TUNNEL



Legend:

- ① Test Leg
- ② Compressor Plant
- ③ Air Storage
- ④ Propane Heater
- ⑤ Blowdown Piping + Control Valves
- ⑥ Model Assembly Building

The question of deciding on a suitable run time for GD3 has been settled in favor of a blowdown system with the capability to make one α polar per run at all test conditions. A blowdown tunnel is preferrable to a continuous tunnel for the high stagnation pressures required because of acquisition and operating costs associated with the compressor in addition to increased flexibility in terms of aerodynamic research programs. For example, the compressor horsepower required for the GD3 facility is 60,000 hp (44,700 kW) while 216,000 hp (162,000 kW) is required for 16S, which operates at a maximum pressure of 13.95 psia (9.6 N/cm^2). If 16S were to be strengthened to operate at 300 psia, as does GD3, the horsepower required would be approximately 1,650,000 hp (1,230,000 kW). A very large cost would be incurred in modifying a tunnel such as 16S, or building a new one of identical size, to withstand internal pressures of 300 psia (206 N/cm^2). GD3 is more flexible for aerodynamic research programs than continuous tunnels because of the time required to pump a large continuous wind tunnel up to operating pressure, get the electric motors on-line and establish the desired test conditions. After a run, additional time is required before the tunnel can be opened for model work. In a blowdown facility, while model work is proceeding, the tanks are being replenished at a low rate of power consumption. Once the tunnel is closed, test conditions are established very quickly, an α polar is run, and the tunnel can be opened within 5 minutes of the closing time. This type of operation is very efficient, especially when large numbers of configuration changes are being evaluated, as in the case in research programs. There is another advantage to the blowdown operation with respect to damage from broken models or model parts. While model damage is undesirable in any type of tunnel, it could be catastrophic with respect to facility damage in a continuous tunnel. In summation, cost, power, and test utility factors dictate the selection of a blowdown wind tunnel over a continuous wind tunnel in this case, as was presented in Volume II.

6.2.8.1 Specifications - The following table gives the physical and operating specifications of the baseline and alternate facility definitions. The baseline facility is the minimum size facility producing one-fifth maximum flight Reynolds number, Alternate 1 is a facility 2.5 times as large as the baseline, but producing the same Reynolds number, and Alternate 2 is the minimum size facility producing one-half maximum flight reynolds number, and is the same size as Alternate 1.

		Baseline	Alternate 1	Alternate 2
Test Section Size	ft (m)	16x16x40 (4.9x4.9x12)	40x40x100 (12x12x30)	40x40x100 (12x12x30)
Mach Number Range		0.5 to 5.0	0.5 to 5.0	0.5 to 5.0
Stagnation Pressure Range	psia (N/cm^2)	17.3 to 300 (12 to 207)	17.3 to 120 (12 to 83)	17.3 to 300 (12 to 207)
Stagnation Temperature	°F (°C)	100 to 250 (37.8 to 121)	100 to 250 (37.8 to 121)	100 to 250 (37.8 to 121)
Minimum Run Time	sec	20	20	20
Tank Pump-Up Time - AVG	hr	1	1	1
MAX	hr	2	2	2
Test Conditions				
o Maximum $\dot{\omega}$				
Mach Number		1.67	1.67	1.67
$Re\sqrt{c}$		6.2×10^8	6.2×10^8	15.5×10^8
P_o	psia (N/cm^2)	140 (96)	56 (39)	140 (96)
T_o	°F (°C)	100 (37.8)	100 (37.8)	100 (37.8)
$\dot{\omega}$	lbm/sec (kg/sec)	88,400 (40,000)	221,000 (100,000)	552,000 (283,000)

		Baseline	Alternate 1	Alternate 2
o <u>Maximum M and P_o</u>				
Mach Number		5.0	5.0	5.0
$Re\sqrt{c}$		2.4×10^8	2.4×10^8	6.0×10^8
P_o	psia	300	120	300
	(N/cm^2)	(207)	(83)	(207)
T_o	°F	200	200	200
	(°C)	(93)	(93)	(93)
$\dot{\omega}$	lbm/sec	9,030	22,600	56,400
	(kg/sec)	(4,100)	(10,250)	(25,600)
o <u>Minimum Mach</u>				
Mach Number		0.5	0.5	0.5
$Re\sqrt{c}$		1.12×10^8	1.12×10^8	2.8×10^8
P_o	psia	35.6	14.2	35.6
	(N/cm^2)	(24.5)	(9.8)	(24.5)
T_o	°F	100	100	100
	(°C)	(37.8)	(37.8)	(37.8)
$\dot{\omega}$	lbm/sec	21,950	54,800	137,000
	(kg/sec)	(9.960)	(24,850)	(63,150)
Compressor Plant Capacity	scfm	193,300	483,000	1,207,000
	(m^3/min)	(5,470	(13,700)	(34,200)
Max. Pressure	psi	500	250	500
	(N/cm^2)	(345)	(172)	(345)
Air Storage Tanks Volume	ft^3	2,870,000	7,410,000	13,000,000
	(m^3)	(81,200)	(210,000)	(368,000)
Max. Pressure	psi	500	250	500
	(N/cm^2)	(345)	(172)	(345)
Propane Heater	Btu/hr	75.6×10^6	189×10^6	473×10^6
	(kW)	(22,200)	(55,400)	(138,000)

The specifications relating to the size of the test legs and their performance are considered in final form as presented in this section. Phase III will emphasize those ancillary items as compressors, exhausters, heaters, and air storage systems representing the major facility costs, but requiring better definition for accurate cost estimating.

6.2.8.2 <u>Facility Component and Cost Summary</u> - Figure 6-32 shows a compilation of the costs estimated for each of the facility components and the operating costs. Estimates were made by the methods discussed in Section 6.1.

FIGURE 6-32a
GD3 FACILITY COMPONENT AND COST SUMMARY

Facility Component	Cost Estimate $1000's		
	Baseline	Alt 1	Alt 2
1. TEST LEG Sub Total	30,811	180,040	383,540
1.1 Main Pressure Structure (Inlet Manifold Assy., Stilling Chamber, Flow Spreader, Screen Assy., Blow-Off Valve, Transition Section, Main Shell, Fixed Diffuser Assy., Bypass Valves, Foundation).	9,741	60,600	152,000
1.2 Nozzle Assembly (Flexible Sideplates and Seals, Sidewall Structure, Top and Bottom Plates and Structure, Electric Screw Jacks, Automatic Jack Position Control System).	6,900	43,200	107,700
1.3 Transonic Cart & Model Support Strut	1,480	12,870	23,100
1.4 Supersonic Cart & Model Support Strut	1,480	9,250	23,100
1.5 Adjustable Diffuser Assembly (Fixed Sideplates, Articulated Top and Bottom Plates and Dynamic Seals, Electric Screw Jacks, Jack Support Structure).	1,000	9,870	15,600
1.6 Ejector System (Nozzles, Piping, Valves).	400	2,500	6,240
1.7 Muffler Assembly	1,530	9,550	23,600
1.8 Building (Control Room, Photo Lab, Instrumentation Areas).	4,200	25,600	25,600
1.9 Tunnel and Model Automatic Control System	800	800	800
1.10 Instrumentation and Data Acquisition (Transducers, Amplifiers, Power Supply, Analog/Digital Converter, Tape Recorder, Schlieren System).	3,280	5,800	5,800
2. COMPRESSOR PLANT Sub Total	17,419	43,307	79,092
2.1 Mechanical Components (Compressors, Inter-Coolers, Oil Filters, Air Dryers, Motors, Controls).	17,107	42,505	77,680
2.2 Electric Substation	312	802	1,412

FIGURE 6-32a (Continued)
GD3 FACILITY COMPONENT AND COST SUMMARY

3. AIR STORAGE TANKAGE	28,200	72,800	123,000
4. PROPANE HEATER	100	250	625
5. BLOWDOWN PIPING (Incl. Pipes, Isolation Valves, Control Valves, Air Ejector Piping).	447	1,345	2,660
6. MODEL ASSEMBLY BUILDING (2 Bay Assembly Building, Test Cart Transfer Cars (2), Heavy Duty Double Tracks from Building to Tunnel).	3,328	16,682	16,682
Total	80,305	314,424	610,597
10% Contingency	8,030	31,442	61,059
Facility-Cost	88,335	345,866	671,656
A&E Fee @ 6%	5,300	20,750	40,300
MGT & Coord. Fee @ 4%	3,540	13,830	26,850
Grand Total	97,175	380,446	738,806

FIGURE 6-32b
DISTRIBUTION OF FACILITY ACQUISITION COSTS – GD3

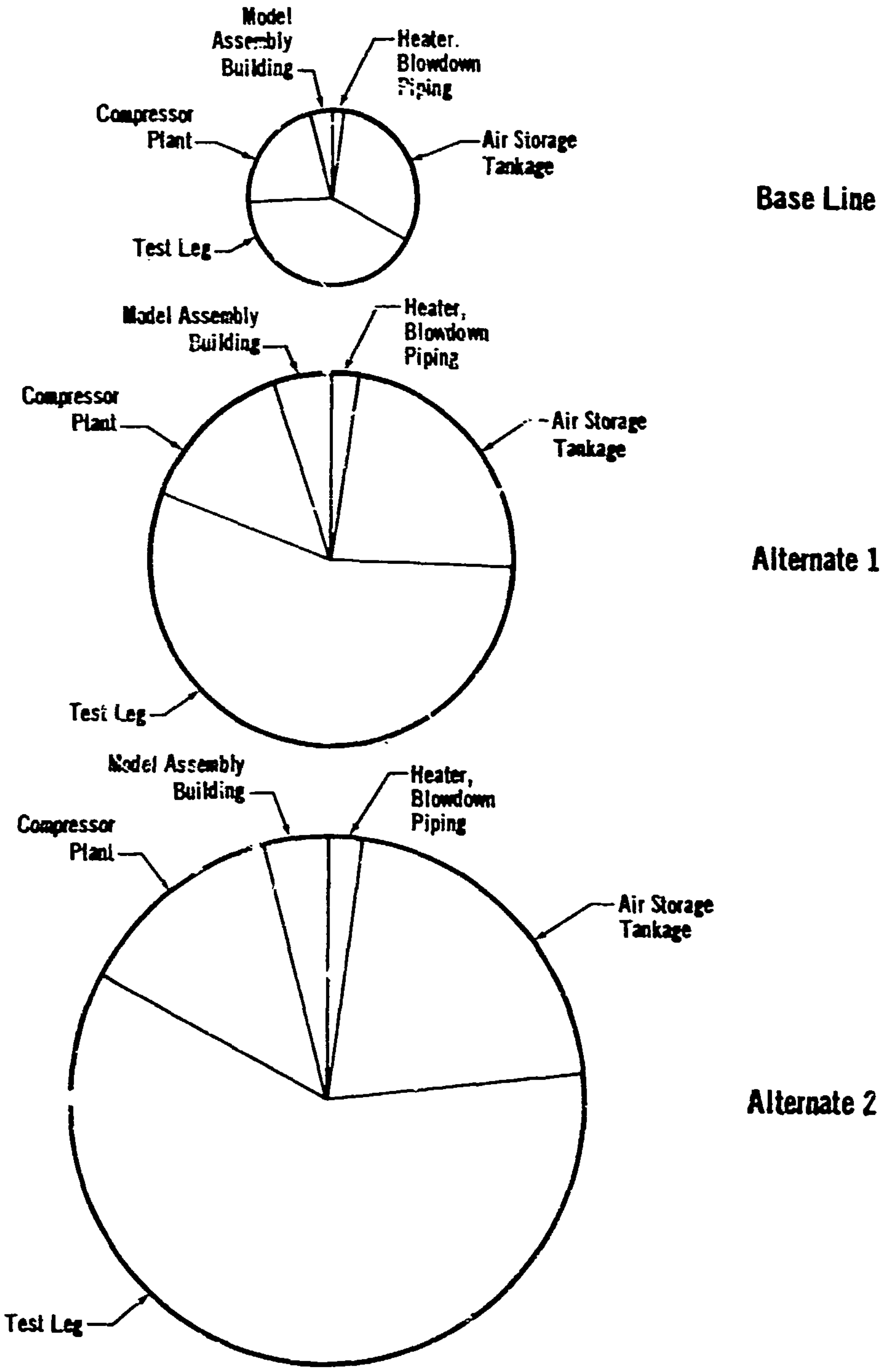


FIGURE 6-32c

GD3 OPERATING COST SUMMARY

Operating Cost – Dollars/Occupancy Hour	Baseline	Alternate 1	Alternate 2
Repair and Maintenance	1,450	5,659	12,000
Staffing	1,000	1,000	1,000
Power	76	195	344
Total	2,526	6,854	13,344

Although the absolute cost levels calculated for the components and totals are informative, the most interesting comparisons are obtained from the "pie" chart. It reveals graphically the facility components which are responsible for the total cost, and are thus candidates for better definition in Phase III.

The three main cost components are the test leg, compressor plant, and air storage tanks. The test leg definition is relatively firm and there appears to be only slight potential cost savings possible through refining this definition. The compressor plant offers a means to obtain a cost reduction without compromising the test conditions or run time, merely by specifying a longer pump-up time for the maximum weight flow case than the two hours chosen. This is a straightforward case of trading off test utility, as represented by number of runs per shift, for reduced acquisition and operating cost. Air storage tankage volume and costs will be refined by optimizing the volume and pressure, and are expected to result in a somewhat higher storage pressure and smaller volume than the conservative values chosen for Phase II.

6.2.8.3 Development Assessment - This facility is essentially a large version of several blowdown wind tunnels now operating in the same Mach number range, and should present a minimum technical risk in terms of functioning as specified. There are several degrees of development factors which affect the assessment of all of the ground facilities in this study. These can be categorized in decreasing confidence level as follows:

o Level 5 - This level assumes all of the hardware necessary for the facility test leg, system, or component is available in industrial usage in the size and performance levels necessary to satisfy the facility requirements. In assembling any ground research facility of the complexity of those in this study, even though all of the individual components operate to specification, the system interactions will produce functional problems which must be solved before complete facility operation is achieved. These problems are not necessarily minor in nature and can require a significant time period, and/or replacement of equipment to remedy the situation. For this case, the confidence that the operational goals will be met and the facility will function as specified are excellent. The de-bugging of the problems that occur during facility shakedown will occur regardless of the technical risk associated with realization of the specified performance. This level represents high confidence and low technical risk with the problems arising from normal construction/fabrication sources rather than non-realization of equipment design goals.

o Level 4 - This level assumes that all of the necessary hardware is developed and in industrial usage, but not quite at the size and/or performance levels required, necessitating a reasonable extrapolation of existing experience. In addition to the expected integration problems associated with Level 5, there is an additional risk that some of the equipment may not initially attain their performance goals, requiring additional development time. The confidence associated with achieving the desired goals at this confidence level is still high, although the potential to encounter additional development problems is greater. Attention to small details, and prototype qualification can reduce these risks if the acquisition schedule permits.

A development program of this scope may increase the hardware costs between 1.5 to 2 times the initial estimated acquisition costs. The confidence level is high that the specified performance of the overall facility or system will be attained, but its attainment is dependent on an adequate development program. Again as in Level 5, the ever present integration problem must be considered.

o Level 3 - This level assumes that the principles of operation of the facility or system have been verified in smaller scale existing facilities and industrial equipment, so that there is no technical reason which would prevent attainment of desired goals in all equipment functions as desired. The hardware is of such a size and performance however, that new designs and/or concepts are necessary to supply the needed conditions. For this level of confidence, without an equipment development program, the confidence in initially achieving the specified performance goals is greatly reduced from Level 4. Some problem areas may require only minimum development programs, but those associated with large, high performance hardware could require a substantial development program.

o Level 2 - This level represents a situation analogous to Level 5, in that most of the support equipment exists in the size and performance necessary to achieve the overall performance. However, the technical principles associated with the facility concept and/or design represent new approaches and techniques not previously applied in the proposed manner. For this level, a development program is necessary to acquire the necessary details to correctly specify the support equipment as well as demonstrate the operational suitability of the concept. Providing the supporting equipment specifications do not materially change, then the primary additional costs will be in developing the new designs. This could increase the cost of the individual components by as much as a factor of 5, but the total impact on the overall costs would be substantially less, perhaps similar to Level 3. Since the basic principles underlying the facility concept need verification, the level of risk is higher than that associated with Level 3. Failure to verify the design concepts would require reassessment of the facility feasibility or necessitate development of satisfactory alternate design concepts.

o Level 1 - This level assumes that the facility concept proposed is based on theoretical analyses and has not been demonstrated in actual hardware at the performance levels and size proposed. This represents the minimum confidence level and greatest technical risk, requiring development of a prototype system to verify the concept as well as development of the necessary support equipment for the full scale facility resulting from the prototype tests. Even with a prototype program, integration of hardware into a complex facility array while developing the basic facility concept itself could result in very costly additional development programs and delays. For this level, the final cost of the facility which achieves the specified design goals could approach 5 to 10 times the initial estimated cost if significant development problems are encountered. This level represents a high risk, with a high probability that serious problems could be encountered.

For GD3, the integration of the hardware into a fully operational facility should constitute the major source of development difficulties. The compressor plant is comprised of machines currently in production; the test leg is of a size already achieved in wind tunnel fabrication, incorporating features similar to that of GD3; and the concept is based on numerous operational existing trisonic wind tunnels. A prototype of the GD3 nozzle system is represented by the AEDC, 1 foot supersonic wind tunnel 1S, which is a scale model of the 16 ft supersonic tunnel of the Propulsion Wind Tunnel facility, and the 16 foot Propulsion Wind Tunnel facility itself, which uses a nozzle system closely resembling the nozzle depicted in Figure 6-30. The development assessment of GD3 would then correspond to a confidence level 5 for a majority of the systems. The air storage system, control valves, and muffler system could be considered level 4. The areas requiring special attention are:

- Design of inlet manifold and stilling chamber, to ensure stable filling of the stilling chamber throughout the wide range of tunnel flow rates and to ensure development of a flat velocity profile.
- Determination of a reasonable projection of control valve technology so that a minimum number of control valves will be specified.
- Design and development of acoustical damping techniques for the stilling chamber and muffler.

6.2.9 TRANSONIC/SUPERSONIC/HYPERSONIC BLOWDOWN WIND TUNNEL (GD20) - Integration of the transonic/supersonic GD3 blowdown wind tunnel with an electrically heated Mach 4.5 to 8.5 blowdown wind tunnel (described as GD15 in Volume II) provides high Reynolds number capability and reasonable run times throughout the range, M = 0.5 to 8.5. This integrated facility is designated as GD20, and is shown in Figures 6-33, 6-34, and 6-35.

Discussion, specifications, component and cost summary, and development assessment of the transonic/supersonic test leg is covered in Section 6.3.5 and will not be repeated here.

The hypersonic test leg operates on a blowdown cycle from high pressure storage tanks and exhausts to atmosphere with the aid of air ejectors. Heated air is provided by a steel matrix storage heater, which is inductively heated prior to each run. Figure 6-[illegible] shows the Reynolds number capability of the hypersonic leg, in conjunction with the capability of the other gas dynamic test facilities studied. Like the others, this facility, in its baseline definition, provides Reynolds numbers equal to at least one-fifth of the maximum flight values for the operational vehicles. This capability is three times the Reynolds number capability at Mach 4.5 and ten times the capabilities at Mach 8.5 available in existing blowdown type wind tunnels.

The test section size of the hypersonic leg baseline definition is 12 ft x 12 ft (3.68 m x 3.68 m), and was chosen as the best size for this Mach number range on the basis of the development in Section 6.3.2 as satisfying the criteria regarding model/balance strength and Reynolds numbers of the operational vehicles.

The maximum Mach number was determined primarily by the minimum stagnation temperature required to avoid air liquefaction. The tunnel is designed with a flexible plate nozzle which has sidewall seals. A simple design was desired, with a minimum of water cooling, so moderate stagnation temperatures were needed. Another restriction on maximum T_0 was the desire to use an economical, durable heater matrix material, with no dust problems. This requirement eliminated the usual refractory materials. A stagnation temperature of 800°F (427°C) satisfied both of these requirements. This temperature limit dictates a maximum Mach number of 8.5. This works out well with respect to air storage tank pressure requirements since the maximum stagnation pressure is 2360 psia (1630 N/cm^2), and storage tank pressure can be held to 5000 psia (3450 N/cm^2), which is consistent with that required to supply the maximum mass flow point at Mach number 4.5.

A blowdown cycle was chosen over continuous operation in order to minimize heater and compressor power. The key research requirement of this facility is its capability to make one full α polar per run and many runs per shift, ideal for configuration aerodynamic research. Like the transonic/supersonic leg, facility damage resulting from model failures, a special hazard because of the high dynamic pressure used, is a point in favor of a blowdown operation. Impulse type operation was not chosen, primarily because of the limitations of test time, and because of the relative ease of providing blowdown operation at low technical risk. Unless very high Reynolds numbers approaching flight values or higher temperatures, corresponding to flight duplicated conditions, are needed, a blowdown tunnel is superior to an impulse facility in this Mach range.

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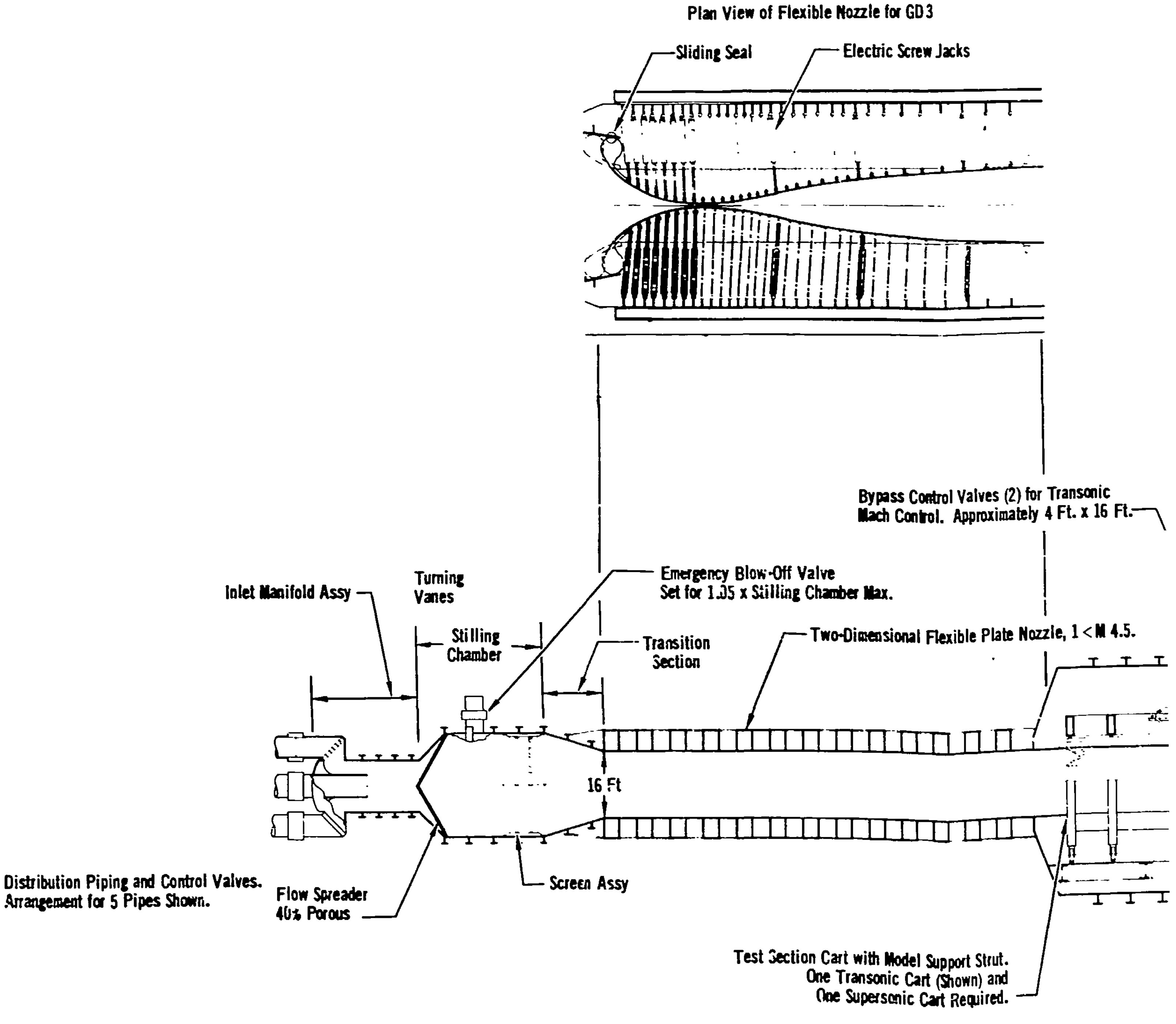
FIGURE 6-33
TRISONIC BLOWDOWN LEG OF FACILITY GD 20
(Identical to GD 3, Figure 6–36)


Plan View of Flexible Nozzle for GD 3

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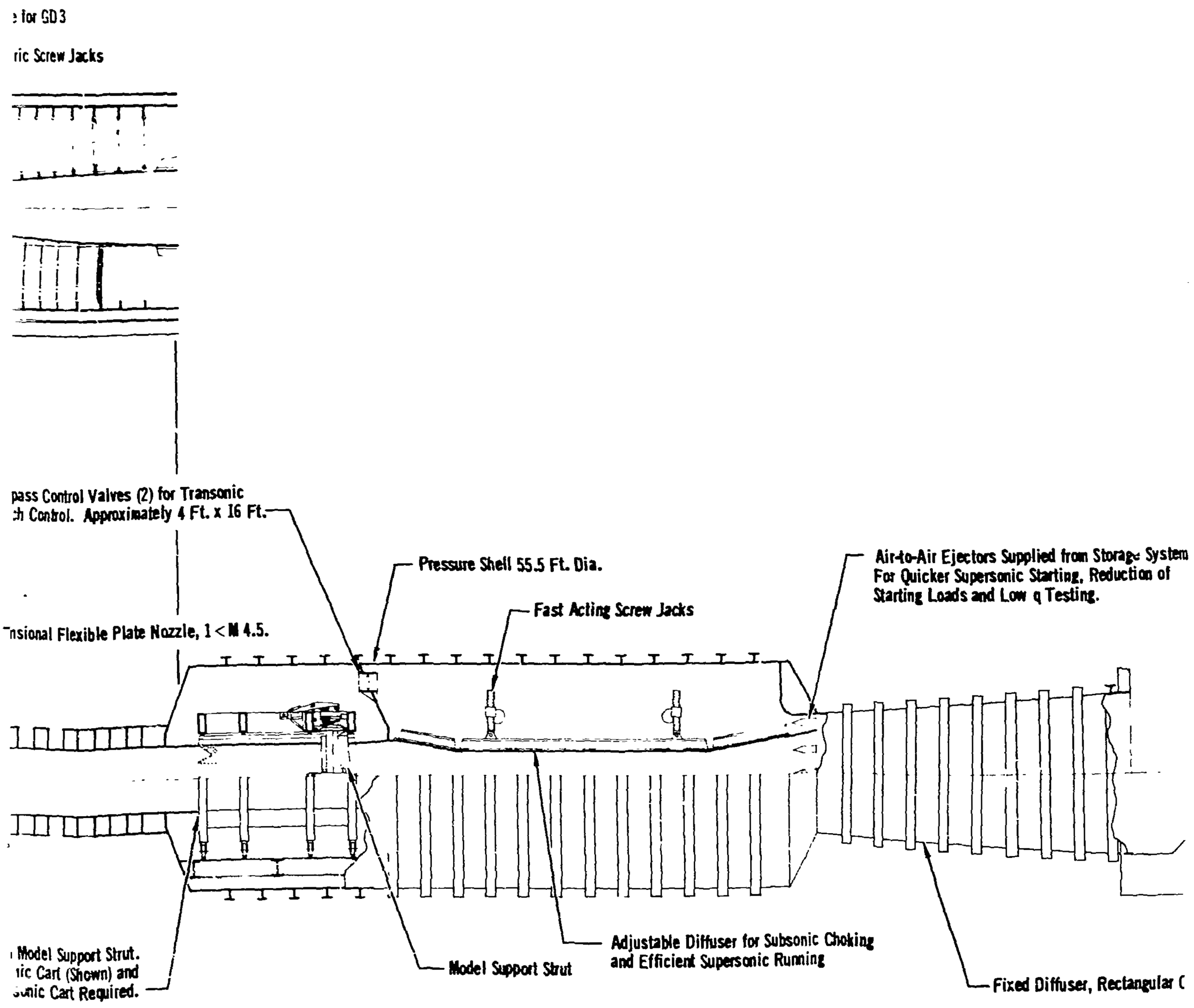

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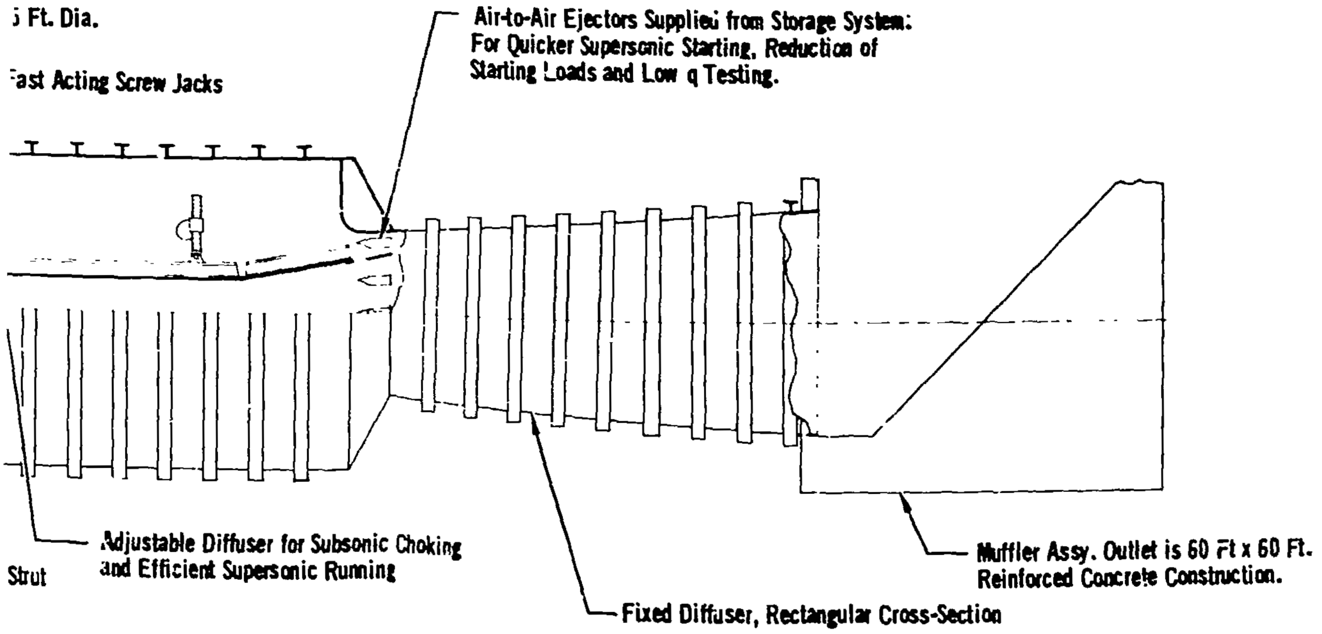

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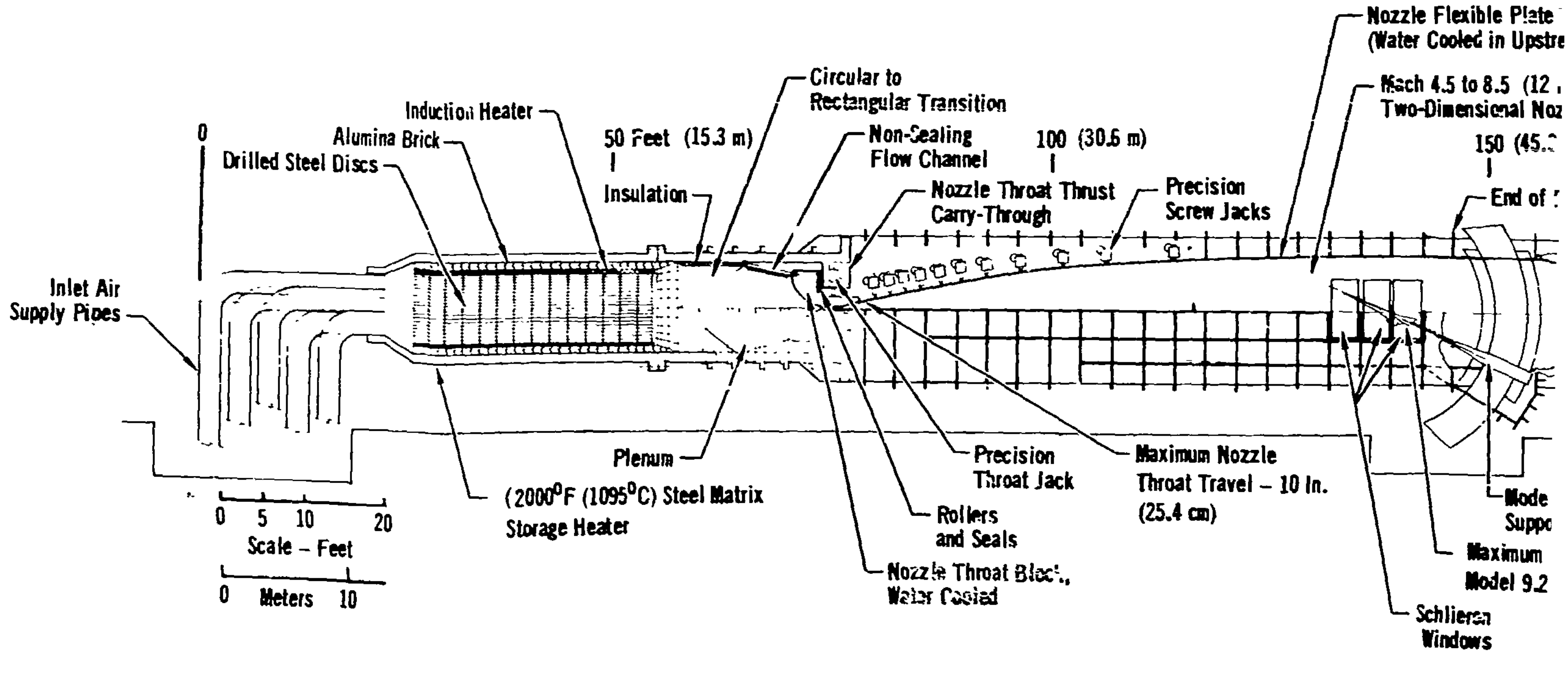

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FIGURE 6-34
HYPERSONIC BLOWDOWN LEG OF FACILITY GD 20

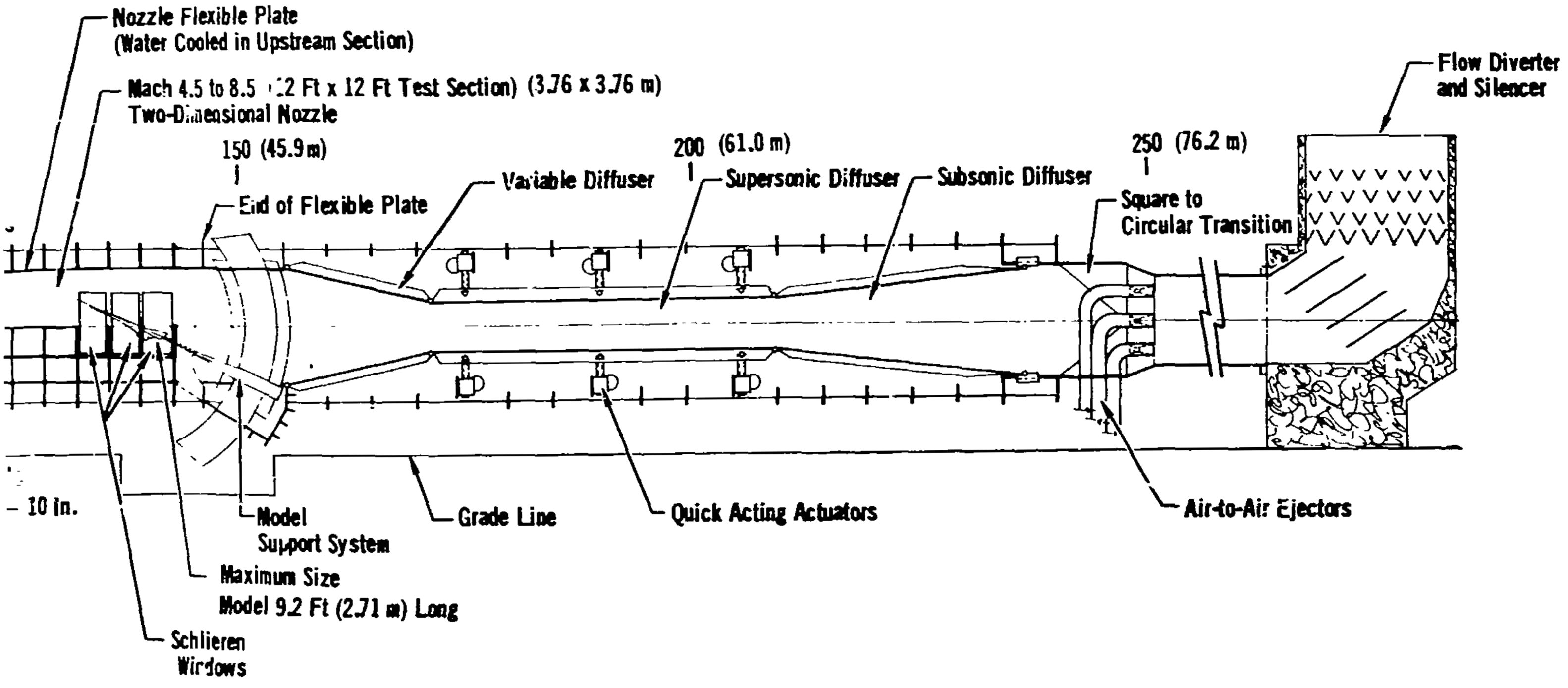
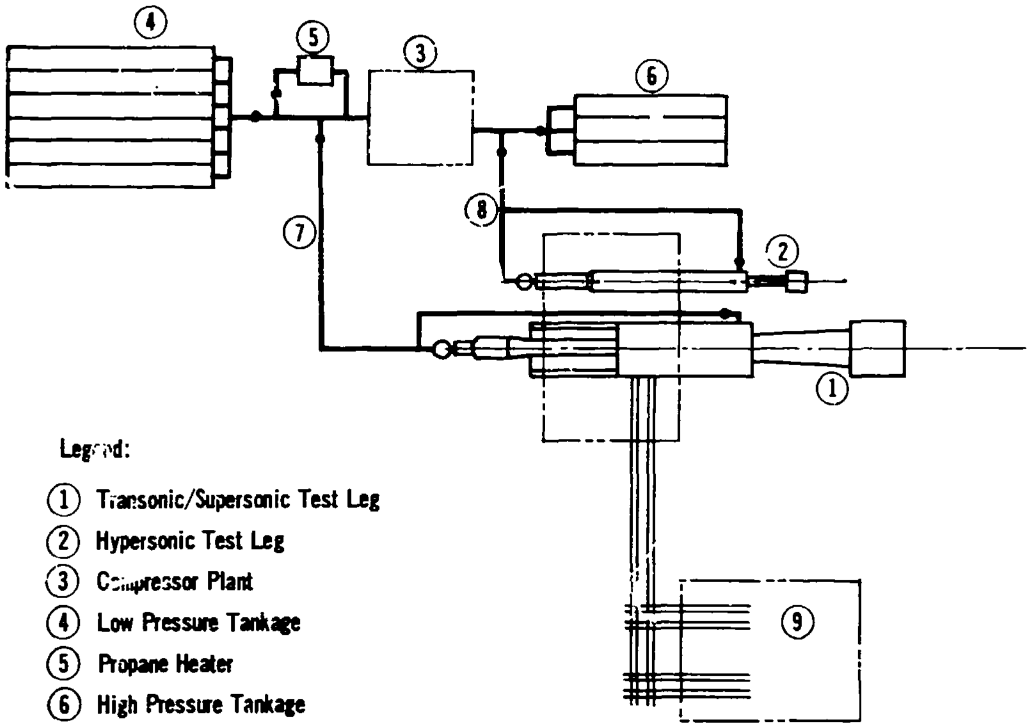


FIGURE 6–35
SCHEMATIC LAYOUT OF GD20 BLOWDOWN WIND TUNNEL COMPLEX
(Transonic/Supersonic Leg Plus Hypersonic Leg)



Legend:

① Transonic/Supersonic Test Leg
② Hypersonic Test Leg
③ Compressor Plant
④ Low Pressure Tankage
⑤ Propane Heater
⑥ High Pressure Tankage
⑦ Low Pressure Blowdown Lines
⑧ High Pressure Blowdown Lines
⑨ Model Assembly Building

A two-dimensional flexible plate nozzle has been specified for the hypersonic test leg. In the Mach number range chosen, a two-dimensional nozzle is practical, although axisymmetric nozzles could be used. Axisymmetric nozzles were not chosen, primarily on the basis of test utility, as measured by time between runs. A series of nozzles would have to be provided, one for each Mach number of interest, and a nozzle installation would have to be done to change Mach number. Although each individual axisymmetric nozzle would be much cheaper than a two-dimensional flexible nozzle, provision of a set of nozzles and their associated handling equipment would probably approximate the cost of a single two-dimensional nozzle. Wind tunnels at NASA Langley and AEDC have been operated successfully using two-dimensional, flexible plate nozzles in this Mach number range.

Integration of the two test legs will provide blowdown test capability throughout the very large Mach number range of .5 to 8.5 in one location at a total acquisition cost increase of approximately 30% of the base cost of the transonic/supersonic leg. This cost is based on sharing such things as the control room building, model assembly building, computer, and some elements of the data acquisition equipment.

A more fundamental cost saving integration will be studied in Phase III, that is, consideration of the technical and economic factors involved in integrating this facility with the complex at AEDC, as discussed in Section 6.2.8.

6.2.9.1 Specifications - The following table gives the physical and operating specifications of the baseline and alternate facility definitions. The baseline facility is the minimum size facility producing one-fifth of the maximum required flight Reynolds number. Alternate 1 is a facility 2.5 times as large as the baseline, producing the same Reynolds number as the baseline facility. Alternate 2 is the minimum size facility producing one-half flight Reynolds number, and is the same size as Alternate 1.

		BASELINE	ALTERNATE 1	ALTERNATE 2
Test Section Size *	ft	12x12	30x30	30x30
	(m)	(3.68x3.68)	(9.13x9.13)	(9.13x9.13)
Mach Number Range *		3 to 8.5	3 to 8.5	3 to 8.5
Stagnation Pressure *	psia	50 to 2360	50 to 944	50 to 2360
	(N/cm^2)	(34 to 650)	(34 to 650)	(34 to 1630)
Stagnation Temperature *	°F	150 to 800	150 to 800	150 to 800
	°C	(65 to 427)	(65 to 427)	(65 to 427)
Minimum Run Time *	sec	20	20	20
Tank Pump-Up Time - Avg.	hr	1	1	1
Max	hr	2	2	2
Test Conditions *				
o Maximum $\dot{w}$, minimum M				
Mach number		4.5	4.5	4.5
$Re_{\sqrt{c}}$		3.0×10^8	3.0×10^8	7.5×10^8
Po	psia	396	158	396
	(N/cm^2)	(273)	(109)	(273)
To	°F	150	190	150
	(°C)	(65.5)	(65.5)	(65.5)

		BASELINE	ALTERNATE 1	ALTERNATE 2
$\dot{w}$	lbm/sec	11,000	27,500	69,600
	(kg/sec)	(5000)	(12,500)	(31,600)
c Maximum M and Po				
Mach Number		8.5	8.5	8.5
Re$\sqrt{c}$		1.3×10^8	1.3×10^8	3.25×10^8
Po	psia	2360	944	2360
	(N/cm^2)	(1630)	(650)	(1630)
To	°F	800	800	800
	(°C)	(427)	(427)	(427)
$\dot{w}$	lbm/sec	2890	7225	18,080
	(kg/sec)	(1310)	(3275)	(8,200)
Compressor Plant				
Low Pressure - Capacity	scfm	217,500	543,000	1,358,000
	(m^3/sec)	(6,140)	(15,400)	(38,500)
Max Press.	psia	500	250	500
	(N/cm^2)	(345)	(172)	(345)
High Pressure - Capacity	scfm	24,050	60,000	150,000
	(m^3/sec)	(680)	(1700)	(4240)
Max Press.	psia	5000	2000	5000
	(N/cm^2)	(3450)	(1380)	(3450)
Air Storage Tank *				
Volume	ft^3	13,400	83,800	82,900
	(m^3)	(379)	(2370)	(2340)
Pressure	psia	5000	2000	5000
	(N/cm^2)	(3450)	(1380)	(3450)
Steel Matrix Induction Heater				
Power	kW	2500	6250	15,600

* For Hypersonic test leg only. Values for transonic/supersonic leg are given in Section 6.2.8.1.

Specifications relating to the size of the test leg and its performance will not be modified in Phase III. Further work will be done in determining the most effective storage volume and pressure, and compressor flow rate.

6.2.9.2 Facility Component and Cost Summary - Figure 6-36a shows a compilation of the costs estimated for each of the facility components and the operating costs. Estimates were made by the methods discussed in Section 6.1.

Although the absolute cost levels calculated for the components and totals are presented, the overall picture of the relative magnitudes is graphically visible from the "pie" charts (Figure 6-36b). They reveal the facility components which are most responsible for the total cost, and are thus most amenable to better definition in Phase III.

FIGURE 6-36a
GD20 COMPONENT AND COST SUMMARY

Facility Component		Cost Estimate $1000's	
	Baseline	Alt 1	Alt 2
1. TRANSONIC/SUPERSONIC TEST LEG Sub Total (Same as GD3 Test Leg)	30,811	180,040	383,540
2. HYPERSONIC TEST LEG Sub Total	8,462	38,199	88,515
2.1 Main Pressure Structure (Inlet Manifold Assy, Stilling Chamber Assy, Main Press. Shell, Test Section, Schlieren Windows, Foundation)	2,016	11,580	28,680
2.2 Steel Matrix Storage Heater (Shell, Alumina Insulation, Steel Matrix Discs, Induction Heating Elements)	990	2,480	6,200
2.3 Nozzle Assembly (Flexible Top and Bottom Plates with Upstream Cooling Passages, Seals, Sidewall Structure, Electric Screw Jacks, Jack Control System)	1,520	9,500	23,700
2.4 Model Support System	150	385	937
2.5 Adjustable Diffuser Assy, (Articulated Top and Bottom Plates, Seals, Sidewall Structure, Electric Screw Jacks)	396	2,470	6,180
2.6 Ejector System (Nozzles, Piping, Valves)	400	2,500	6,240
2.7 Muffler Assembly	90	563	1,405
2.8 Tunnel and Model Automatic Control System	800	800	800
2.9 Instrumentation and Data Acquisition (Transducers, Amplifiers, Power Supply, Schlieren System). Analog/Digital Connector and Tape Recorder is shared with T/S Leg.	2,100	3,680	3,680
3. COMPRESSOR PLANT Sub Total	29,734	69,005	145,850
3.1 Mechanical Components (Compressors, Intercoolers, Oil Filters, Air Dryers, Motors, Controls)	28,232	61,707	128,040

FIGURE 6-36a (Continued)
GD20 COMPONENT AND COST SUMMARY

3.2 Elec. Substation (Includes Power for Compressors and Heater)	1,502	7,298	17,810
4. LOW PRESSURE TANKAGE	28,200	72,800	128,000
5. PROPANE HEATER	100	625	1,560
6. HIGH PRESSURE TANKAGE	1,315	3,250	8,360
7. LOW PRESSURE BLOWDOWN PIPING	447	1,345	2,660
8. HIGH PRESSURE BLOWDOWN PIPING	746	1,870	3,060
9. MODEL ASSEMBLY BUILDING (Same as GD3)	3,328	16,682	16,682
Total	103,143	383,816	778,227
10% Contingency	10,314	38,382	77,823
Facility Cost	113,457	422,198	856,050
A&E Fee @ 6%	6,810	25,300	51,300
MGT & Coord. Fee 4%	4,540	16,900	34,200
Grand Total	124,807	464,398	941,550

FIGURE 6–36b
DISTRIBUTION OF FACILITY COMPONENT COSTS – GD20

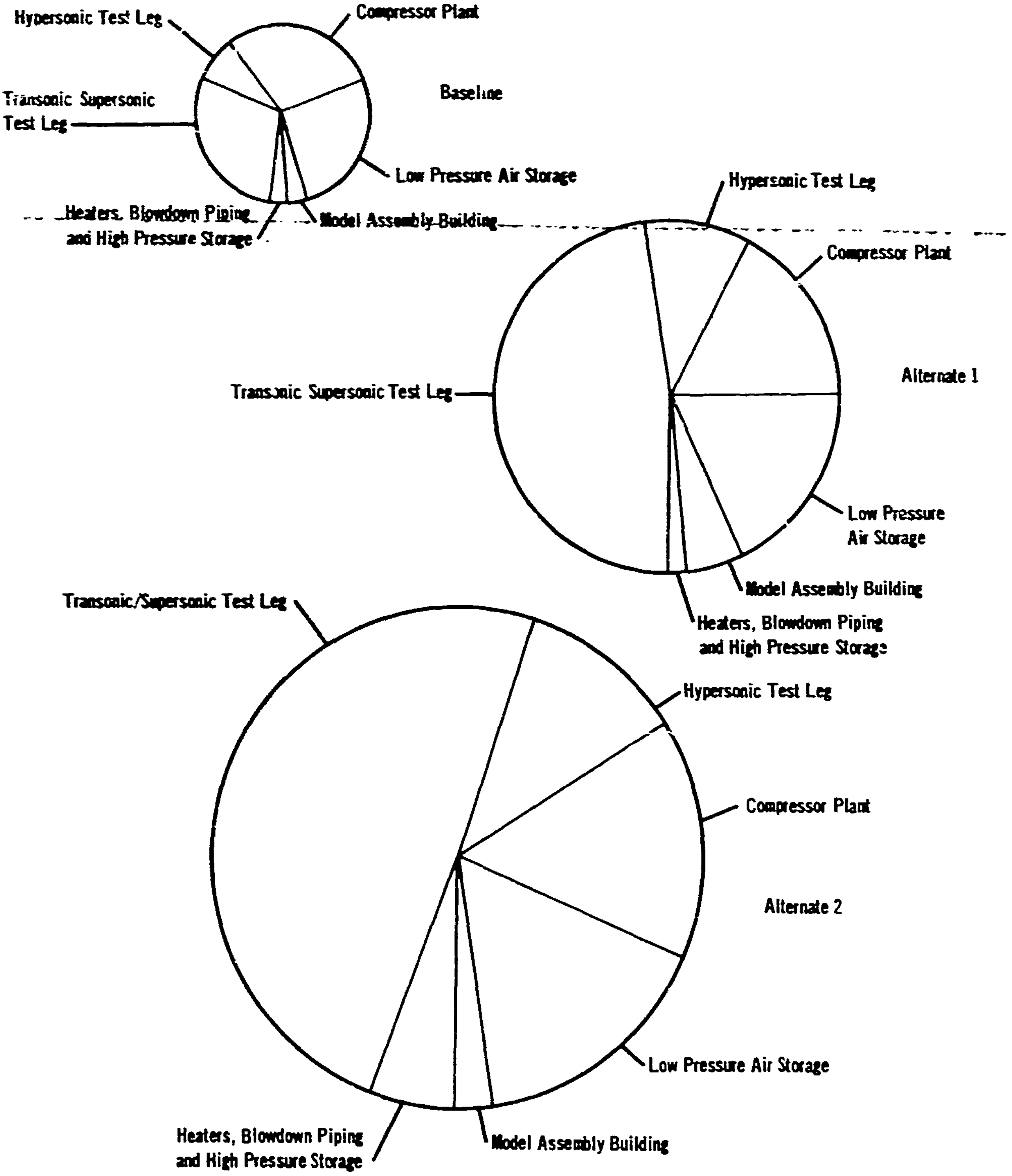


FIGURE 6-36c
GD20 OPERATING COST SUMMARY

Operating Cost – Dollars/Occupancy Hour	Baseline	Alternate 1	Alternate 2
Repair and Maintenance	1,876	7,024	15,105
Staffing	1,000	1,000	1,000
Power	365	1,770	4,325
Total	3,241	9,794	20,430

The transonic/supersonic test leg, the low pressure air storage and the compressor plant comprise the three main cost items, with the hypersonic test leg costing approximately 27% of the transonic/supersonic test leg. The major specifications of the two test legs which drive their cost are firm, and no major cost savings are expected to be made in this area. As in GD3, a tradeoff of compressor flow rate for reduced test utility can be made to reduce compressor costs, while refinement of the storage volume and pressure requirements should result in smaller storage volume costs.

A cost analysis will be made in Phase III which reflects the savings to be expected by integrating the GD20 facility with the 16T and 16S tunnels at AEDC. Savings will be attained by sharing of at least part of the compressor capacity with AEDC facilities, elimination of the separate electric substation for GD20 and sharing of the model assembly building with the 16T and 16S facilities.

6.2.9.3 Development Assessment - The integrated facility GD20 consists of two test legs of relatively conventional design, differing from existing facilities mainly in size. No major technological risks should be present, but detailed studies and scale model evaluation should be done in the areas indicated in Section 6.2.8.3 for the transonic/supersonic test leg and the hypersonic test leg before a commitment to a firm engineering design is made. As defined in Section 6.2.8.3, the confidence level associated with this facility is primarily level 5. The air storage system because of its size and storage pressure combination should be considered level 4. The technical risk associated with achieving the performance goals is minimal, the practical problems of integrating the hardware items into an operational facility, however, could be significant and probably will depend to a significant degree on the attention paid to small details when designing the actual tunnel complex.

6.2.10 GAS PISTON DRIVEN HYPERSONIC IMPULSE WIND TUNNEL (GD7) - This facility is an impulse type hypersonic wind tunnel operating from Mach 8 to 13, and employing the gas piston driver concept, as developed at the NOL and using nitrogen as the test gas. The details of the facility test leg are shown in Figure 6-37 and the schematic drawing of the facility is Figure 6-38. The gas piston concept was refined as an operational research facility by Professor Victor Zakkay of New York University. In principle, it is an attempt to extend the run time of an existing class of wind tunnels, the reservoir heated impulse tunnel. This concept has been further refined by the Naval Ordnance Laboratory (NOL), Silver Springs, Maryland. This concept can be applied to nearly any enthalpy source concept which stores a hot, pressurized gas in a closed reservoir. A characteristic of this type facility is that as mass is removed from the reservoir, the pressure and temperature decrease, continually changing the test section conditions. The reservoir is normally sized so that the rate-of-decay of the reservoir pressure and temperature is slow enough that quasi-steady state conditions apply. That is, in the time an air parcel moves over the model and some distance downstream, the conditions are approximately constant. For facilities in this category, such as Hotshot impulse wind tunnels, a nominal criterion is a density decay of 1% per millisecond, based on initial conditions at the time of diaphragm rupture. For this criterion, the ratio of arc chamber volume to throat area is:

$$\frac{V_R}{A^*} = 964.6 \frac{\left(\frac{T_o}{1000}\right)}{\left(\frac{H_o}{1000}\right)^{.391}}$$

V_R = reservoir volume (in^3)
A^* = throat area (in^2)
H_o = stagnation enthalpy (Btu/lb)
T_o = stagnation pressure (°R).

Only the gas energy is pertinent in determining the decay rate, and the absolute pressure affects only the enthalpy corresponding to a given temperature.

LTV Corporation, Aerospace Division, approached the problem of rapid pressure and temperature decays for their 14-inch (.354 m) Hotshot tunnel by designing a hydraulically driven piston which was the rear wall of the reservoir volume. The piston could then be driven at a speed providing constant properties in the arc chamber, plus providing for expulsion of most of the gas in the reservoir (Reference (13)). This design provided one or more seconds of uniform testing. Professor Zakkay's concept replaces the mechanical driven piston with a gas piston in order to reduce the complexity in design, operation, and control associated with the mechanical system. The gas piston consists of admitting cold gas to the heater reservoir at a rate equal to that flowing through the throat. Since the cold gas is from four to eight times more dense than the hot gas, it can, under the proper conditions, act as a piston, providing constant pressure and temperature in the reservoir, while expelling most of the heated gas. For a vertical heater, with the cold gas entering at the bottom of the reservoir, minimal mixing occurs between the cold and hot gas, providing the interface velocity is low subsonic. For a

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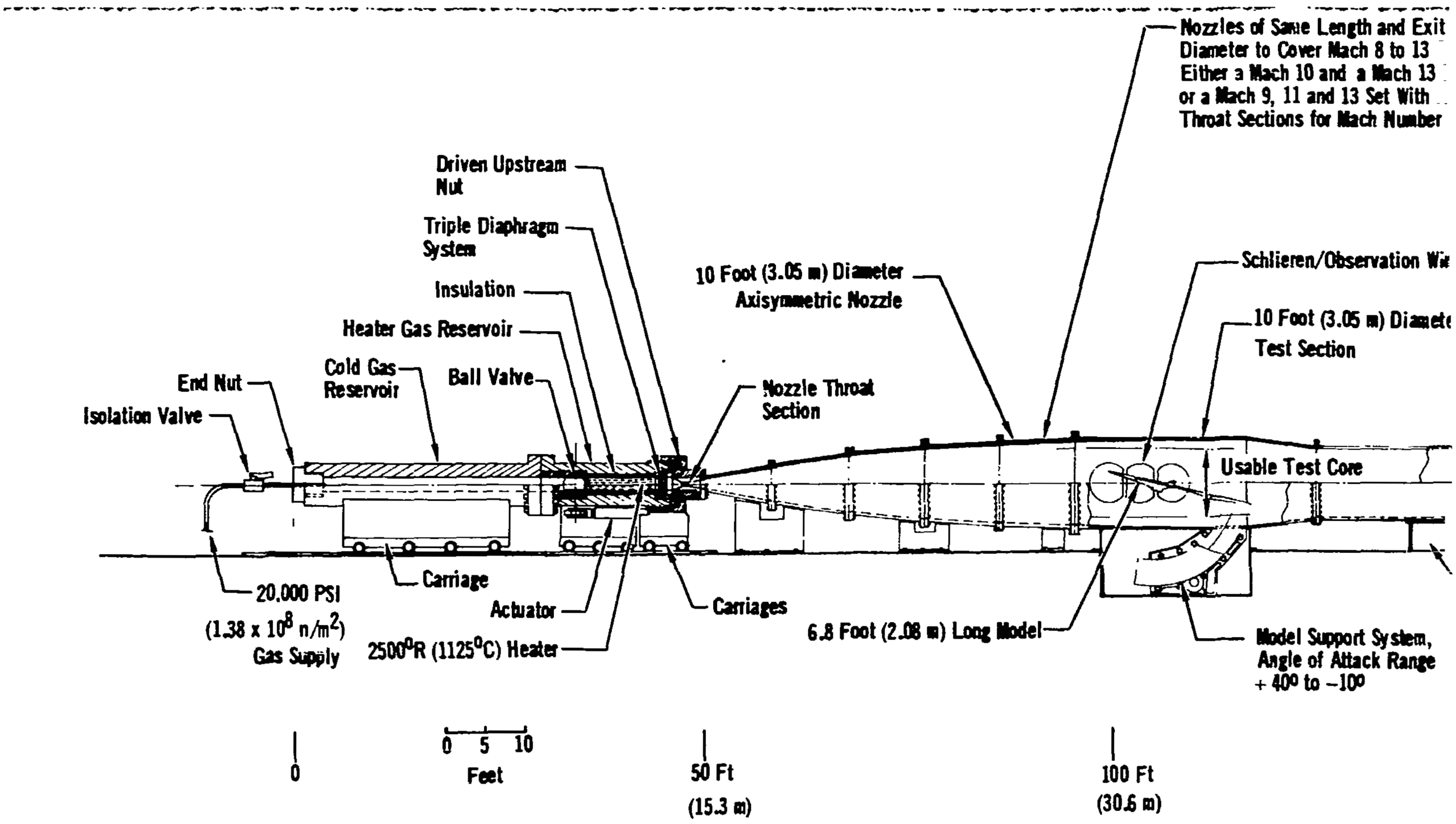
FIGURE 6-37
GD 7, GAS PISTON HYPERSONIC WIND TUNNEL
(Mach Number 8 to 13)



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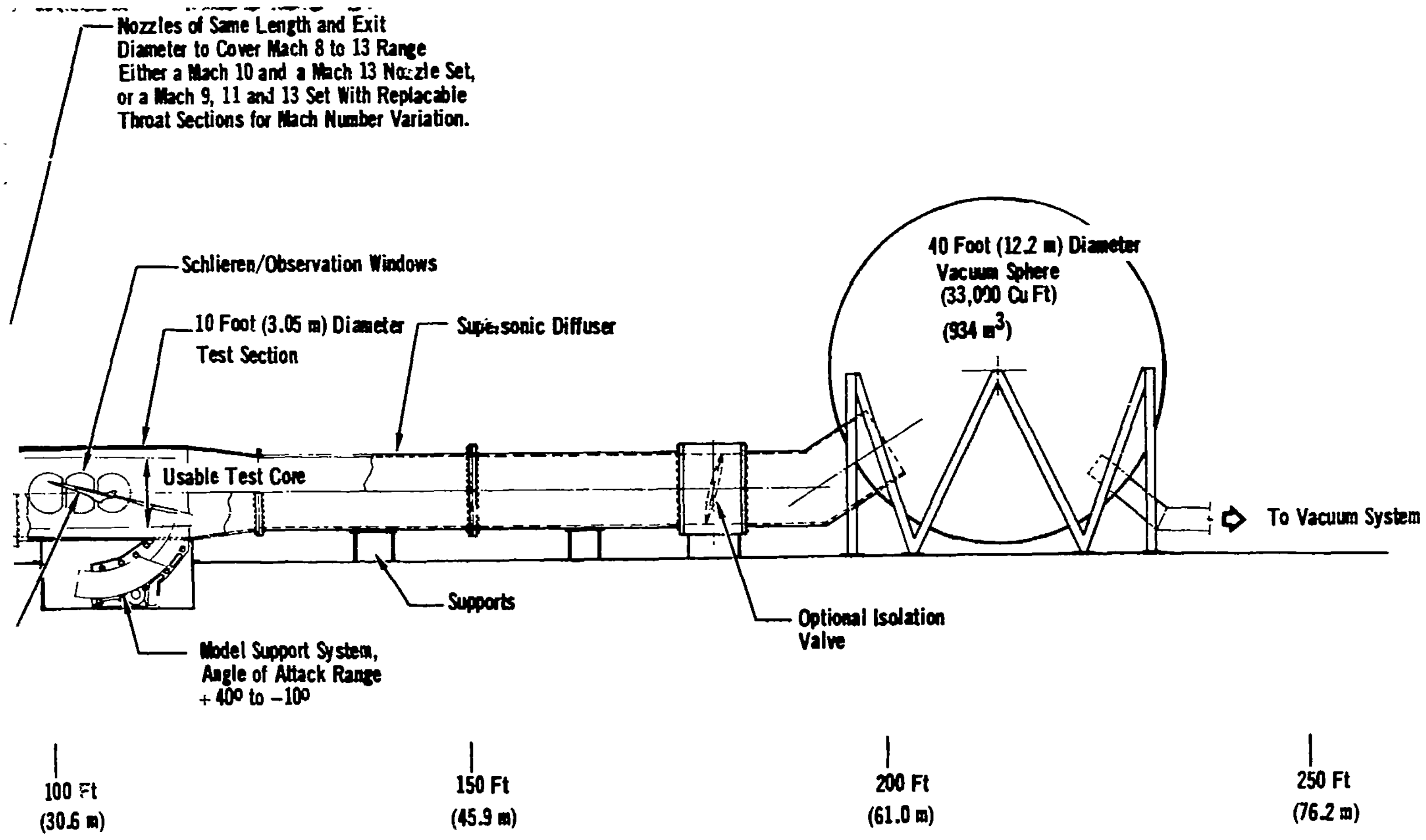
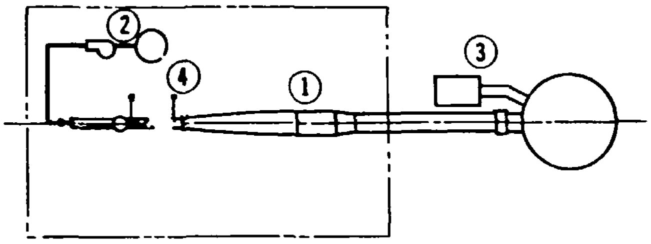


FIGURE 6-38
SCHEMATIC LAYOUT OF GD7 HIGH REYNOLDS NUMBER GAS PISTON DRIVEN HYPERSONIC WIND TUNNEL



Legend:

① **Test Leg**
② **Nitrogen Gas Supply**
③ **Vacuum Pumps**
④ **Electric Heater**

horizontal heater, the interface must move at specific velocity limits based on the Froude number of the interface velocity. The Froude number is:

$$F_R = \sqrt{\frac{V^2}{2gD}} \geq 12 \qquad D = \text{chamber diameter}$$

with the minimum value permissible for restricting the undercutting of the cold gas indicated (from NOL data). As indicated, nearly any reservoir heating system could be employed, some examples being:

- Inductive or capacitance energy storage arc heater system as for Hotshot impulse wind tunnels, for temperatures between 1800°R (1000°K) and 9000°R (5000°K) with nitrogen.
- Arc heater reservoir heating system proposed by W. B. Boatright of NASA Langley based on a continuous operation arc heater (HEAT) for temperatures up to 7200°R (4000°K) in clean air.
- Electric heater employing a metal matrix for temperatures up to 2500°R (1400°K) with clean air.
- Electric heater employing a graphite matrix for temperatures up to 5400°R (3000°K) with nitrogen.

Because of the experience accumulated at NOL through developing and operating graphite heaters, the last concept was chosen as the best initial step, having the least risk, as it is based on equipment already in operation and offering less repair and maintenance problems such as associated with very large Hotshot facilities. However, any of the above concepts could be utilized, depending on their degree of development, operating costs, and the requirement for air instead of nitrogen (such as for combustion studies) at the time serious consideration is being given to acquiring such a facility. One of the more straightforward substitutions would be replacing the graphite heater elements with superalloy metal heaters to achieve an air testing capability.

Like the other gas dynamic facilities, this facility, in its baseline definition, operates at one-fifth of the maximum flight Reynolds number throughout its range. Its performance in relation to the other gas dynamic facilities is shown in Figure 6-28.

An impulse mode of operation was chosen because of the stagnation pressure and temperature requirements for Mach 13. The high water cooling capability that a continuous or intermittent operating facility would require, in addition to the very costly compressor acquisition and operating costs, make the impulse mode very attractive in this case. The traditional factor of poor test utility based on the short run times of impulse facilities is minimized by the selection of the gas piston driver mechanism. Instead of run times of around 100 microseconds associated with shock tube drivers, or of 100 milliseconds associated with hot shot type drivers, the gas piston is expected to produce run times on the order of 1 to 4 seconds. A high pitch rate hydraulically operated model support strut will be able to complete one pitch polar per shot in this test time, in contrast to the more usual one data point per shot. This feature of a variable angle of attack system for an impulse wind tunnel has been accomplished in hotshot wind tunnels at both MCAIR and AEDC. This results in a ten-fold improvement in test utility. In addition, the relatively low pressures and temperatures specified (in comparison with most impulse facilities), should result in a driver design which requires comparatively low amounts of maintenance. This results in a high shot rate, estimated at 4 per 8 hour shift.

The test section size of GD7 is 10 ft (3.05 m) in diameter, and like all the gas dynamic facility test sections, has been sized on the basis of the development in Section 6.2.2.

6.2.10.1 Specifications - The following table gives the physical and operating specifications of the baseline and alternate facility definitions. The baseline facility is the minimum size facility producing one-fifth flight Reynolds number, Alternate 1 is a facility 2.5 times as large as the baseline, but producing the same Reynolds number, Alternate 2 is the minimum size facility producing one-half flight Reynolds number, and is the same size as Alternate 1.

		Baseline	Alternate 1	Alternate 2
Test Section Diameter	ft	10	25	25
	(m)	(3.05)	(7.63)	(7.63)
Mach Number Range		8 to 13	8 to 13	8 to 30
Stagnation Pressure	psia	1000 to 18,800	400 to 7,520	1,000 to 18,800
	(N/cm^2)	(690 to 12,970)	(276 to 5,180)	(690 to 12,970)
Stagnation Temperature	°R	1260 to 2500	(1260 to 2500	1260 to 2500
	(°K)	(700 to 1390)	(700 to 1390)	(700 to 1390)
Run Time	sec	1 to 4	1 to 4	1 to 4
Tunnel Recycling Time	hr	2	2	2
Test Conditions				
o Maximum Mach				
Mach Number		13	13	13
$\mathrm{Re}\sqrt{c}$		$6.55\mathrm{x}10^7$	$6.55\mathrm{x}10^7$	$16.4\mathrm{x}10^7$
P_o	psia	18,800	7,520	18,800
	(N/cm^2)	(13,000)	(5,190)	(13,000)
T_o	°R	2,500	2,500	2,500
	(°K)	(1,390)	(1,390)	(1,390)
$\dot{\omega}$	lbm/sec	837	2,090	5,230
	(kg/sec)	(380)	(950)	(2,370)
o Minimum Mach				
Mach Number		8	8	8
$\mathrm{Re}\sqrt{c}$		$1.5\mathrm{x}10^8$	$1.5\mathrm{x}10^8$	$3.75\mathrm{x}10^8$
P_o	psia	3,210	1,283	3,210
	(N/cm^2)	(2,210)	(874)	(2,210)
T_o	°R	1,200	1,200	1,200
	(°K)	(700)	(700)	(700)
$\dot{\omega}$	lbm/sec	2,114	5,290	13,200
	(kg/sec)	(960)	(2,400)	(6,000)
Gas Piston Driver Working Pressure	psia	20,000	8,000	20,000
	(N/cm^2)	(13,800)	(5,500)	(13,800)
Electric Power for Heater	kW	100	250	625
Volume Hot Chamber	ft^3	4.57	11.4	28.6
	(m3)	(.129)	(.323)	(.809)
Volume Cold Chamber	ft^3	13.7	34.2	85.5
	(m^3)	(.388)	(.967)	(2.42)

		Baseline	Alternate 1	Alternate 2
Booster Pump				
Capacity	scfm (m^3/min)	20 (.566)	50 (1.41)	125 (3.54)
Pressure	psia (N/cm^2)	20,000 (13,800)	8,000 (5,500)	20,000 (13,800)
Vacuum System				
Volume	ft^3 (m^3)	33,500 (948)	83,800 (2,370)	210,000 (5,940)
Pump Capacity	scfm (m^3/min)	400 (11.3)	1,000 (28.3)	2,500 (70.7)
Min. Pressure	psia (N/cm^2)	.0354 (.0244)	.01417 (.0098)	.0354 (.0244)

6.2.10.2 Facility Component and Cost Summary - Figure 6-39 shows a compilation of the costs estimated for each of the facility components and the operating cost. The estimates were made by the methods discussed in Section 6.1.

The "pie" chart breakdown (Figure 6-39b) indicates that, unlike most of the other gas dynamic facilities, the test leg is the component most important to total cost. This is the direct result of choosing an impulse type facility with its very low auxiliary equipment requirements. Consequently, this indicates that refinement of the cost estimates of the test leg components will lead directly to a high confidence level in the total costs. This refinement is required also on a technical basis, as will be pointed out in the following section, because of the use of a new driver concept.

Operating costs are low, but are also very sensitive to a better facility definition. For instance, power and consumables for the baseline definition are 21% of the total costs. This item is almost 100% comprised of liquid nitrogen supply cost, the cost of electricity for the booster pump, heater, and vacuum pump being negligible. This nitrogen cost may be eliminated upon further design refinement, if it is deemed practical to use air as the test gas.

6.2.10.3 Development Assessment - This facility concept is based on an existing design under development at the Naval Ordnance Laboratory for three test legs of Mach number 10, 15, and 20, but of a size smaller than GD7. Based on the knowledge acquired in the development of the NOL facilities, GD7 should have a confidence level of 5 for most of its components. The exception is the air storage system which represents a volume/pressure combination consistent with level 4, or level 3, depending on the interpretation of the existing capability. The control valves for this pressure level and mass are certainly level 3. Detailed studies and scale

FIGURE 6–39a
GD7 COMPONENT AND COST SUMMARY

Facility Component	Cost Estimate $1000's		
	Baseline	Alt 1	Alt 2
1. TEST LEG Sub Total	9,203	48,602	89,465
1.1 Gas Piston Driver Assy, (Upstream Chamber, Downstream Chamber, Quick Opening Ball Valve, Electric Heating Elements, Throat Assy, Support Carts and Track, Electric Substation)	4,286	26,825	66,760
1.2 Contoured Aluminum Axisymmetric Nozzle	123	1,920	1,920
1.3 Test Section and Schlieren Windows	383	5,970	5,970
1.4 Model Support (Hydraulically Actuated)	100	250	625
1.5 Diffuser Assembly	264	4,120	4,120
1.6 Vacuum Sphere	147	367	920
1.7 Building (Control Room, Photo Lab, Inst. Lab., Office Area, Model Set-Up Area	700	4,370	4,370
1.8 Tunnel and Model Automatic Control System	100	100	100
1.0 Instrumentation and Data Acquisition (Transducers, Amplifiers, Power Supply, Analog/Digital Converter, Tape Recorder, Schlieren System)	3,100	4,680	4,680
2. NITROGEN (Storage Dewar, Transfer Lines, LN_2 Pump, Heat Exchanger, Booster Pump, Distribution Piping and Valves	125	312	780
3. VACUUM PUMPING SYSTEM	360	900	2,250
Total	9,688	49,814	92,495
Contingency @ 10%	969	4,981	9,249
Facility Cost	10,657	54,795	101,744
A&E Fee @ 6%	639	3,290	6,100
MGT & Coord @ 4%	427	2,190	4,070
Grand Total	11,723	60,275	111,914

FIGURE 6-39b
DISTRIBUTION OF FACILITY ACQUISITION COSTS - GD7

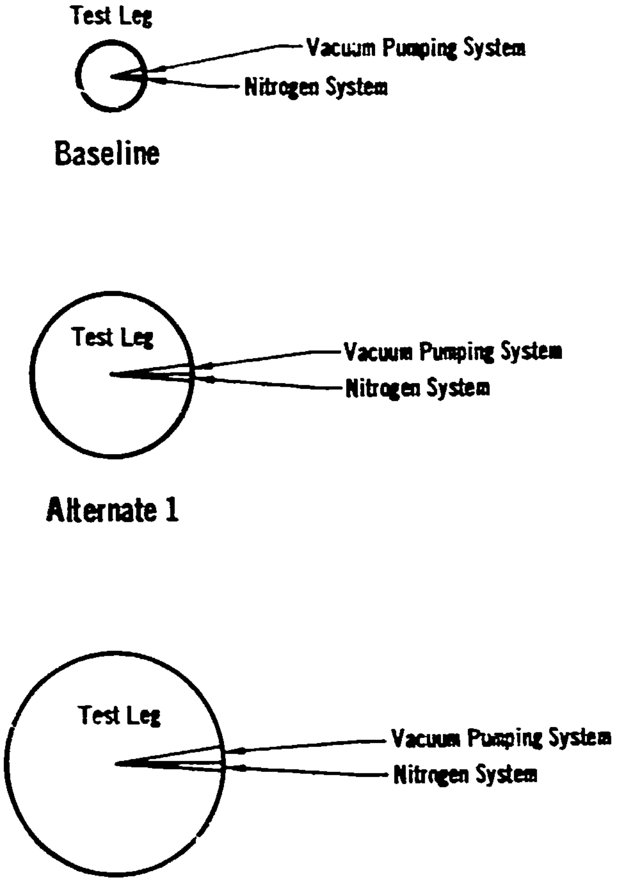


FIGURE 6-39c
GD7 OPERATING COSTS

Operating Costs – Dollars/Occupancy Hours	Baseline	Alternate 1	Alternate 2
Repair and Maintenance	175	900	1,680
Staffing	500	500	500
Power and Consumables	181	455	1,140
Total	856	1,855	3,320

model prototype development work could be required on the following items.

- Development of proper proportioning and sizing of gas piston driver geometry, and control valve operation so that non-decaying pressure and temperature can be achieved throughout the desired test time. Current work in this field has been focused on driver development for higher Mach number facilities than GD7.
- Evaluation of the impact of using air as the test gas (rather than nitrogen) on the electric heating elements and the reliability and maintenance of the driver assembly. If practical, the use of air would result in a worthwhile operating cost saving, and perhaps a better research value. This additional research value would arise primarily from the propulsion area, since for low temperature Reynolds number facilities, no distinct difference should arise from using air and nitrogen, unless combustion is involved.

6.2.11 EVALUATIONS AND CONCLUSIONS - The gasdynamics facilities provide increased research value as their maximum Reynolds number capability is increased. Figure 6-40 shows this trend for the C/1 combination, which consists of GD20 plus GD7, covering the entire Mach number range of the potential operational vehicles, from Mach number 0.3 to Mach number 12. The baseline facilities about triple existing maximum capability, and the second alternate facilities provide about seven times the existing maximum capability in terms of Reynolds number. The increase in research value is not a linear function of Reynolds number capability, and providing seven times the Reynolds number capability only increases research value by two and one-half times. Two factors should be noted in interpreting the research value. The evaluation was made on the basis of achieving a given fraction of the maximum Reynolds number consistent with the maximum projected performance of the nine potential operational hypersonic aircraft (Volume VI). As discussed in Volume II, attainment of 1/5 of the maximum Reynolds number means that for the most probable cruise conditions of some of the potential operational vehicles, this capability represents attainment of from 3/5 to 4/5 of the cruise Reynolds numbers. Existing facilities which were nominally rated at 1/15 the maximum Reynolds number (see Figure 6-28) can provide about 1/5 of the cruise Reynolds number. As shown, attainment of 1/5 of the maximum Reynolds number yields a research value of about 60%. Extrapolating this curve to near full scale values implies a research value of nearly 95%. Thus, the research value of the facilities, in areas not requiring attainment of maximum Reynolds numbers as dictated by the 2000 psf (95,700 N/m^2) dynamic pressure limit, are higher than indicated in Figure 6-40. Figure 6-41 shows the increase in research value obtained by increasing facility size while maintaining a given Reynolds number capability, and Figure 6-42 relates the research value to increased acquisition costs. The baseline facility is the minimum size capable of providing the desired Reynolds number. There is only a small increase in research value with facility size, because the model size for the baseline facility is already large enough that additional size gains very little in actual research capability. Translating Figures 6-40 and 6-41 into cost comparisons vs research value, the amount of money required to provide increased Reynolds numbers

FIGURE 6-40
COMPARISON OF MAXIMUM REYNOLDS NUMBER CAPABILITY WITH RESEARCH VALUE FOR MINIMUM SIZED GASDYNAMIC FACILITIES

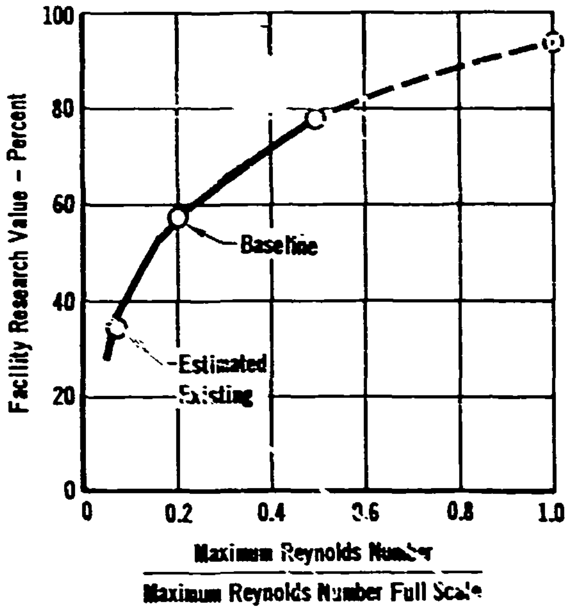


FIGURE 6-41
COMPARISON OF WIND TUNNEL SIZE FOR 1/5 MAXIMUM FULL SCALE REYNOLDS NUMBER SIMULATION, WITH FACILITY RESEARCH VALUE

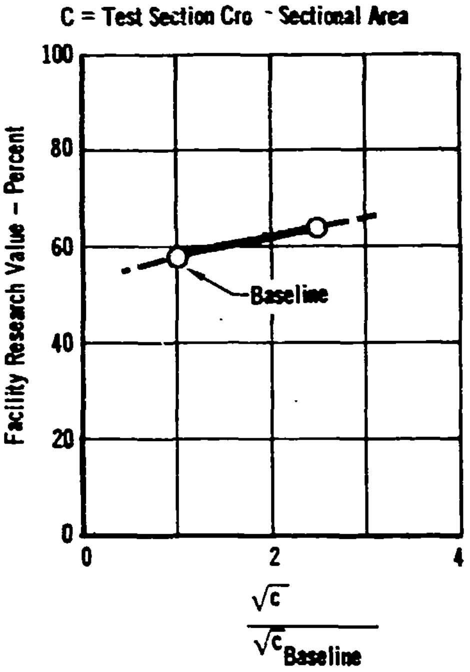
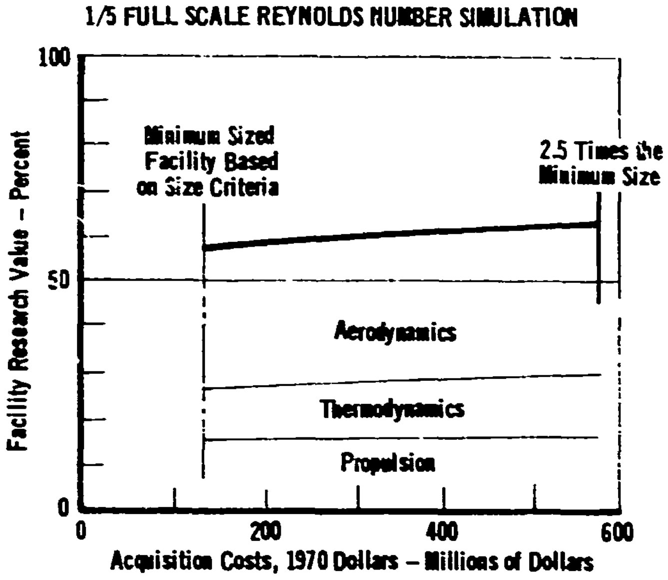


FIGURE 6-42
EFFECT OF FACILITY SIZE ON RESEARCH CAPABILITY AND COSTS FOR A GIVEN REYNOLDS NUMBER CAPABILITY



is very large. Figure 6-43 demonstrates the cost increment between one-fifth maximum Reynolds number simulation and one-half maximum Reynolds number simulation. If the cost relationship were extrapolated to full scale Reynolds number simulation capability, the total acquisition cost approaches 5.9 billion dollars. These costs shown in Figure 6-43, are for the C/1 combination. Attaining maximum Reynolds number capability is very costly. The one-fifth maximum Reynolds number facilities already can achieve near full scale Reynolds number simulations for many of the cruise conditions. Extending the capability to one-half the maximum Reynolds number provides additional simulation primarily for altitudes lower than cruise and approaches maximum vehicle performance. In this context, the additional research return does not seem to be justified by the costs.

This data is summarized in tabular form in Figure 6-44. The upper table in that figure shows the increase in research capability and cost as facilities are combined to achieve a full Mach number range. The GD20 facility consists of GD3 plus an additional hypersonic leg derived from the Phase I GD15 facility. Because the facility mass flow and size decreases with increasing Mach number, the cost of acquiring additional Mach number capability becomes more economical. The most costly increment in the operational envelope of the potential operational hypersonic aircraft is the 0.3 to 5 range. This lower Mach number range is probably an essential element in the overall research necessary for the potential operational hypersonic aircraft.

FIGURE 6-43
COMPARISON OF REYNOLDS NUMBER CAPABILITY WITH RESEARCH CAPABILITY AND ACQUISITION COSTS

FOR APPLICABLE RESEARCH OBJECTIVES IN AERO/THERMODYNAMICS AND PROPULSION

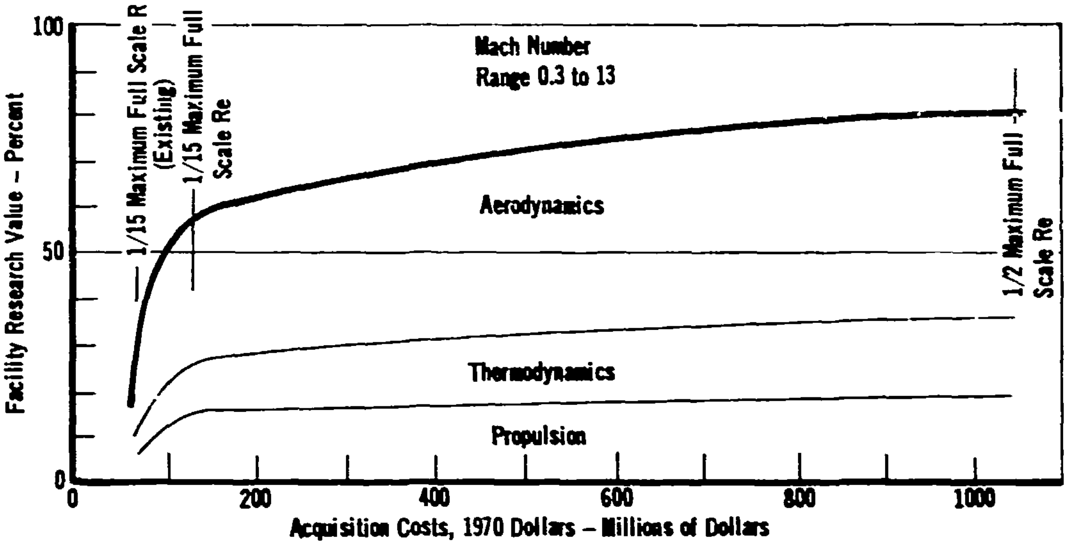


FIGURE 6-44
FACILITY EVALUATIONS (GAS DYNAMICS)

Facility	Average Facility Research Value (Percent)	Acquisition Cost (Millions of Dollars)	Mach Number Range
GD3	44	97.2	0.3 to 5
GD20	53	124.8	0.3 to 8
GD20 + GD7	60	136.5	0.3 to 13

Average Thermo/Propulsion Research Objectives

Facility	Average Facility Research Value (Percent)	Acquisition Cost (Millions of Dollars)	Mach Number Range
GD20 + GD7 Baseline	60	136.5	0.3 to 13
GD20 + GD7 Alternate 1	63	524.7	0.3 to 13
GD20 + GD7 Alternate 2	78	1,053.5	0.3 to 13

Based on the analysis of the cost breakdowns presented for each facility, the component which provides the test capability (tunnel leg) generally requires the least dollar outlay and is the best defined. Therefore, for Phase III the tunnel legs will be considered "near optimum" and major emphasis will be placed on the facility system as a whole and providing better definition of the more costly, and less precisely defined support hardware.

6.3 ENGINE RESEARCH FACILITIES

The engine research facilities are provided to accomplish research associated with the propulsion, operational, and subsystem research objectives, and, when augmented with aerodynamic nozzles, accomplish research associated with the thermodynamic and structural research objectives. The fundamental purpose of these facilities is to provide flight duplicated conditions for as large an engine as necessary or practical. For the turbo-machinery and subsonic combustion ramjets operating at Mach numbers less than six, full scale engine/inlet capability can be provided. For supersonic combustion ramjets (SCRAMJETS) and convertible scramjets, it does not appear possible to provide full scale, complete engine capability for all sizes of engines and testing is limited in some cases to modified direct testing techniques for subscale engine modules. Both classes of facilities exceed present capability in providing flight duplicated conditions at very large mass flows by a considerable margin. For most of the engine facilities, the concepts are based on specific hardware components in operation at existing installations, but larger in size and with higher performance levels. Increasing their performance levels appears to be within the current technology. The continuous air heaters represent a significant challenge to the current technology and are the hardware items pacing facility development, in most cases. For one of the scramjet facilities, the equipment requirements significantly exceed current technology limits. The size and performance of the engine facilities is based on analyses of the potential operational hypersonic aircraft and their associated engines.

6.3.1 DESIGN CRITERIA - The primary criterion is trajectory duplication. Figure 6-45a presents the isentropic reservoir conditions, and mass flow per unit area in the test section as a function of flight Mach number and altitude. For reference, the general bounds of the operational hypersonic aircraft are given (see Figure 6-15). These are the conditions required in the reservoir of a nozzle for free jet testing. Provision of these conditions on a continuous basis in excess of Mach number 6 for the mass flow and enthalpy required for full scale engines is quite a challenge. The primary limitation is the heater required to obtain gas temperatures greater than 3000°R (1670°K). There is another natural demarcation at Mach 6 in that duct pressures, heat transfer, and net thrust considerations favor transition to supersonic combustion, although subsonic combustion could be maintained up to Mach numbers as high as eight at higher equivalence ratios. Free jet testing capability up to Mach number 6 with flight duplicated conditions could be provided for full scale turbomachinery and ramjets. For reference to specific engine sizes, see Volume V. In many cases, the necessity for free jet testing is not consistent with the additional cost, and direct connect testing is sufficient for turbomachinery and ramjets. Figure 6-45b gives the reservoir conditions and mass flow per unit area, as a function of altitude and Mach number, for subsonic combustion, direct connect testing. The shaded area represents the simulation capability provided for the Phase II turbomachinery and ramjet test facilities. For both free jet and direct connect testing, a maximum duct pressure of 150 psia ($103 N/cm^2$) was used. Compared to free jet testing, the direct connect pressures are less challenging. Figure 6-45c gives the reservoir conditions and mass flow per unit area, as a function of altitude and Mach number, for modified direct connect testing of supersonic combustion ramjets. Because of the very high reservoir pressures required for free jet testing, using modified direct techniques permits full duplication to Mach number 9, and some simulation at higher altitudes up to Mach number 12. The light shaded area indicates

FIGURE 6–45a
RESERVOIR CONDITIONS AND MASS FLOW REQUIRED FOR TEST SECTION DUPLICATION OF FLIGHT CONDITIONS, FREE JET ENGINE TEST, OR WIND TUNNEL

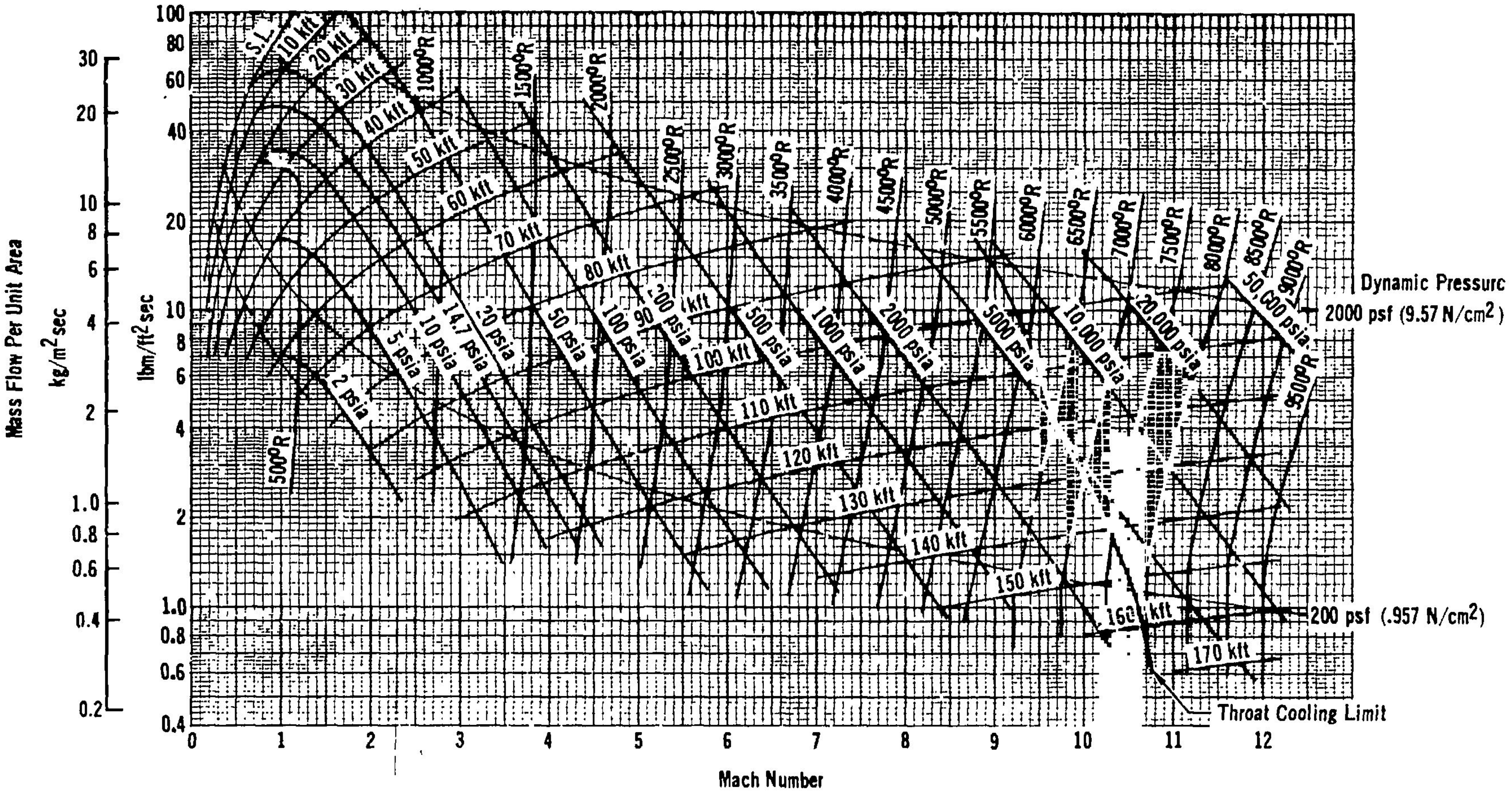


FIGURE 6-45b
RESERVOIR CONDITIONS AND MASS FLOW REQUIRED FOR TEST SECTION DUPLICATION OF FLIGHT CONDITIONS, ENGINE TEST FACILITIES, DIRECT CONNECT, TURBOMACHINERY, RAMJET

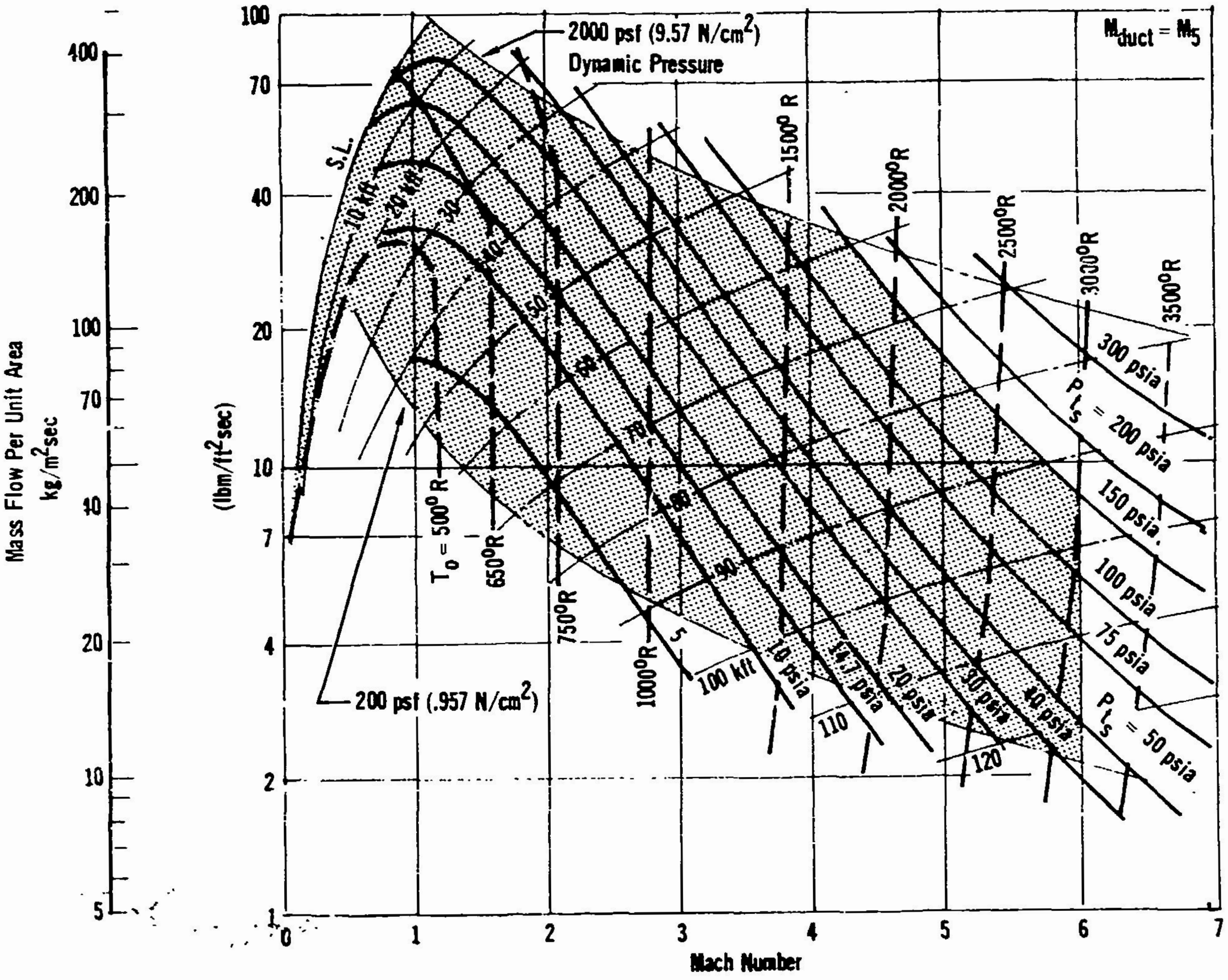


FIGURE 6-45c
CONDITIONS AND MASS FLOW REQUIRED FOR TEST SECTION DUPLICATION OF FLIGHT CONDITIONS, ENGINE TEST FACILITIES, MODIFIED DIRECT CONNECT, SCRAMJET, CONVERTIBLE SCRAMJET

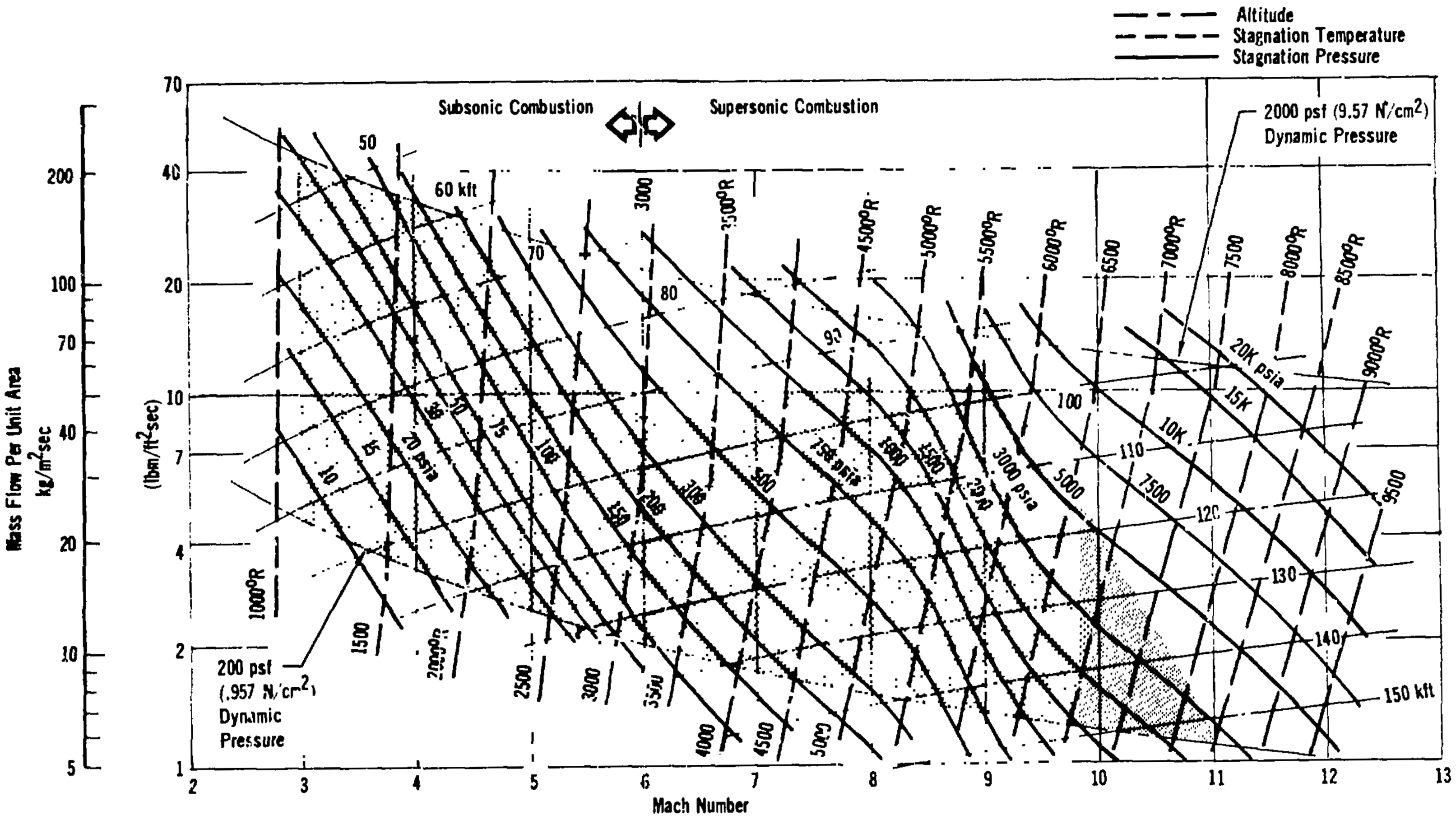


FIGURE 6-45d
INTERNATIONAL SYSTEM OF UNITS CONVERSIONS FOR RESERVOIR CONDITIONS AND MASS FLOW
TEST SECTION DUPLICATION OF FLIGHT CONDITIONS

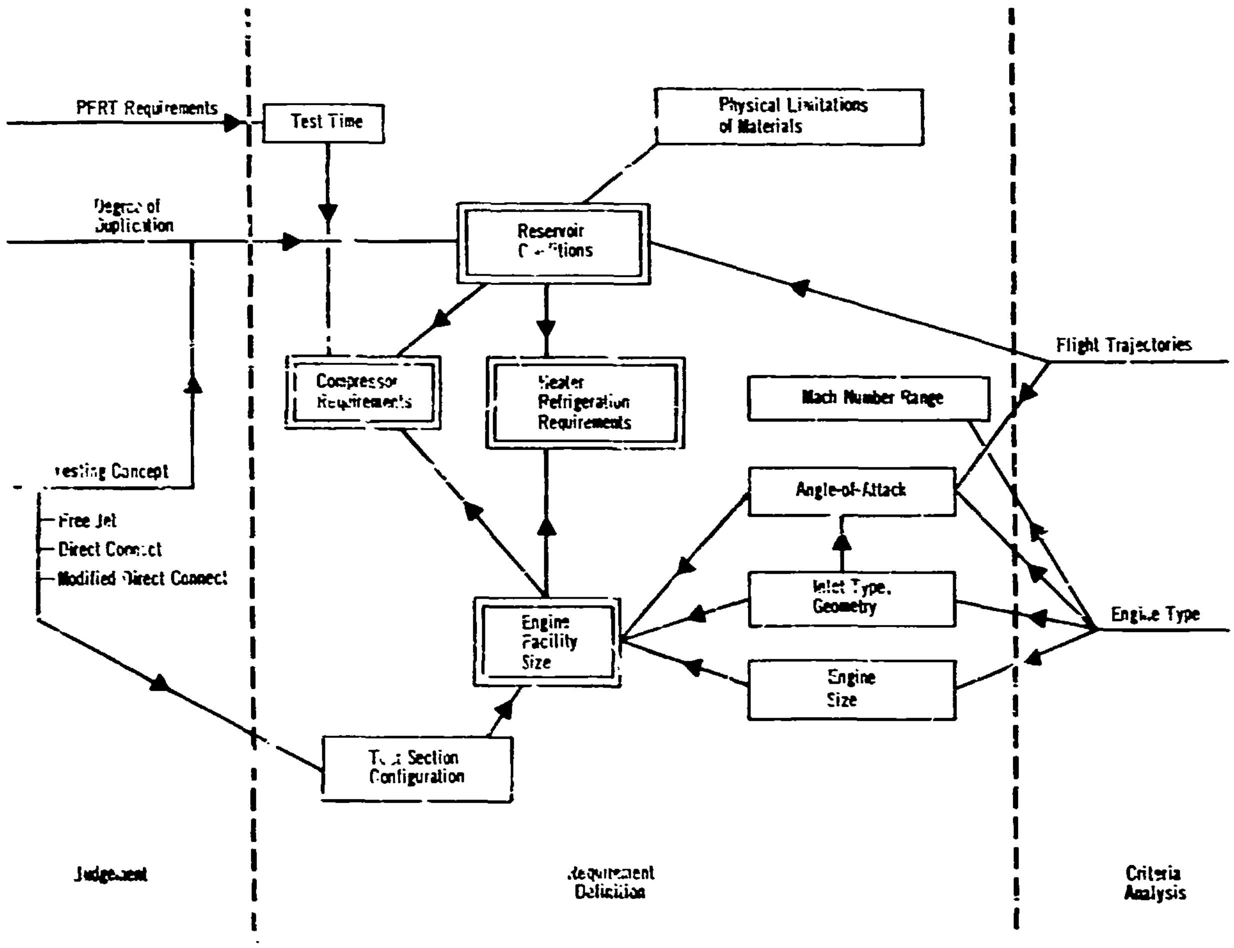
Pressure		Temperature		Geometric Altitude	
psia	N/cm^2	^0R	^0K	kilofeet	kilometers
5.8	4	450	250	0	0
10.1	7	900	500	16.4	5
14.5	10	1350	750	32.8	10
29.0	20	1800	1000	49.2	15
58	40	2250	1250	65.6	20
101	70	2700	1500	8.9	25
145	100	3250	1750	98.4	30
290	200	3590	2000	114.0	35
580	400	4060	2250	131.0	40
1,015	700	4500	2500	147.0	45
1,450	1,000	4950	2750	164.0	50
2,900	2,000	5400	3000	180.0	55
5,800	4,000	5850	3250	197.0	60
10,150	7,000	6300	3500	213.0	65
14,500	10,000	6750	3750	229.0	70
21,700	15.000	7200	4000	246.0	75
29,000	20,000	7640	4250		
58,000	40,000	8100	4500		
		9000	5000		

the area of duplication possible with the hybrid scramjet facility (E9) and the darker area, E9, as supplemented by the multirecompression heater (E8). The unshaded triangular region between the 2000 psf (9.57 N/cm^2) and 200 psf (0.957 N/cm^2) dynamic pressure limits on the extreme right side of the figure indicates a region where flight duplicated conditions are available only on an impulse basis. The throat heat transfer in this area exceeds cooling capabilities, using existing backside, high speed water film cooling data. The depression in the central shaded area represents the subsonic combustion inlet pressure limit of 150 psia (103 N/cm^2). Conversion to supersonic combustion is assumed to occur at Mach number 6, with a minimum altitude (94,000 ft, 28.7 km) acceleration to the 2000 psf (9.57 N/cm^2) dynamic pressure limit (see Figure 6-15). Figure 6-45d lists International System conversion factors for the callouts in parts a, b, and c.

The trajectory duplication dominates the reservoir conditions required for the engine facilities, while the engine size dominates the overall facility size. An additional consideration contributes significantly to the cost of the supporting compressor plant, refrigeration plant, and exhauster systems, which can represent 75% of the total facility cost. That consideration is facility run time. The assumption made in the conceptual development of these engine facilities was that engine research had to include actual investigations into the total engine operation and useful life. There may be many different flight conditions where the engine system and components must be developed to provide a necessary useful life. The facilities are capable of providing sufficient run time so that the equivalent to a PFRT schedule or preliminary qualification can be accomplished for one flight condition in about one month.

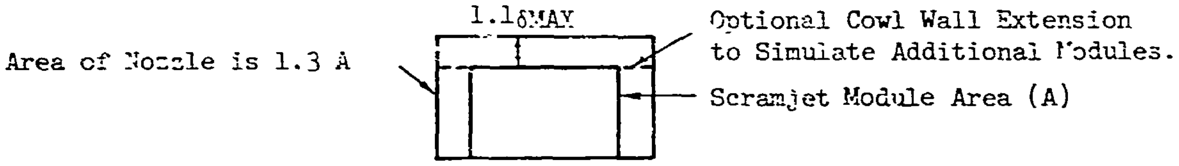
A diagrammatic representation of the engine facility synthesis is given in Figure 6-46. The interrelationships of the various inputs are such that small changes in the degree of duplication or test time have a major impact on the final facility cost and capability.

FIGURE 6-46
ENGINE FACILITY SYNTHESIS

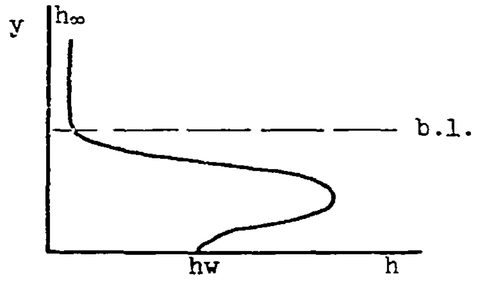


6.3.2 OPERATIONAL MODE PHILOSOPHY - Other than the trajectory duplication criterion, the single factor most affecting the engine facility concept was the judgment concerning the requirements for engine research. For the turbomachinery and ramjet engines it was considered vital that the research programs include the entire full scale engine. It was also considered vital that sufficient run time be provided so that research programs could include endurance of the complete engine system at different flight conditions. For this reason, sufficient run capability was provided for the equivalent of PFRT in one calendar month. The engine facilities are therefore continuous running facilities, which are capable of intermittent operation, if so desired. It was assumed in the calculation of the operational costs that the engine facilities could be capable of up to seven hours operation in any ten hour period.

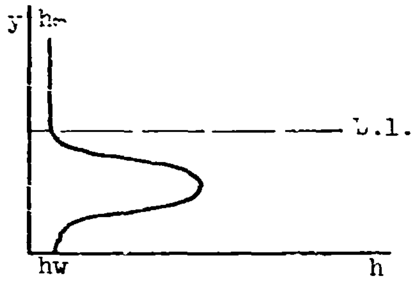
For the turbomachinery engines, the free jet test section concept departs from established practice, but the direct connect is similar to present test philosophy. The scramjet and convertible scramjet engine module test section is a new concept in modified direct connect test sections. For modified direct connect testing, the supersonic flow field upstream of the cowl of the engine module is duplicated in a nozzle system, permitting air flow through the engine module as well as around the three sides, as depicted below:



In this simulation scheme, the upstream supersonic flow and internal shock systems originating from the cowl are duplicated. The bottom wall of the nozzle represents the vehicle compression surface, and the flow adjacent to this nozzle wall enters the engine module. If conventional nozzle wall cooling practice is followed, the enthalpy distribution in the wall boundary layer would be so different from flight distributions that wall heat transfer and temperature would be greatly reduced. As depicted below, the enthalpy distribution would be substantially different.



Flight



Water Cooled Nozzle

The difference is due largely to the large amount of heat removed from the boundary layer in the process of cooling the throat. This depleted energy is not replaced from the free stream energy and the nozzle boundary layer is much colder than the corresponding flight boundary layer, because the free stream flow is isentropic, that is, constant entropy with no heat losses.

In order to provide a similar temperature in the nozzle boundary layer entering the engine, the concept presented in Figures 6-47a and 6-47b was developed. The three walls of the nozzle, whose boundary layer does not enter the engine, are conventional backside, water film cooled walls (Section A-A, Figure 6-47b). The bottom wall, where the boundary layer enters the engine module, is an attempt to duplicate the aircraft ramp structure and temperatures. To provide duplication of the Mach number upstream of the cowl, the nozzle must be adjustable through a Mach number range of about 1.7 to 5.5. (This corresponds to flight Mach numbers from 3 to 13.) To make this concept practical, the aerodynamic nozzle generating the flow was selected as an asymmetric, two-dimensional nozzle, providing one fixed wall. To provide a simple flexible nozzle concept, considering the modest Mach number requirements, a single jack flexible plate nozzle was employed. The fixed wall, opposite the flexible nozzle, is divided into three sections. The throat block region is constructed of refractory metal clad steel, which operates at a wall temperature of about 3000°R (1670°K) (Section D-D of Figure 6-47b). Backside water film cooling is provided, as the heat transfer rate in the throat region would produce surface temperatures in excess of 3000°R (1670°K) without cooling. Downstream of the throat region the heat transfer decreases rapidly as the cross section area increases, to levels characteristic of the vehicle. The structure transitions into an insulated, refractory metal shingle structure, typical of a potential operation vehicle (Section C-C in Figure 6-47b). Depending on the engine design, somewhere upstream of the engine the insulated structure is terminated and a cryogenically cooled structure begins and continues into the engine module (Section B-B, Figure 6-47b). The entire engine module is, of course, a cryogenically cooled structure. This concept then provides a realistic environment for the scramjet module in terms of boundary layer enthalpy distribution, surface condition, and aerothermodynamic conditions upstream of the engine cowl. Water cooled boiler plate engines can also be tested with little modification.

The operational engine module hardware is mounted on a thrust stand in the test section. The external flow and nozzle expansion contribute to this thrust so that some realism in the flow external to the engine and in the flow expanding from the module should be provided. An attempt to provide some degree of simulation is reflected in the external flow nozzle concept downstream of the scramjet test section. A significant portion of the fuselage afterbody contour downstream of the scramjet module exit is provided as an expansion surface. A simple replaceable construction is shown so different contours can be readily evaluated. The external flow velocity and static pressure should be closely matched if reasonable exhaust expansion is to be achieved. To provide this match, a fixed contour, adjustable nozzle is provided on the upper wall, downstream of the cowl inlet. This expands the flow from the conditions at the engine cowl to near free stream values at the module exit. For example, at the trajectory point, Mach 10 at 110,000 feet (33.5 km), the required conditions are:

P_o = 12,500 psia (8,600 N/cm^2)

T_o = 6500°R (3610°K)

V_∞ = 10,002 ft/sec (3050 m/sec)

p_∞ = .125 psia (.086 N/cm^2)

M_∞ = 10

FIGURE 6-47a
CONVERTIBLE SCRAMJET, SCRAMJET MODULE TEST SECTION
FOR 15 SQ FT (1. 39 m^2) CAPTURE AREA MODULE

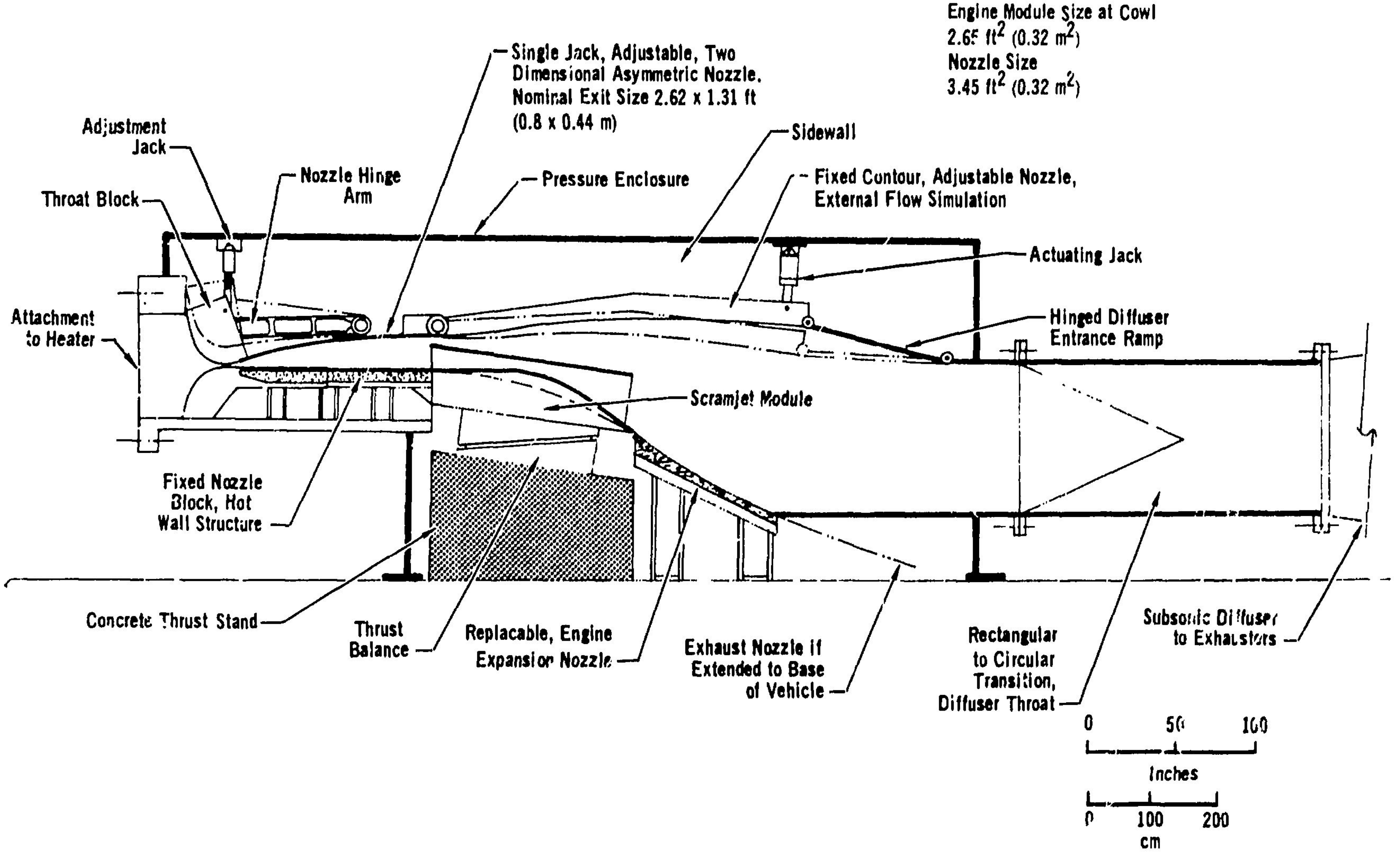
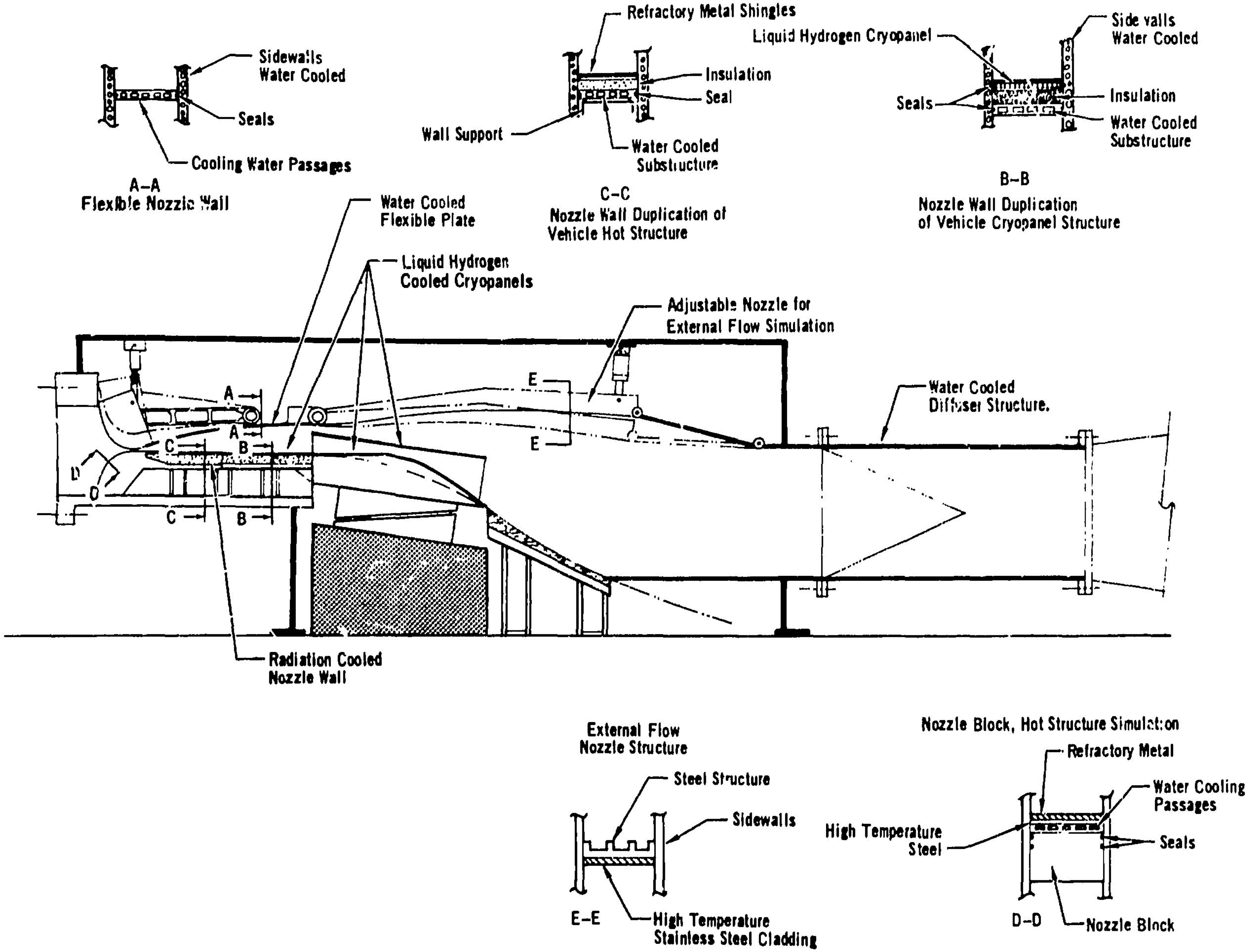


FIGURE 6-47b
CONVERTIBLE SCRAMJET, SCRAMJET MODULE TEST SECTION FOR 15 SQ FT ($1.39 m^2$) CAPTURE AREA MODULE



The modified direct connect conditions corresponding to the above trajectory point, and external flow field conditions are:

P_o = 8700 psia (6000 N/cm^2)

T_o = 6500°R (3610°K)

V_∞ = 9730 ft/sec (2980 m/sec)

P_∞ = .125 psia (.086 N/cm^2)

M_∞ = 9.5

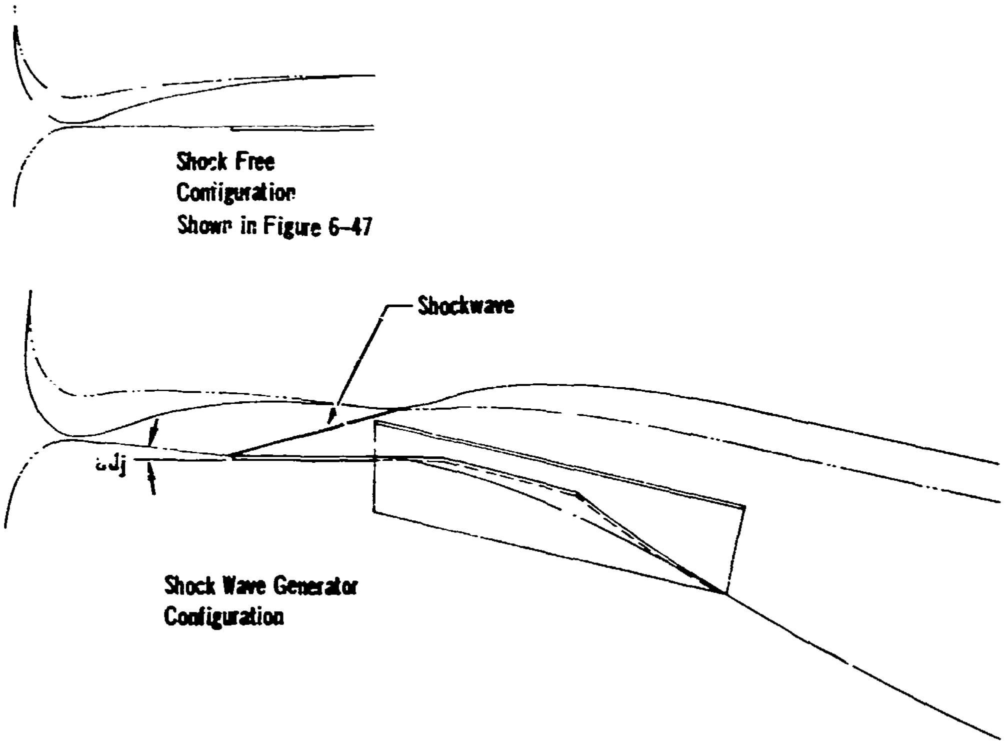
External flow conditions (M_∞, V_∞, and P_∞) very closely approximating actual flight conditions are provided by the external flow nozzle. The exhaust expansion is nearly two-dimensional, being restrained from lateral expansion by the nozzle sidewalls. This is most valid for the engine modules in the center of a cluster, and least valid for the outer modules, resulting in a need to correct the measured thrust for lateral expansion.

As a whole, this scramjet engine test section provides a relatively close duplication of the inlet and exhaust conditions, giving a reasonable basis for establishing module performance, cooling requirements, structural integrity, and operational life.

A feature which can add to the experimental simulation is the concept which provides for the ramp shock system to be adjusted on either side of the cowl lip. If the nozzle system is tilted, at a point where the shingled structure ends and the cryogenically cooled structure begins on the bottom wall, the arrangement presented in Figure 6-48 becomes possible. This one shock wave does not have the strength of three or four coalesced waves from the fuselage/inlet ramps, but an increment can be established. In this manner, an additional degree of realism might be added to the simulated environment.

This scramjet test section represented the basic experimental device to which the various energy sources were attached, to provide a range of environmental duplication consistent with each facility concept.

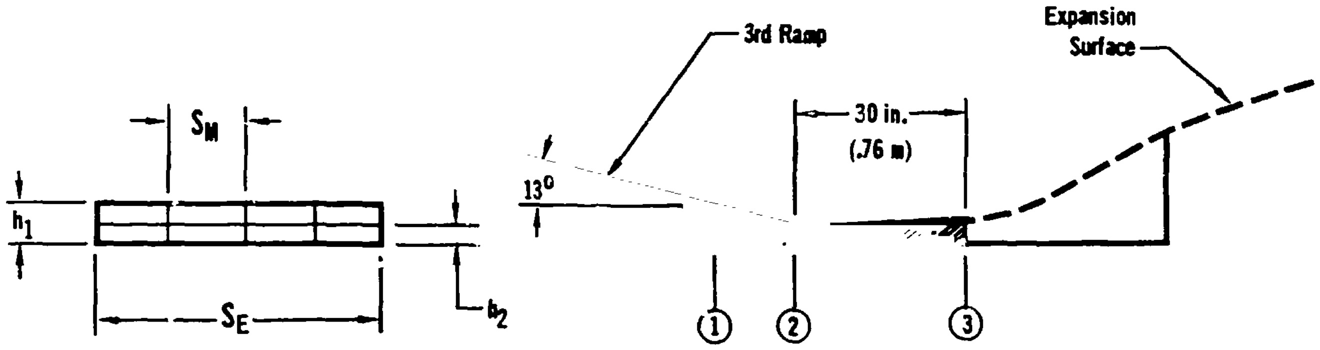
FIGURE 6–48
ALTERNATE ARRANGEMENT OF SCRAMJET ENGINE MODULE TEST SECTION TO PROVIDE LIMITED LIP SHOCK SIMULATION



6.3.3 ENGINE FACILITY PARAMETRIC VARIATION - The criteria employed to develop the turbomachinery facility design limited the number of parameters which could be arbitrarily varied. However, two tradeoff studies were made concerning the extent to which duplicated flight conditions are provided in the transonic flight regime for the free jet test leg of E20. This free jet leg primarily provides additional research capability in engine/airframe integration investigations in the supersonic flight regime. Significant cost savings might be possible by relaxing the transonic duplication requirements where the maximum facility mass flow occurs, and engine/inlet integration problems are usually less severe. Engines used to define the turbomachinery facilities are described in detail in Volume V and are summarized below:

Engine as given in Figure 2-13, Volume V	Duct diameter in (m)
turbojet ①	79 (2.0)
turbojet ②	47 (1.2)
turboramjet ③	71 (1.8)
turboramjet ④	60 (1.5)
turbofan ⑪	96 (2.4)

The scramjet engine facilities did permit variation of the size of the engine which could be accommodated in the test section. One purpose of this variation was to establish the size of the facility and technical risk involved in acquiring a capability to test a given engine size. Since the size of the scramjet engine is not dependent on the size of rotating components, considerable variations are possible. This preliminary analysis will be further refined in Phase III as better definitions of engine geometric relationship are established. The assumptions made in assessing the engine sizes were based on the geometric arrangement shown below:



$A_c = 0.045\ S_w$ = geometric capture area

$A_2 = A_c/11.3 = s_E h_2$ $\qquad \left(\frac{W}{S_w}\right)_{TAKEOFF} = 98\ \text{lb/ft}^2\ (4700\ \text{N/m}^2)$

$h_1 = 2h_2$

$h_3 = 1.2h_2$ $\qquad 16 \leq \frac{s_E}{h_2} \leq 20$

$\delta_3 = 13°$ $\qquad s_M \leq 4.2$ ft (1.28 m)

$h_2 = \sqrt{\frac{A_2}{C_1}}$ $\qquad \frac{s_E}{h_2} = C_1$

One of the considerations in reducing the size of the test engine is the ability to maintain positive thrust. As an indication of the reduction in thrust as size is reduced, the ratio of the module surface area to module cowl area (station 1) was determined for the shaded area in the above sketch. The fixed 30 inch (.76 m) length is based on chemical kinetic studies as necessary for the combustion of the hydrogen fuel. As this dimension is independent of the size of the module it is shown as a constant. The surface area per unit cowl area is then:

$$\frac{A_{SUR}}{A_{COWL}} = \frac{3.245}{\left(\frac{C_1}{N}\right)} + 4.388 + \frac{2.73}{h_2\left(\frac{C_1}{N}\right)} + \frac{2.5}{h_2}$$

where: N is the number of modules, h_2 is throat height in feet.

As the surface area increases, frictional forces reduce the net thrust available. The results of this analysis is given in the following table.

ENGLISH UNITS

A_c	S_w	TOGW	N	h_2	h_1	s_E	s_M	$\frac{A_{sur}}{A_{cowl}}$	A_c/N
ft^2	ft^2	lb.		ft	ft	ft	ft		ft^2
900	20,000	1,060,000	10	2.16	4.32	38.8	3.88	7.0	90
480	10,700	1,050,000	7	1.54	3.08	27.6	3.96	6.9	68.6
270	6,000	559,000	5	1.15	2.30	20.7	4.14	7.4	54.0
140	2.890	283,000	4	.829	1.66	14.9	3.72	7.9	35.0
80	1,780	174,000	3	.627	1.25	11.3	3.76	8.7	26.7
40	665	65,100	2	.373	.746	6.72	3.36	11.3	20
10	222	21,800	1	.233	.466	4.19	4.19	15.1	10
4	89.0	8,740	1	.141	.282	2.54	2.54	23.8	4
1	22.2	2,180	1	.0735	.147	1.32	1.32	39.8	1

S.I. UNITS

A_c	S_W	TOGW	N	h_2	h_1	s_E	s_M	$\frac{A_{sur}}{A_{coul}}$	$^{A}c/_{N}$
m^2	m^2	kg		m	m	m	m		m^2
83.6	1858.	480,000	10	.55[illegible]	1.32	11.8	1.18	7.0	8.36
44.6	994.	477,000	7	.470	.940	8.42	1.21	6.9	6.36
25.1	557.	268,000	5	.351	.702	6.31	1.26	7.4	5.00
13.0	268.	128,500	4	.253	.506	4.54	1.13	7.9	3.24
7.43	165	79,000	3	.191	.382	3.35	1.15	8.7	2.47
3.72	61.8	29,600	2	.114	.228	2.05	1.02	11.3	1.86
.929	20.6	9,900	1	.071	.142	1.28	1.28	15.1	.929
.372	8.27	3,970	1	.043	.086	.745	.745	23.0	.037
.093	2.06	990	1	.022	.044	.403	.403	39.8	.093

The sizes selected as variations for the scramjet engine research facilities were:

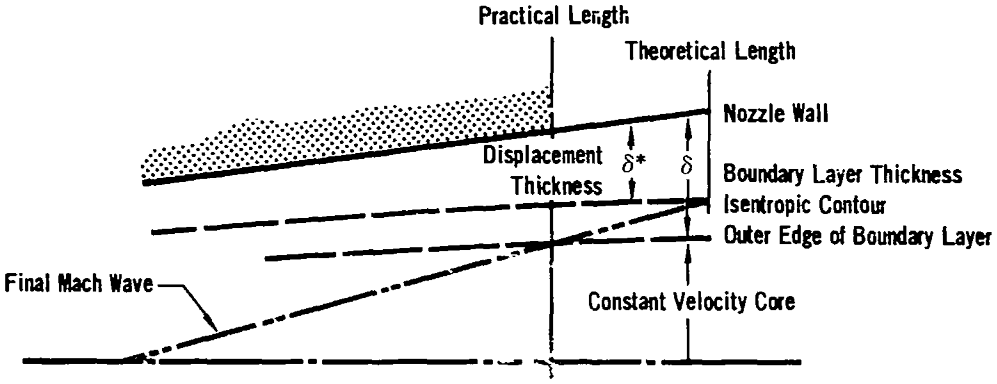
- Mininum size ≈ 15 ft^2 (1.39 m^2) module capture area (A_{cm}), with the h_2 corresponding to the 80 ft^2 (7.43 m^2) engine. This appears to be the smallest module size with a wetted area to cowl area ratio not significantly different than the larger engines, and gives the capability to test a full height, 2/3 width module corresponding to a research size aircraft.

- An intermediate level corresponding to a module capture area of 45 ft^2 (4.18 m^2), with an h_2 corresponding to the 270 ft^2 (25.1 m^2) engine. This provides the capability to test a full height, 2/3 width module, corresponding to an intermediate sized operational hypersonic aircraft.

- A maximum level corresponding to a module capture area of 90 ft^2 (8.36 m^2) capable of testing a full scale module of a large sized operational hypersonic aircraft.

These preliminary results do indicate that for small modules, the wetted to cross-sectional area ratio rapidly increases, probably requiring significant corrections to data obtained on smaller engine module sizes for determining full scale values.

6.3.4 THERMODYNAMIC/STRUCTURAL RESEARCH LEGS - The engine facilities are the only flow facilities providing the capability of duplicating the actual flight environment, that is, free stream pressure, temperature and flight velocity. For this reason these facilities provide a source of thermodynamic research where both gas conditions and material temperatures consistent with flight values are obtainable, and a source of data on full scale structural components subjected to a duplicated flight environment. To provide this aerothermodynamic testing capability, aerodynamic nozzles must be provided to generate these flow fields. For the turbomachinery test facilities, the free jet nozzle which is provided for inlet-engine compatibility testing can also be used for thermodynamic and structural research. For the scramjet facilities, a series of aerodynamic nozzles must be provided, to be installed in place of the scramjet test module. A series of nozzles covering the Mach number range from 6 through 12 are represented in Figure 6-49a. The throat area of these nozzles corresponds to that for the scramjet test section for the trajectory point of interest, and therefore have the same mass flow as the scramjet test section. The nozzle area ratio is for real gas flows as given in Reference 14. The potential flow contours were based on data obtained from Reference 12 and approximate the actual relative size of an actual nozzle. The nozzles are not the full theoretical length, but are shortened to the point where the last Mach wave intersects the boundary layer edge, as indicated:

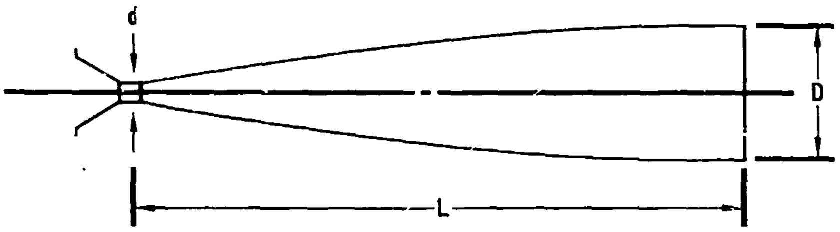


The boundary layer corrections used for these nozzles are based on data obtained in the McDonnell Aircraft Company's Hypervelocity Impulse Tunnel, and are published in Reference 13. This correction has been used to construct a Mach number 1 through 17 parallel flow nozzle which operates up to temperature 5000°K, and 20,000 psia (13,000 N/cm^2) with parallel flow. The equations for the exit boundary layer thickness are:

$$\frac{\delta^*}{x} \simeq 0.4\,\frac{\delta}{x} = 0.0264\,\frac{M_\infty^{.824}}{Re_L^{.156}}$$

where: Re_L is the free stream unit Reynolds number multiplied by the nozzle length from the source point to the theoretical nozzle exit.

FIGURE 6-49a
AXISYMMETRIC AERO NOZZLES FOR ENGINE TEST FACILITIES, E8 and E9, TO PROVIDE STRUCTURAL AND THERMODYNAMIC TESTING CAPABILITY



	Mach Number	6	8	10	12
Design Conditions	$Re_{\sqrt{c}}$	3.6×10^6	5.1×10^6	5.75×10^6	7.32×10^5
	P_0 psia (N/cm^2)	353 (243)	4100 (2825)	7000 (4830)	3200 (2210)
	T_0 °R (°K)	3000 (1670)	5600 (3110)	6600 (3660)	9500 (5280)
	H_0 Btu/lb (J/kg)	845 (1.96×10^6)	1640 (3.8×10^6)	1800 (4.17×10^6)	2650 (6.15×10^6)
Dimensions	Length in. (m)	260 (6.6)	500 (12.7)	650 (16.6)	760 (19.3)
	Exit Diameter in. (m)	57.6 (1.46)	107 (2.71)	130 (3.3)	184 (5.72)
	Throat Diameter in. (cm)	6.68 (17)	3.7 (9.4)	3.25 (8.3)	2.16 (5.46)
	D_{Pot}[1] in. (m)	52.2 (1.33)	93.4 (2.37)	112.6 (2.86)	145 (4.42)
	D_{Vel}[2] in. (m)	44.2 (1.12)	73 (1.85)	87.6 (2.21)	89 (2.26)

[1] D_{Pot} = Diameter of Potential Flow Core at Nozzle Exit

[2] D_{Vel} = Diameter of Constant Velocity Core at Nozzle Exit

therefore, if D_p is the diameter of the potential flow core, then the exit diameter of the nozzle is:

$$D_N = D_p + 2\delta^* \qquad 6.3\text{-}3$$

The diameter of the constant velocity core is then:

$$D_V = D_N - 5\delta^* \qquad 6.3\text{-}4$$

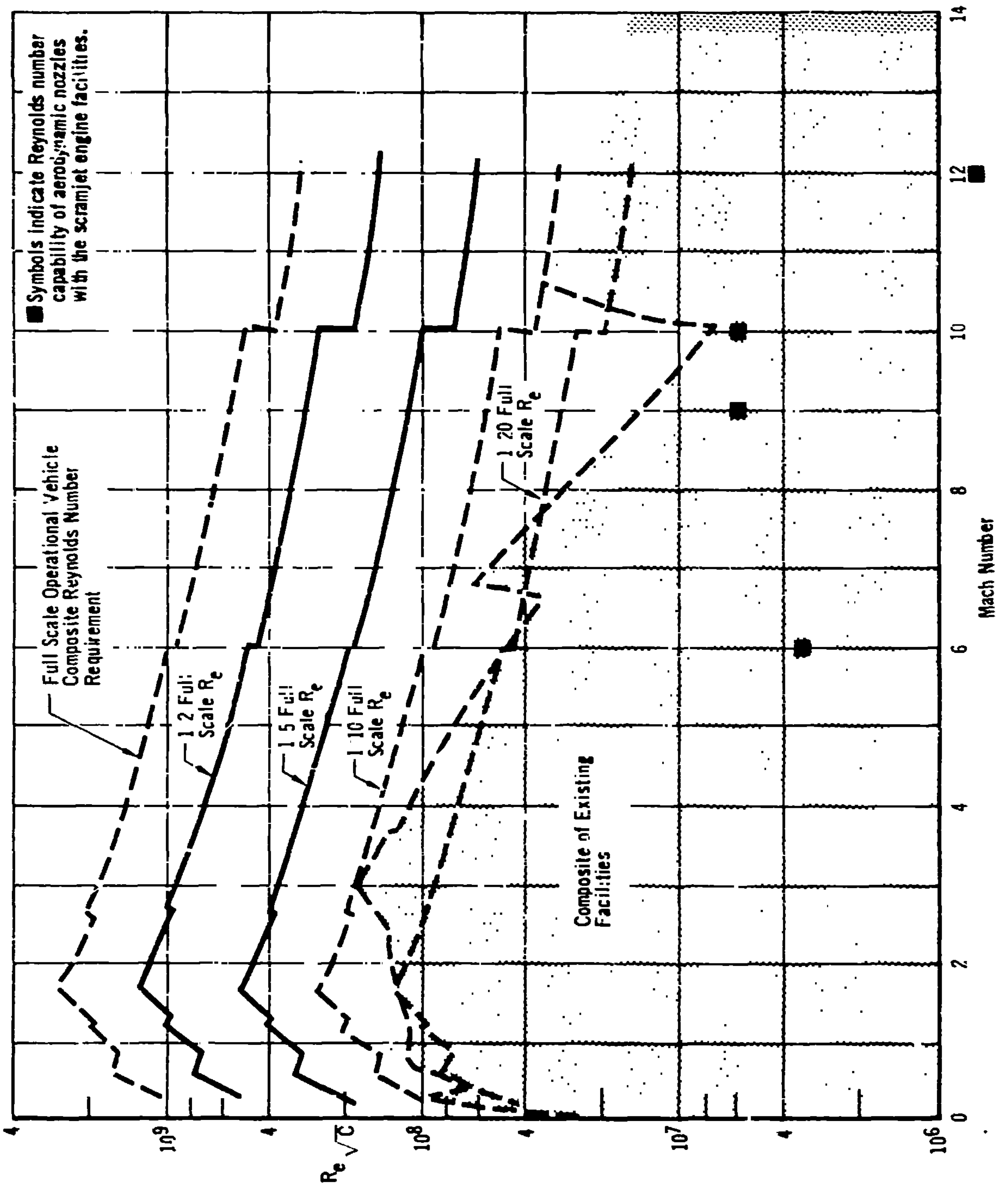
Because the flight unit Reynolds number is duplicated, any model tests will be less than the full scale Reynolds number by the model scale. That is, a 2% model will have 2% of the full scale Reynolds number. However, for a full scale structural component, the full scale Reynolds number will be duplicated, as based on the dimensions of the component. For a full scale leading edge component, the flight conditions and Reynolds number are duplicated. Based on the gas dynamics criteria for model size, the Reynolds number simulation is low as shown in Figure 49b.

Figure 6-50 shows the complete scramjet test leg, minus the enthalpy source. The thermodynamic test leg can be installed between the fixed portion of the subsonic diffuser on the right hand side of the drawing, and the enthalpy source on the left hand side of the drawing. The test section is moved laterally, while the piping is lifted out by crane and stored in an adjacent area. The test cabin is then laterally moved in on rails, with the nozzle and diffuser section lifted in by crane, using the same supports as for the scramjet leg, as depicted in Figure 6-52. The test cabin can be translated axially to accommodate the Mach 6 through Mach 12 nozzles, as depicted in its extreme positions.

This system provides the largest wind tunnel of its kind capable of flight duplicated conditions to Mach number 12. The cost of the nozzle/diffuser system is about 2.5 percent of the total facility cost, but doubles its utility and research value.

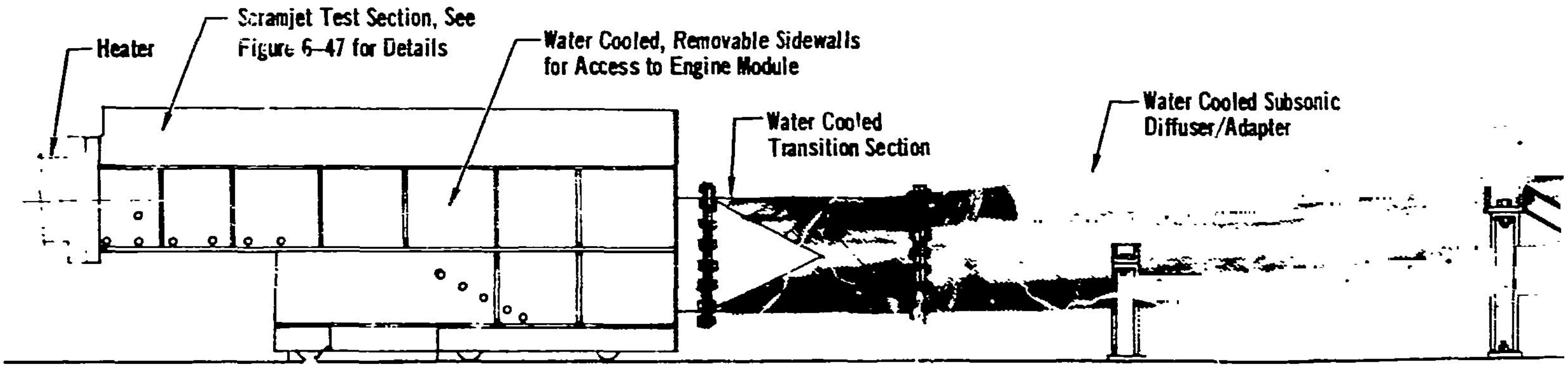
FIGURE 6–49b

DEGREE OF REYNOLDS NUMBER SIMULATION FOR OPERATING HYPERSONIC AIRCRAFT COMPARED TO EXISTING GAS DYNAMIC FACILITY CAPABILITY

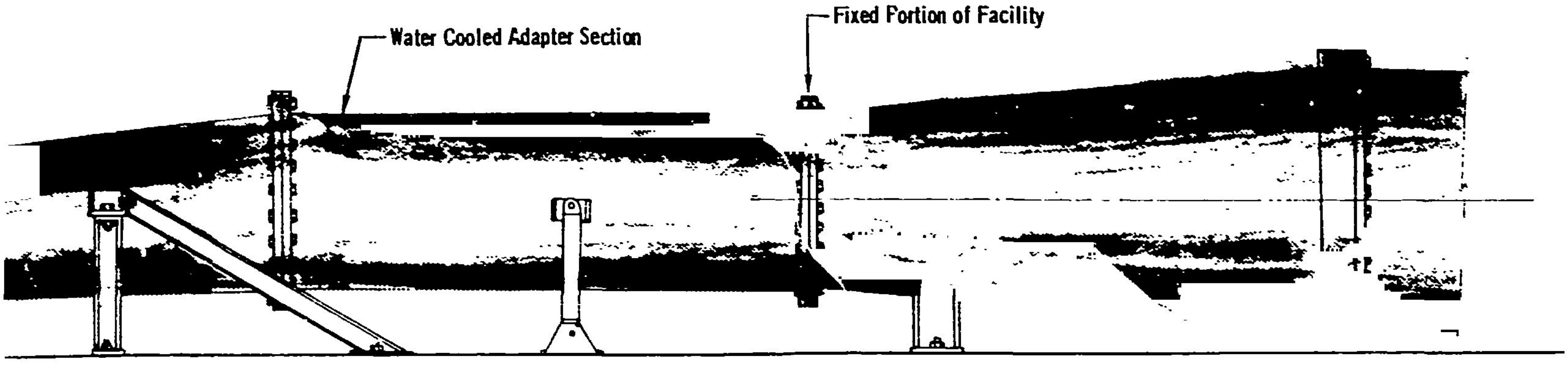


FOLDOUT FRAME 1

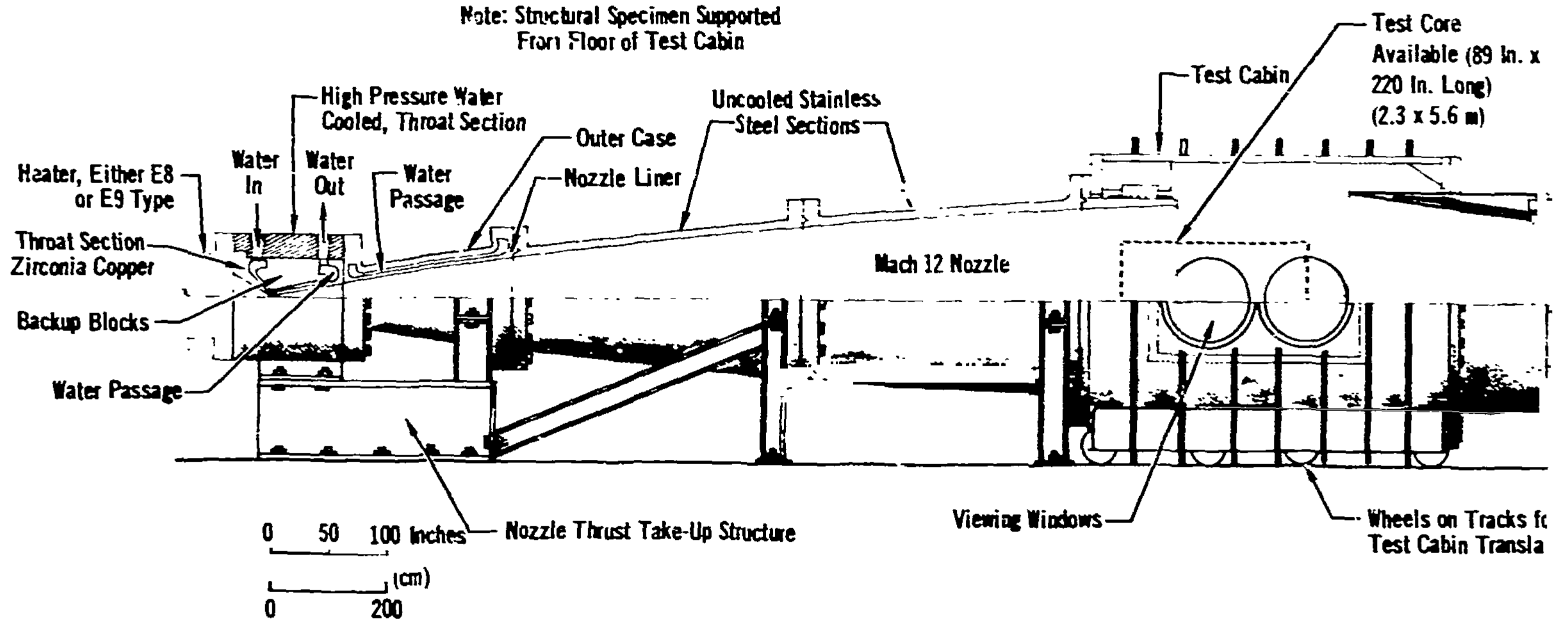
FIGURE 6-50
SCRAMJET, CONVERTIBLE SCRAMJET ENGINE MODULE TEST FACILITY LEG, CONFIGURED TO ACCEPT AERODYNAMIC NOZZLES FOR THERO/STRUCTURAL TESTING



FOLDOUT FRAME 2



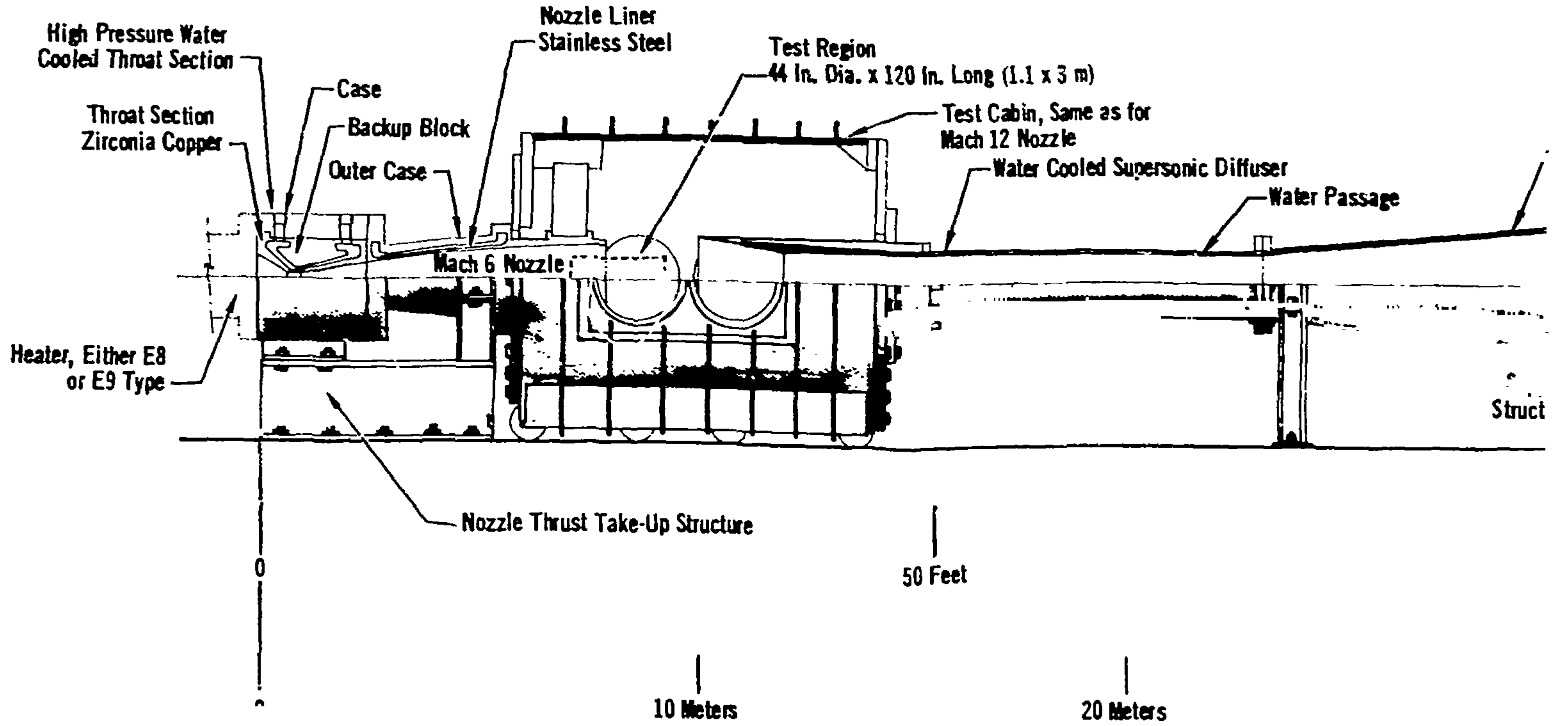
FOLDOUT FRAME 1



STRUCTURAL TEST LEG U

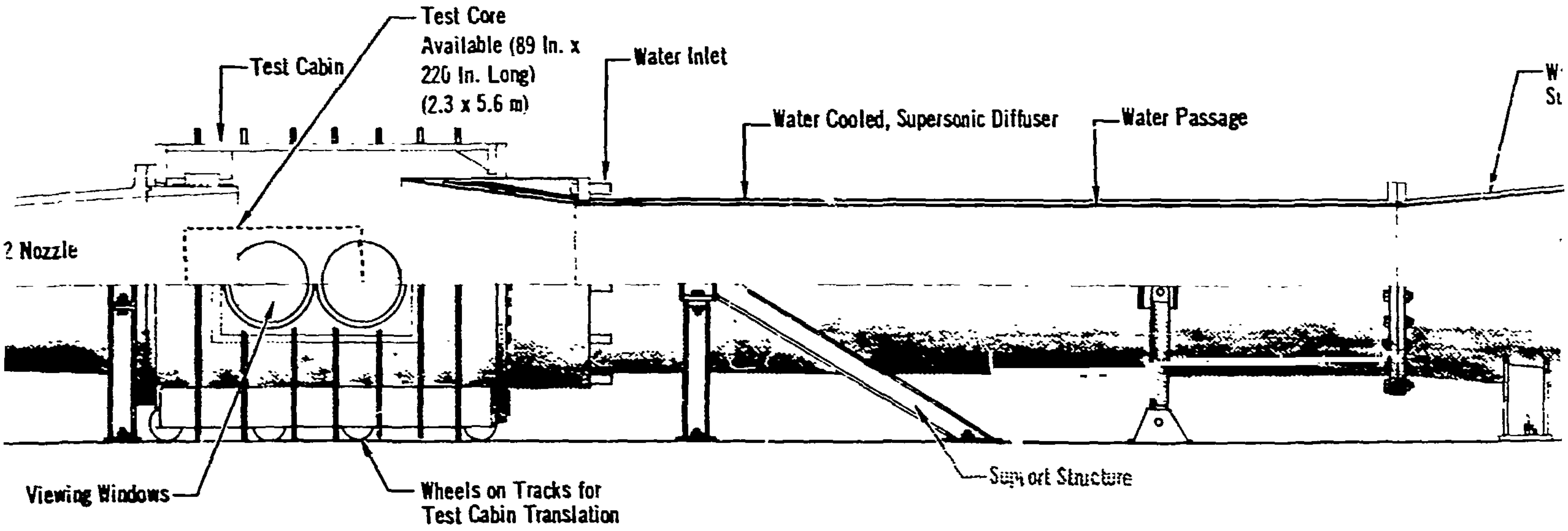
HEATER AND PUMPING SYSTE

MACH 6, FROM 90,000

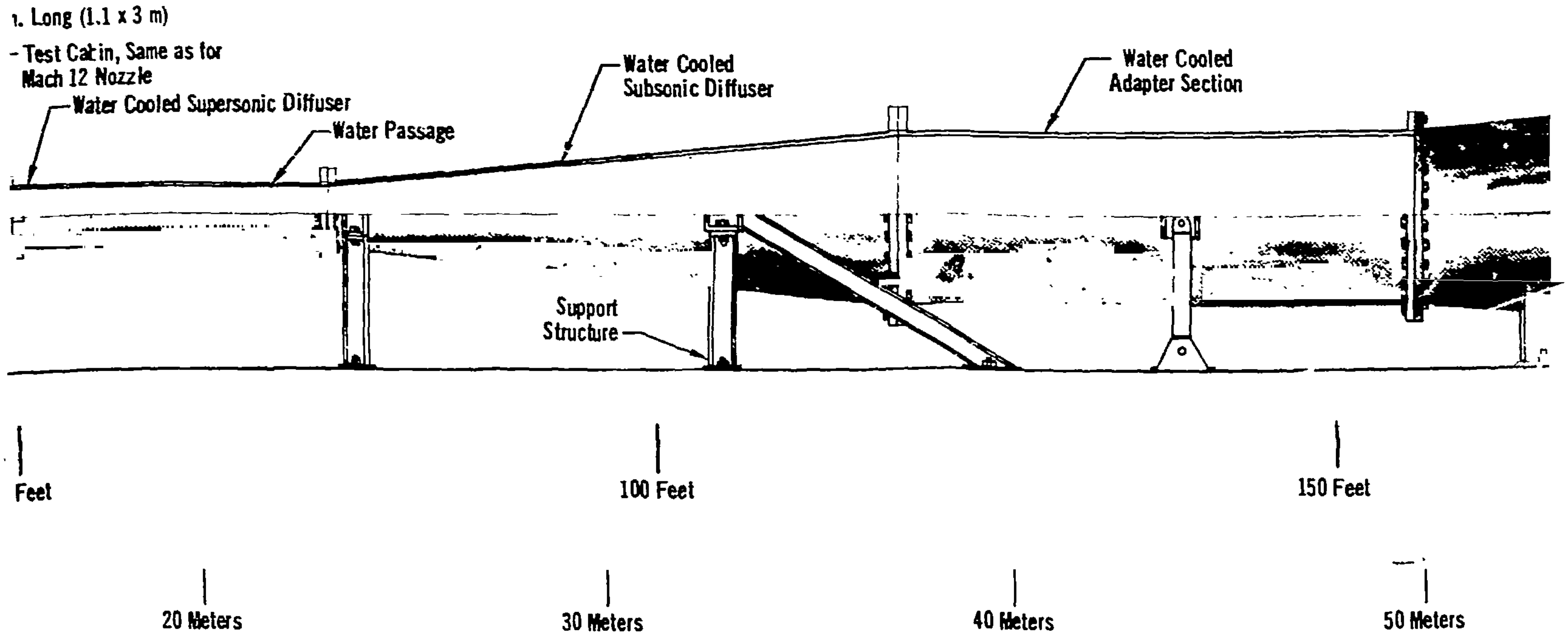


FOLDOUT FRAME 2

STRUCTURAL TEST LEG
HEATER AND PUMPING SYST
MACH 12, FROM 140,

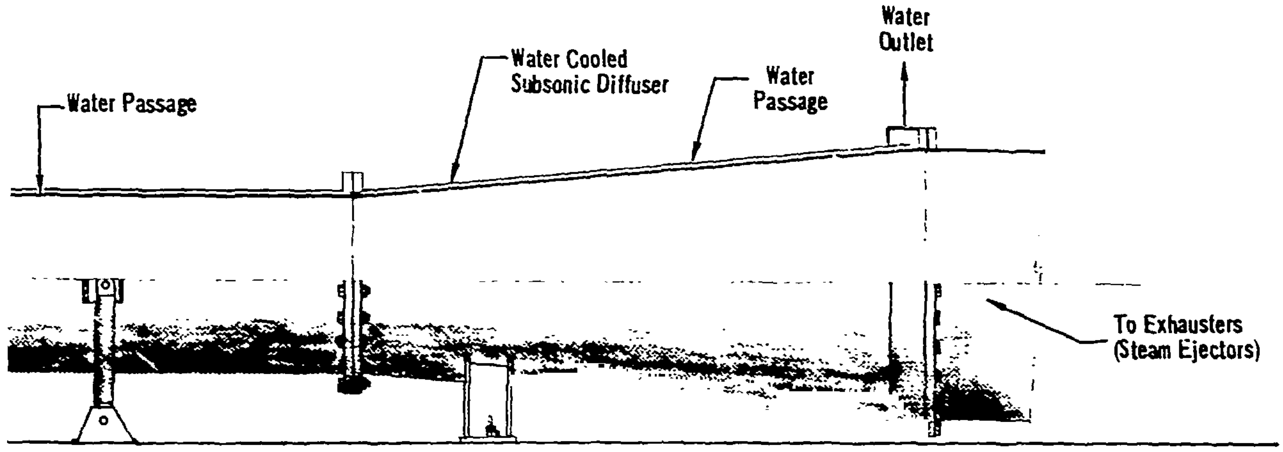


STRUCTURAL TEST LEG UTILIZING SCRAMJET ENGINE TEST FACILITY
HEATER AND PUMPING SYSTEM, DUPLICATED VELOCITY AND ALTITUDE FOR
MACH 6, FROM 90,000 TO 140, 000 FT (27 TO 42 km)



FOLDOUT FRAME 3

(U) FIGURE 6-51
STRUCTURAL TEST LEG UTILIZING SCRAMJET ENGINE TEST FACILITY HEATER AND PUMPING SYSTEM DUPLICATED VELOCITY AND ALTITUDE FOR MACH 12, FROM 140, 000 TO 160,000 FT ALTITUDE (42 TO 49 km)



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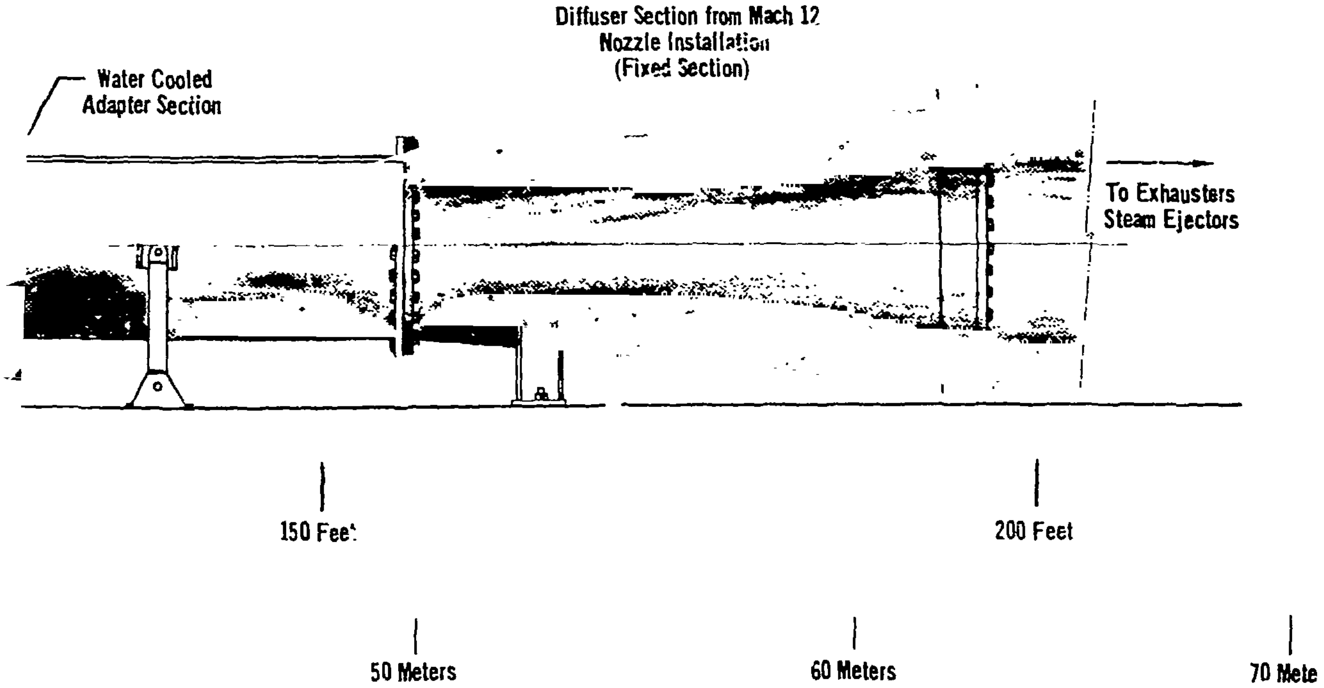


6.3.5 PRIME MOVER POWER DENSITY - In considering primary drive systems for very large shaft power requirements, two factors dominated prime mover selection. One was the total shaft power required on a single drive train, the second was the requirement for variable shaft speed during facility operation. The facility which presented the most challenging task in the definition of the drive system was the scramjet engine module engine facility using the multirecompression heater concept (E8). This is specifically discussed in Section 6.3.8. The more general considerations of the energy density of the prime movers are discussed in this section.

Figure 6-52 provides a size comparison of some of the largest equipment available based on existing capability. The Apparatus Division of the Westinghouse Corporation was used as a source of technical information concerning electric motors. In their opinion, single motors up to 100,000 horsepower (74,600 kW) could be provided through development of a design for a specific application. The two synchronous motors depicted represent the largest sizes on which engineering data is available without specific design programs. These two motors are given at their nominal design power based on frame size as well as a maximum delivered power capability. This estimate was obtained from Westinghouse using their experience with the nominal 184,000 kW drive supplied for the AEDC 16S and 16T propulsion wind tunnels. The motors can be installed in an in-line installation, where no gearing is required to provide large shaft powers. Where gearing is required, such as on facility E8, the capability of assembling large shaft powers is severly limited.

Discussions with Mr. Harold Kron, Chief Engineer at the Philadelphia Gear Company, Incorporated, resulted in establishing a limit to the current experience in gearing for parallel and cross shafting. These limits were:

19,000 kW for cross shafting helical gears (right angle drives)
45,000 kW for parallel shafting helical gears.

For these limits, we could not at this time obtain a cost estimate for such gearing. In Phase III with better definitions of the loads, this may be possible.

Another factor relating to the synchronous motor drives is that the rotational speed is constant based on the 60 cycle alternating current power available in the United States. Three standard speeds available are 900, 1800, and 3600 rpm. For many applications a continuous variation in rotational speed is required for facility operation.

Because of the power levels under consideration in this study, no type of gearing is feasible. Operating a synchronous motor out of synchronization results in a very large increase in power factor plus the loss of precise speed control. The starting current for a synchronous motor is about 6 times its running load. Considering that some of the proposed facilities would require from one-third to two-thirds of the peak power of some of the largest power pools in the United States, such starting conditions are impossible to accommodate. The motors would have to be brought up to synchronous speed before the field current could be applied. To provide the variable speed drives using the synchronous motors (which, in most cases, are necessary to maintain rotational speed accuracy) a variable frequency generator driven by a wound rotor motor assembled as a motor generator set controlling a synchronous motor would have to be provided, if technically feasible for these powers.

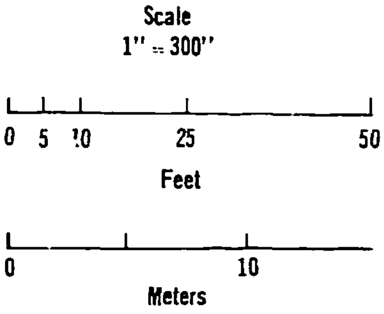
Including inefficiencies in power transmission and equipment efficiencies, about 318,000 kilowatts of electrical motor and generators (100,000 kW synchronous motor, 106,000 kW variable frequency generator, 112,000 kW wound rotor motor) are required to supply 100,000 kW of shaft power. Such a system is very costly and its acceleration capability is probably marginal.

An alternate approach is to utilize gas turbine drive systems using free turbine power takeoff. Depicted in Figure 6-52 are four systems based on current engine designs. The Pratt and Whitney FT4A system is based on the JT4 aircraft turbojet engine. A number of different dash number installations are available from 21,000 kW to 24,000 kW. A similar ground power installation system is available from the General Electric Company based on the core engine of the TF-39 turbofan engine. It is of similar size and is capable of delivering 19,500 kW, and is denoted as LM2500. The arrangement using the supersonic transport engine, the General Electric GE 4/J5P, is not currently available as shown for ground power usage. This engine has the largest gas generator mass flow (633 lb/sec - 193 kg/sec) of any engine available in the United States. Based on discussions with General Electric, such a system as proposed in Figure 6-52 is feasible. Multiple engine drives (Figure 6-52) provide a source of very large shaft powers, capable of variable rotational speeds, with small exterior envelopes. For the large ground research facilities of this study, this method appears to be the only technique of providing a variable speed drive, with no gearing, at a reasonable cost.

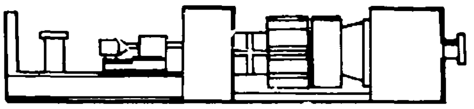
A 43,000 kW ground gas turbine drive is available from General Electric as the GE series 7000 system, which has growth potential to 52,000 kW. This system is not an aircraft conversion as the other gas turbine systems are, but a direct drive system specifically designed for electrical power generation. It is not depicted in Figure 6-52, because its direct drive design (compressor and power output shaft turbine coupled) are more applicable to constant speed operation than the free turbine concept.

The prime mover cost estimates for Phase II were for synchronous motors utilizing purchased power. Gas turbine drives were used whenever they became either a definite cost advantage or where space precluded the volume associated with lower power density electric motors. Gas turbine prime movers are being considered for all ground facility requirements as an alternative to electric motor drive using an electric utility company supplier. The ease of obtaining large increments of power without having to consider network loads, energy absorption capacity in the event of a failure, operational times restricted to off-peak hours, and demand charges make gas turbines attractive power sources. This is even true when electrical power is necessary and gas turbines are used to drive electrical generating equipment, as discussed in Section 6.1.5. The engines used to provide ground power are aircraft turbojet engines with free turbine shaft drives, with one exception, the General Electric Series 7000 System, which is a direct drive system specifically designed for ground application. These engines have been used for a number of years for ground installations, except the GE 4/J5P. The engines used to develop the cost relationship in Figure 6-10, with their performance, are given in the following listings.

FIGURE 6-52
REPRESENTATIVE SIZES OF LARGE SHAFT HORSEPOWER SOURCES

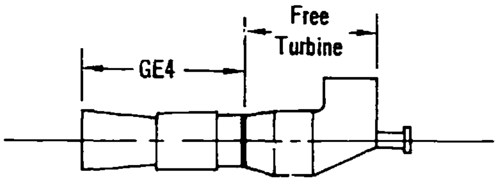


Direct Drive Industrial Gas Turbine

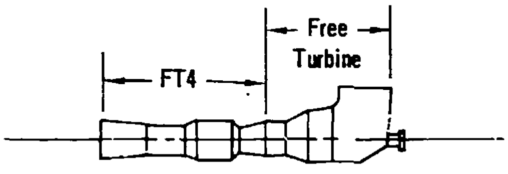


GE MS 7000 43,000 kW
Gas Turbine Drive

Free Turbine, Aviation Gas Turbines, Single Engine

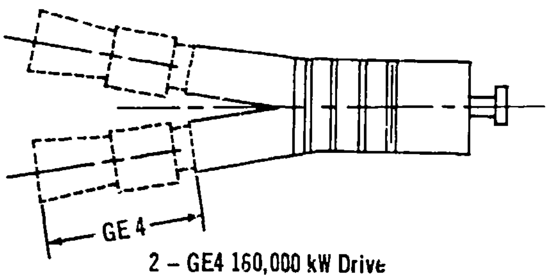


82,000 kW GE4/J5P
Gas Turbine Drive

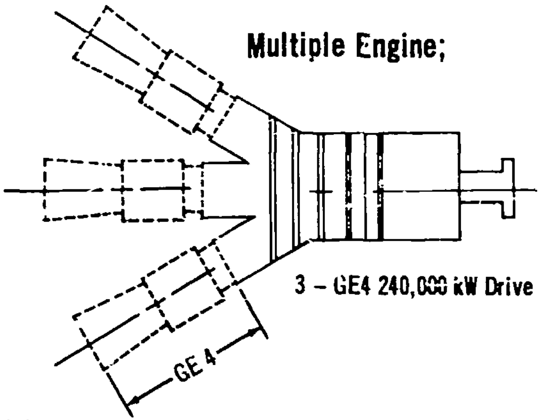


22,000 kW P&W FT4A
Gas Turbine Drive

Multiple Engine;

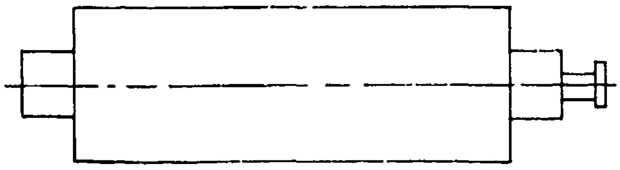


2 – GE4 160,000 kW Drive

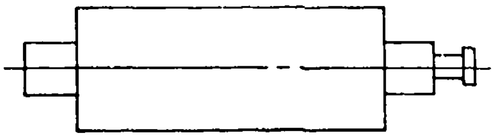


3 – GE4 240,000 kW Drive

Synchronous Electric Motors



48,000 kW Motor Frame
Up to 65,000 kW Delivered



34,000 kW Motor Frame
Up to 48,000 kW Delivered

Pratt and Whitney Aircraft - Turbopower and Marine Dept.

FT4A-2 Engine

Ratings	Free Turbine Power		Free Turbine Speed	Est. SFC Fuel LHV* 18,500 Btu/lb (43,000 J/g)		Estimated Exhaust Gas Temp		Estimated Exhaust Gas Mass Flow	
	hp	kW	rpm	$\frac{lb}{hp\text{-}hr}$	$\frac{kg}{kW\text{-}hr}$	°F	°C	lb/sec	kg/sec
Normal	21,500	16,000	3600	.505	.307	736	391	234	106
Max Continuous	25,500	19,000	3600	.475	.289	790	421	248	113
Max Intermittent	30,000	22,350	3600	.470	.286	855	458	261	119

Based on 14.7 psia @ 80°F inlet conditions (10.2 N/cm^2 @ 26.7°C)

*LHV - lower heating value for fuel

Pratt and Whitney Aircraft - Turbopower and Marine Dept.

FT4A-12 Engine

Ratings	Free Turbine Power		Free Turbine Speed	Est. SFC Fuel LHV 18,500 Btu/lb (43,000 J/g)		Estimated Exhaust Gas Temp		Estimated Exhaust Gas Mass Flow	
	hp	kW	rpm	$\frac{lb}{hp\text{-}hr}$	$\frac{kg}{kW\text{-}hr}$	°F	°C	lb/sec	kg/sec
Normal	29,950	22,300	3600	.49	.299	770	410	260	118
Max Continuous	30,200	22,500	3600	.49	.299	817	437	268	122
Max Intermittent	31,500	23,500	3600	.49	.299	840	44	270	123

Horsepower ratings based on 59°F and level pressure 14.7 psia with no inlet or exhaust duct losses (15°C and 10.2 N/cm^2)

FT4A-6 Engine

Ratings	Free Turbine Power		Free Turbine Speed	Est. SFC Fuel LHV 18,500 Btu/lb (43,000 J/g)		Estimated Exhaust Gas Temp		Estimated Exhaust Gas Mass Flow	
	hp	kW	rpm	$\frac{lb}{hp\text{-}hr}$	$\frac{kg}{kW\text{-}hr}$	°F	°C	lb/sec	kg/sec
Normal	20,400	15,200	3600	.525	.32	720	382	228	103
Max Continuous	24,100	18,000	3600	.510	.311	767	408	240	109
Max Intermittent	28,300	21,100	3600	.500	.305	828	442	252	114

Based on 14.7 psia @ 80°F inlet conditions (10.2 N/cm² @ 26.7°C)

FT4A-8LF Engine (liquid fuel)

Ratings	Free Turbine Power		Free Turbine Speed	Est. SFC Fuel LHV 18,500 Btu/lb (43,000 J/g)		Estimated Exhaust Gas Temp		Estimated Exhaust Gas Mass Flow	
	hp	kW	rpm	lb/hp-hr	kg/kW-hr	°F	°C	lb/sec	kg/sec
Base Load	20,700	15,400	3600	.505	.308	735	390	222	101
Peaking	24,000	18,300	3600	.475	.290	791	422	235	107
Max Peaking	28,050	21,600	3600	.470	.286	856	467	248	113

Based on 14.2 psia @ 80°F conditions (9.8 N/cm² @ 26.7°C)

FT4A-8GF Engine (gaseous fuel)

Ratings	Free Turbine Power		Free Speed	Est. SFC Fuel LHV 20,650 Btu/lb (47,800 J/g)		Estimated Exhaust Gas Temp		Estimated Exhaust Gas Mass Flow	
	hp	kW	rpm	lb/hp-hr	kg/kW-hr	°F	°C	lb/sec	kg/sec
Base Load	20,700	15,400	3600	.450	.274	735	390	222	101
Peaking	24,600	18,300	3600	.425	.259	791	422	235	107
Max Peaking	28,950	21,600	3600	.415	.253	856	467	248	113

Based on 14.2 psia @ 80°F conditions (9.8 N/cm² @ 26.7°C)

- A related engine, FT4A-8DF, may use liquid or gaseous fuel interchangeably.

General Electric Company, Marine Division

LM 2500, based on core engine of TF-39

Marine Rating	60°F Ambient Temperature (15.6°C)				80°F Ambient Temperature (26.7°C)				100°F Ambient Temperature (37.8°C)			
	Power		SFC		Power		SFC		Power		SFC	
	hp	kW	lb/hp-hr	kg/kW-hr	hp	kW	lb/hp-hr	kg/kW-hr	hp	kW	lb/hp-hr	kg/kW-hr
A	26,200	19,500	.399	.243	24,700	1[illegible]0	.401	.244	22,500	16,800	.409	.250
B	25,200	18,800	.398	.242	23,400	17,400	.403	.246	20,900	15,600	.415	.253
C	23,500	17,500	.400	.244	20,900	15,600	.4[illegible]	[illegible]	1[illegible],600	13,900	.425	.259
D	21,500	16,000	.405	.247	18,900	14,[illegible]00	[illegible]	[illegible]	16,600	12,400	.438	.267

A, B, C, D marine ratings refer to gas gene[illegible] inlet temperature parameters.

General Electric Company, Heavy Duty Industrial Gas Turbine Dept.

GE Series 7000

57,000 shp (42,500 kW) @ 3600 rpm, growth potential to 70,000 shp (52,100 kW)
Simple, straight through machine requires 9800 Btu/hp-hour (13,860,000 J/kW-hr) fuel input, costs $2,900,000.
Regenerative cycle machine requires 7400 Btu/hp-hour (10,470,000 J/kW-hr) fuel input, costs $3,500,000.

Industrial design, not based on aircraft engine.

General Electric Company, Aircraft Engine Division

GE 4/J5P

110,000 shp (82,000 kW), 633 lb/sec (288 kg/sec) engine mass flow

More data will be obtained on the basic performance of the GE4 engine. The engine performance when used in a ground power application was determined by scaling LM2500 (TF-39) data. According to GE, this approach is valid, except that the specific fuel consumption will be higher than for the TF-39 core engine because of a lower compressor pressure ratio.

To minimize modification to the basic aircraft engine, the ground installation utilizes the engine as a gas generator driving a free turbine, as shown in Figure 6-53. The free turbine could be a specially designed unit, or be a commercial unit such as a Worthington ER 224 twin exhaust expander turbine. Using such installations, shaft powers from 20,000 to 220,000 horsepower (14,900 to 164,000 kW) are available as single or dual units.

There are a large number of these installations in use throughout the United States. Data from Pratt & Whitney shows a total of 464 units delivered with a total of 1,192,310 operational hours accumulated. Some of the operational units consist of eight FT4A engines driving four twin expander turbines on a single shaft. Considering the 30,000 hour overhaul life, this appears to be a very feasible manner of combining engines without sacrificing operational efficiency.

An approximate summary of the normalized performance of these engines as taken from the engine brochures is presented in Figure 6-54.

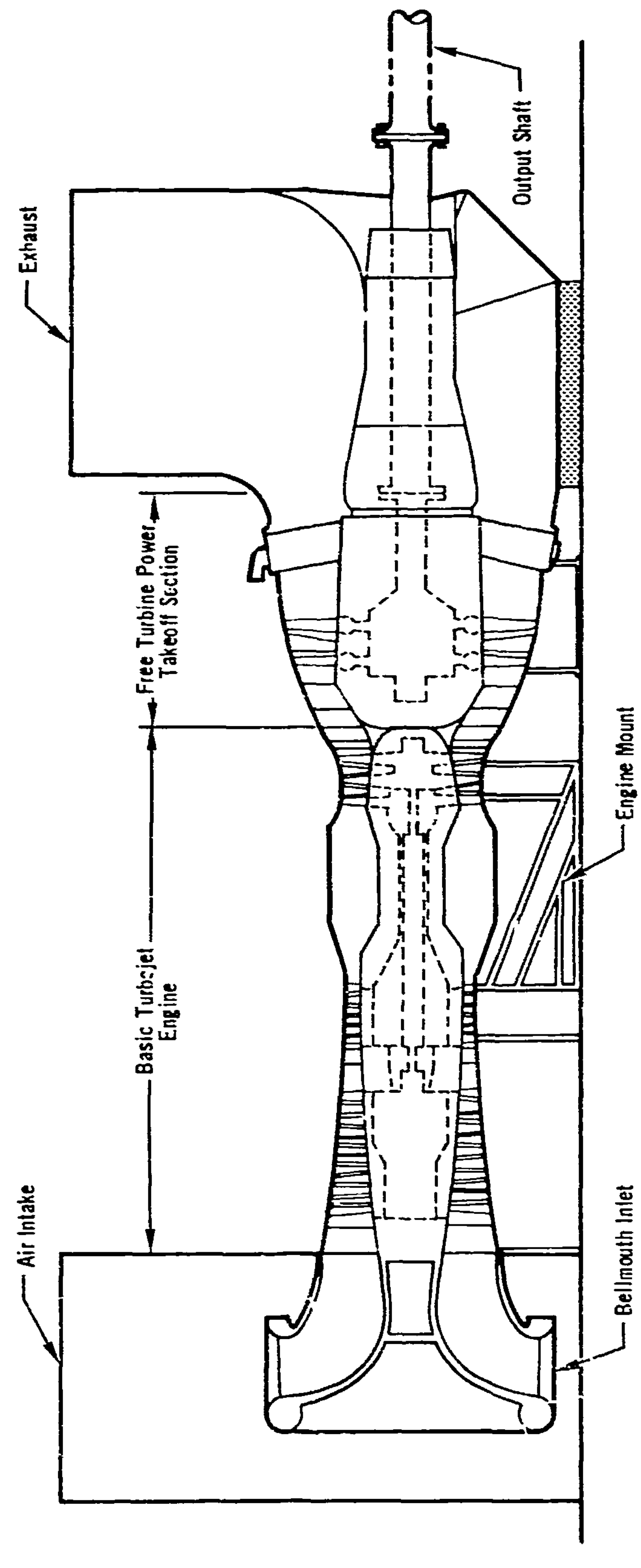
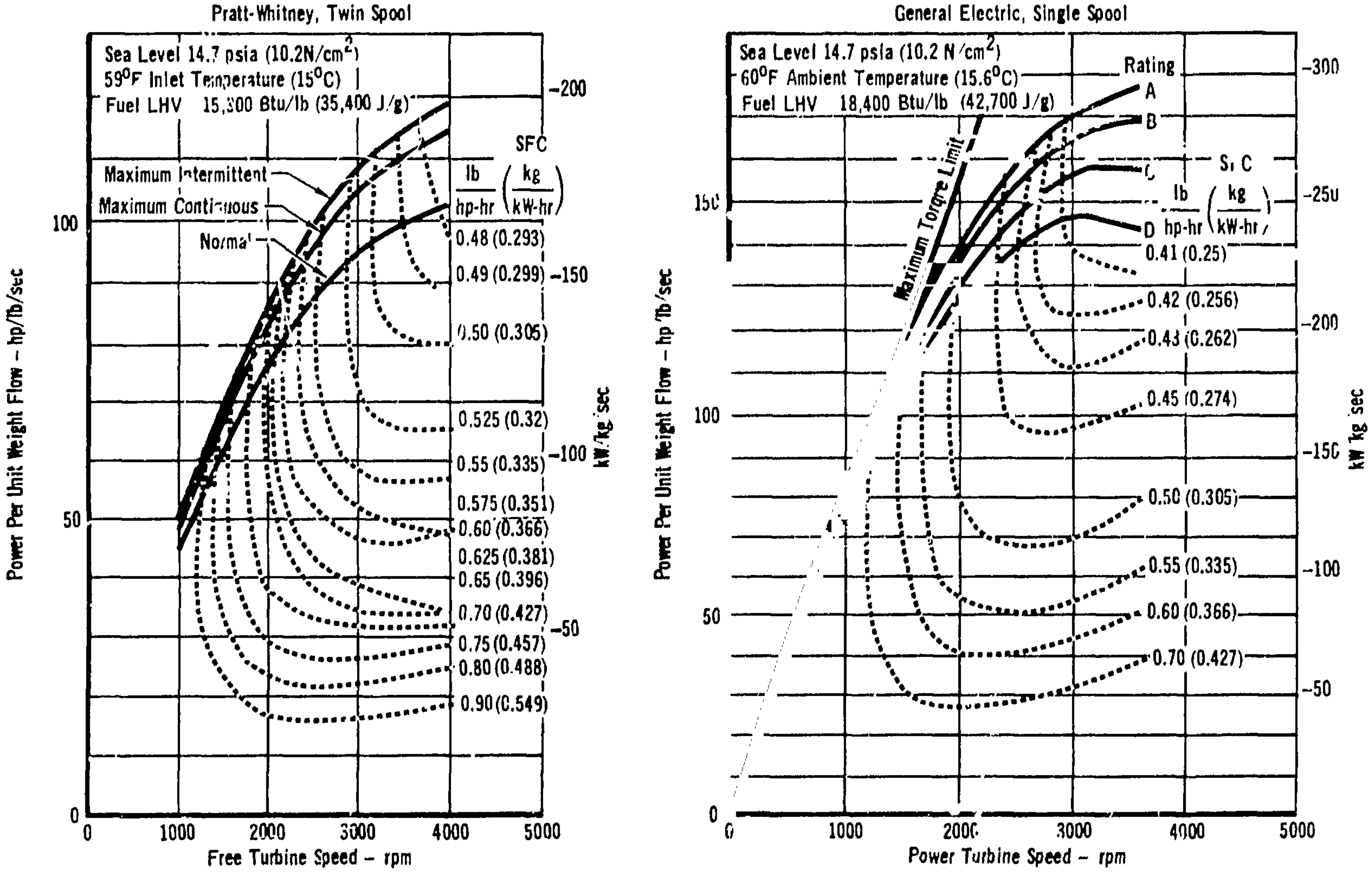


FIGURE 6-53
REPRESENTATIVE GROUND INSTALLATION OF AIRCRAFT TURBOJET ENGINE TO PROVIDE SHAFT POWER SOURCE, SINGLE ENGINE INSTALLATION

FIGURE 6–54
APPROXIMATE PERFORMANCE OF AIRCRAFT TURBOJET ENGINES AS INSTALLED IN GROUND POWER APPLICATION



6.3.6 DIRECT CONNECT TURBOMACHINERY TEST FACILITY (E6) - This facility is designed for performance and PFRT testing on full scale turbojet, turbofan, turboramjet, and ramjet engines using the direct connect test mode on a continuous basis. Details of the engine test leg are shown in Figure 6-55 and a schematic of the entire system is shown in Figure 6-56.

The facility was specified to provide full flight duplication throughout the flight Mach range of 0.3 to 5.5, as exemplified by Figure 6-45, for full scale engines. Because of this specification, there were no size/capability studies required, the main requirement being that the facility test leg be sized to be able to accommodate the largest advanced technology engines, in terms of test cell size, thrust capability, and mass flow, that represent current engine sizes. These engines are typified by engines ①, ②, ③, and ④ in Volume V. A mass flow schedule based on engine ① has been used to determine the facility requirements for Phase II. This schedule will be increased in the Phase III study to account for projected growth versions of engine, consistent with the requirements of the potential operational hypersonic aircraft. The test cell size as specified now will handle engines up to 90 in (2.3 m) diameter, and will probably not significantly change in the Phase III refinement.

Direct connect testing has been chosen for this facility because it represents the lowest cost method of obtaining continuous testing. In this test mode, the engine is connected directly to a subsonic duct, or bellmouth, which provides the engine with the correct flow rate at the duct stagnation pressure and temperature which would exist in the aircraft inlet duct after the flow had been decelerated to a subsonic Mach number. The cost of this method is less than that of free jet testing because much lower maximum facility stagnation pressures are required, and only the mass flow actually needed to go through the engine is provided. This reduced cost is obtained at the expense of full similitude of dynamic conditions in the flow provided to the engine. These dynamic factors affect inlet duct/engine compatibility and are typified by time variant pressure recovery, temperature and pressure distortion, and turbulence. These can be best evaluated in free jet testing of the inlet/engine combination throughout the full flight trajectory and angle of attack range. Evaluation of static flow distortions produced by the inlet duct system can be done by testing large scale wind tunnel inlet models and the static distortions measured can then be produced by distortion screens in the direct connect facility.

Additional ability to provide some time variant distortions and correct boundary layers can be obtained by using the E6 facility with a two-dimensional, single jack, flexible plate, low Mach number nozzle in place of a subsonic bellmouth. This is the modified direct mode of testing, wherein a low supersonic Mach number flow is provided to a portion of the actual airplane duct system which then feeds the engine. The entire duct system is used, from just forward of the duct throat to the engine. In this manner, a better representation of the effects of actual duct contours and wall temperature on the flow velocity profile and boundary layer growth is obtained, as well as some simulation of the time variant parameters.

The continuous air heater presents a significant design and operational problem. Supplying nearly 1000 lbm/sec (454 kg/sec) of air at temperatures of 2500°R (1390°K) on a continuous basis represents quite a challenge to the state-of-the-art. The

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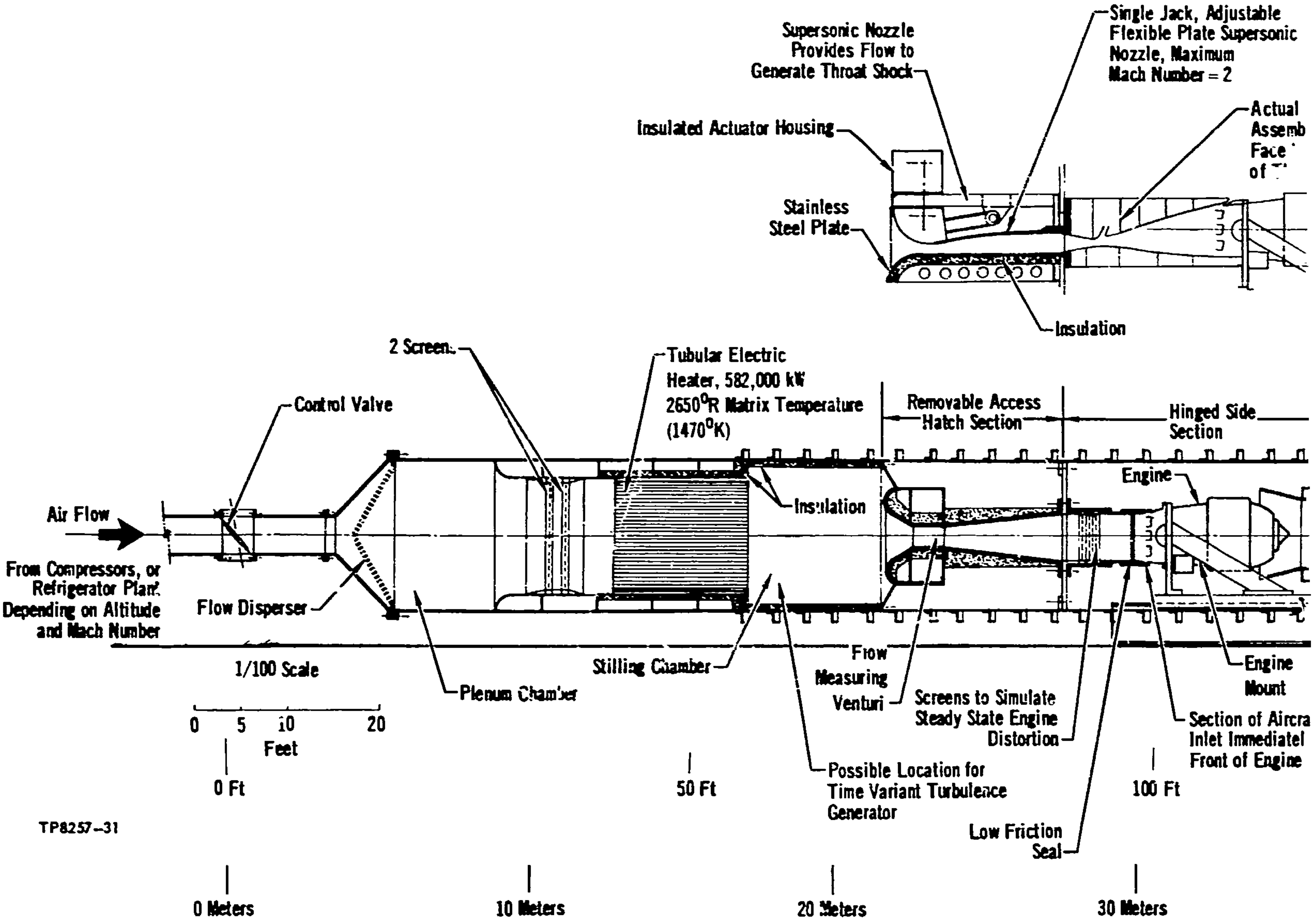
FIGURE 6–55
E6 TURBOMACHINERY, DIRECT CONNECT ENGINE TEST FACILITY



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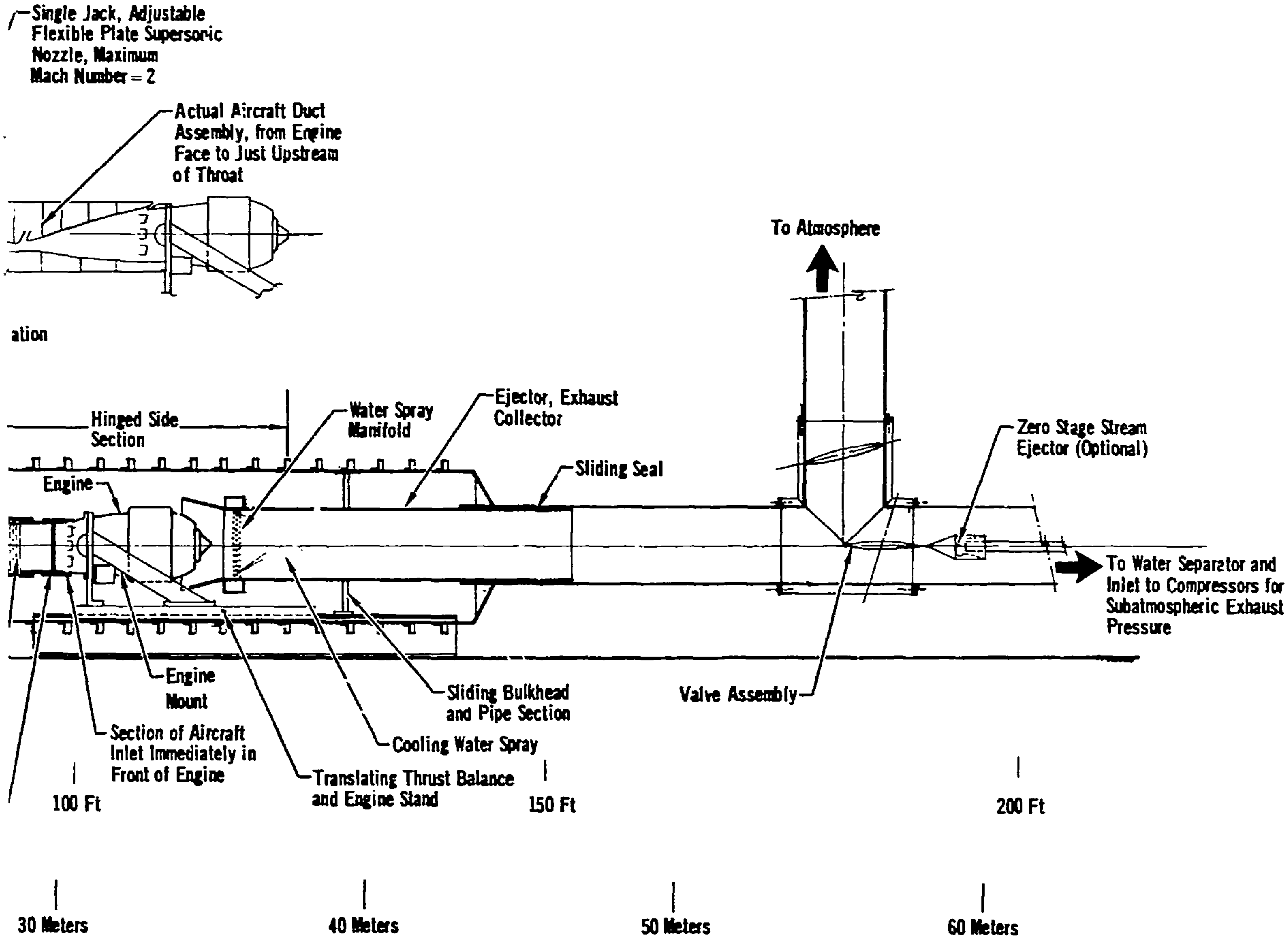
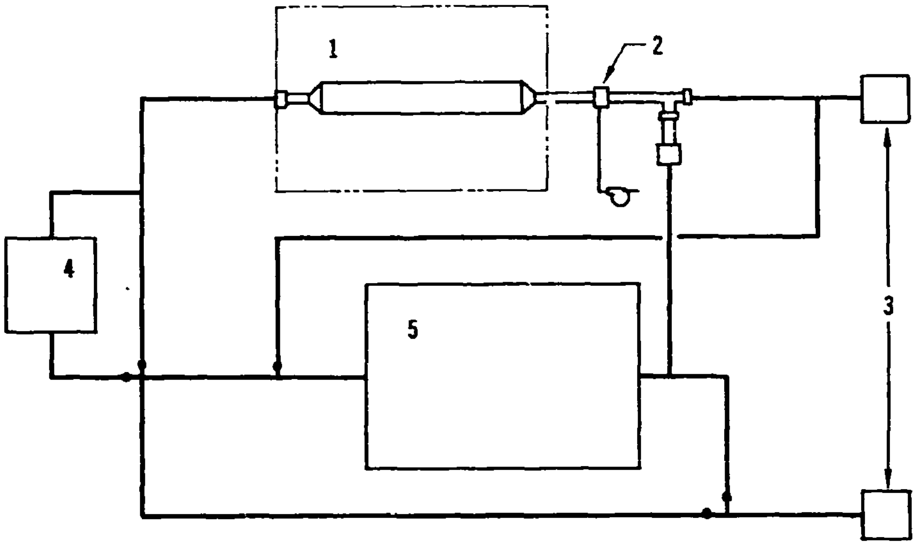


FIGURE 6-56
SCHEMATIC LAYOUT OF E6 DIRECT CONNECT TURBOMACHINERY TEST FACILITY



Legend:

1 **Direct Connect Test Leg**
2 **Water Spray**
3 **Intake and Exhaust Towers**
4 **Refrigeration Plant**
5 **Compressor Plant**

heater concept will be further refined in Phase III when the level of detail is sufficient to determine major alternatives and design problems. A major limitation of electric resistance heaters is that physical contact must be made with each heater element to provide the electrical connection. One concept which avoids this limitation is the induction heater concept where the current is induced into the heater matrix. Experience from steel mill billet heaters and the NASA Lewis inductively heated graphite heater at Plumbrook shall provide a base to evaluate specific applications.

Another major consideration is the heater element matrix material and configuration. The matrix configuration should be such to ensure a reasonably uniform temperature distribution during heat-up and provide good heat transfer from the matrix to the air. Conventional high alloy steels could probably be used up to 1800 to 2000°R (1000 to 1100°K). To attain 2500°F (1390°K) however, super alloy materials such as T.D. Nickel, Molybdenum, or columbium would be necessary.

6.3.6.1 Specifications - The following table presents the physical and operating specifications of the E6 direct connect facility. Only a single facility is specified, as there were no different size or performance facilities chosen. The first section of the table deals with a gross description of pertinent parameters. The second section shows the Mach number/altitude performance of the test section and the stagnation conditions required to achieve this performance. The third section shows some of the specifications of the system components necessary to provide the mass flow and stagnation pressure and temperature.

- Test Leg Description

Maximum Engine Inlet Diameter	90 in. (2.4 m)
Maximum Engine Length	50 ft. (15 m)
Maximum Engine Thrust	100,000 lb. (444,800 N)
Mach Number Range	0.3 to 5.5
Altitude Range	0 to 120 kft (0 to 36 km)
Stagnation Pressure Range	3 to 150 psia (2 to 103 N/cm^2)
Stagnation Temperature Range	432 to 2500°R (240 to 1400°K)
Mass Flow Range	100 to 1300 lbm/sec (45 to 590 kg/sec)
Run Time	Continuous

- Test Section Performance

M	Altitude kft	(km)	P_o* psia	(N/cm^2)	T_o °R	(°K)	$\dot{w}$ lbm/sec	(kg/sec)
.3	0	(0)	15.65	(10.8)	528	(293)	680	(308)
	18	(5.5)	7.2	(4.97)	462	(256)	100	(45.4)
.5	0	(0)	17.45	(12.03)	544	(302)	820	(372)
	30	(9.15)	4.8	(3.31)	432	(240)	100	(45.4)
1.0	0	(0)	27.9	(19.2)	622	(346)	1160	(527)
	48	(14.65)	3.1	(2.14)	468	(260)	100	(45.4)
1.2	0	(0)	35.2	(24.3)	668	(371)	1300	(590)
	55	(16.8)	2.95	(1.96)	505	(281)	100	(45.4)
1.7	21	(6.4)	31.2	(21.5)	700	(389)	1300	(590)
	68	(20.7)	3.1	(2.14)	616	(342)	100	(454)
2.0	27	(8.24)	37.4	(25.8)	760	(422)	1300	(590)
	75	(22.9)	3.5	(2.41)	710	(394)	100	(45.4)
2.5	37	(11.3)	50.0	(34.5)	880	(489)	1300	(590)
	85	(25.9)	4.5	(3.1)	900	(500)	100	(45.4)
3.0	44	(13.4)	74.5	(51.3)	1080	(600)	1300	(590)
	93	(28.4)	6.1	(4.2)	1120	(622)	100	(45.4)
3.5	51	(15.56)	108	(74.5)	1300	(722)	1300	(590)
	100	(30.5)	8.1	(5.58)	1350	(750)	100	(45.4)
4.0	56	(17.1)	150	(103.5)	1600	(890)	1190	(494)
	105	(32.0)	10.2	(7.03)	1650	(917)	100	(45.4)
4.5	65	(19.8)	150	(103.5)	1850	(1028)	1070	(485)
	111	(33.8)	11.6	(8.0)	2050	(1138)	100	(45.4)
5.0	75	(22.9)	150	(103.5)	2200	(1222)	920	(418)
	116	(35.4)	14.4	(9.93)	2350	(1306)	100	(45.4)
5.5	84	(25.6)	150	(103.5)	2500	(1390)	760	(345)
	120	(36.6)	16.7	(11.5)	2750	(1528)	100	(45.4)

*Stagnation pressure required at each Mach number is based on the highest recovery factor likely for typical inlet systems for the low altitude condition, and on the lowest recovery factor likely for the high altitude condition, thus giving the widest range of P_o for each Mach number.

- System Component Specifications

Compressor Plant: (Frictional losses in distribution piping were calculated to find the minimum compressor pressure requirement at each test condition).

Maximum Throughput = 1,020,000 scfm at 116 psia
= (28,900 m^3/min) at (80 N/cm^2)

Maximum Pressure = 157 psia at 935,000 scfm
(108.2 N/cm^2) at (26,500 m^3/min)

Electric Heater: Maximum power needed is 600 MW at 1900°F (1038°C)

Refrigeration Plant: Maximum refrigeration is needed at the M = .3, Z = 18 kft point is 2240 tons* (7880 kW)

* Corresponds to the cooling capacity of one ton (905 kg) of ice melting in one day which is defined as 12,000 Btu/hr (12,700 kW)

These specifications describe the E6 facility as it is currently defined, for existing engine concepts. As previously mentioned, in Phase III, a better projection of the mass flow requirements of advanced engines will be obtained and this may result in a redefinition of the compressor and heater specifications.

6.3.6.2 Facility Component and Cost Summary - Figure 6-57 shows a compilation of the costs estimated for each of the facility components. Estimates were made by the methods discussed in Section 6.1.

The most informative picture of the costs is presented in the "pie" charts, which reveal graphically the relative proportions of each facility element to the total cost. The largest cost elements are those which are most amenable to better definition and cost estimating in Phase III. The two most critical elements are the compressor plant and the electric heater, the capabilities and cost of which are directly proportional to the facility mass flow. The methods of estimating the cost of these two items for Phase II are based on maximum flow rate for the compressor, and on power for the heater, but in Phase III cost estimates will be obtained from manufacturers of these items.

Since the compressor costs are so large, a method of reducing the overall facility cost would be to integrate this test leg with existing engine test facilities and to add only an increment of compressor capability. This will be studied in Phase III as an important factor in site selection criteria for E6, if existing plants of sufficient magnitude in volume flow are available to use as a base.

6.3.6.3 Development Assessment - This facility is very similar to some of the altitude test cells located at AEDC, differing primarily in the fact that it is designed to provide full pressure and temperature duplication throughout the facility Mach number range. This factor translates into compressor, heater, and refrigeration requirements that are much greater than available at existing facilities.

FIGURE 6-57a
E6 FACILITY COMPONENT AND COST SUMMARY

Facility Component		Cost Estimate $1000's
		Baseline
1. DIRECT CONNECT ENGINE TEST LEG	Sub Total	19,832
1.1 Main Pressure Structure		1,815
1.2 Electric Heater		12,000
1.3 Bellmouth Assemblies (4)		900
1.4 Single Jack 2-D Nozzle Assembly		500
1.5 Engine Support and Thrust Stand		500
1.6 Telescoping Diffuser Assy.		14
1.7 Engine Fuel System - Storable and Cryogenic Fuels		1,303
1.8 Lab/Office/Control Bldg.		1,400
1.9 Facility Automatic Control System		400
1.10 Instrumentation and Data Acquisition System (Transducers, Amplifiers, Power Supply, Analog/ Digital Converter, Tape Recorder).		1,000
2. WATER SPRAY UNIT (Motor, Pump, Piping, Spray Ring Manifold, Water Separator).		500
3. INTAKE AND EXHAUST TOWERS		2,000
4. REFRIGERATION PLANT		1,280
5. COMPRESSOR PLANT	Sub Total	71,033
5.1 Mechanical Components (Compressors, Intercoolers, Oil Filters, Air Dryers, Motors, Controls, Distribution Piping and Valves).		55,329

FIGURE 6-57a (Continued)
E6 FACILITY COMPONENT AND COST SUMMARY

5.2 Electric Substation (Includes Power for Compressors and Electric Heater).	15,704
Total	94,645
Contingency @ 10%	9,464
Facility Cost	104,109
A&E Fee @ 6%	6,240
MGT & Coord @ 4%	4,170
Grand Total	114,519

FIGURE 6-57b
DISTRIBUTION OF FACILITY COMPONENT COSTS - E6

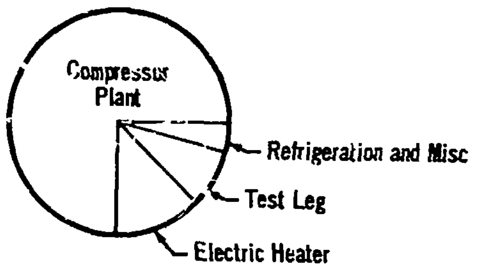


FIGURE 6-57c
E6 OPERATING COST SUMMARY

Operating Costs - Dollars/Occupancy Hours	
Repair and Maintenance	1,728
Staffing	1,000
Power	3,820
Total	6,548

The test leg is based on existing technology and facilities and would have a confidence level of 5 associated with it, as defined in 6.2.8.3. Development problems will primarily be associated with systems integrations. The compressor plant and refrigeration plant would be level 4, as machines of the category required do exist and are operating, but have not been assembled into a plant of the total capacity required for E6. The heater is level 3 at the very least, and will require a prototype to verify design specifications and operation. In order to minimize risks, the total heating capacity would probably be represented by several heaters, each within the current experience level. The matrix material required for operation to 2500°R (1390°K) will probably require some development if long life and minimum operational costs are desired. The overall risk of the facility is minimal in terms of technical goals. Integration problems could be significant, but, the greatest single risk lies in the continuous air heater. Initial operation could be accomplished with a non-refractory metal matrix at reduced temperatures until experience is gained in operating the facility to minimize major problems during initial operation.

6.3.7 INTEGRATED TURBOMACHINERY TEST FACILITY (E20) (DIRECT CONNECT AND FREE JET TEST LEGS) - This facility is comprised of a direct connect test leg (E6), integrated with a free jet test leg (E7 from Phase I), and served by a common compressor/exhauster plant and refrigeration plant. Both test legs are designed for PFRT testing of full scale turbojet, turbofan, turboramjet, and ramjet engines on a continuous basis. Details of the test legs are shown in Figures 6-58 and 6-59 and a schematic of the entire system is shown in Figure 6-60.

Discussion of the direct connect test leg and its specifications is given in Section 6.3.6 and will not be repeated here, except insofar as provision of the direct connect test capability affects the overall facility costs or test philosophy.

The free jet test leg was designed to provide full flight duplication at angles of attack throughout the flight Mach number range of 0.3 to 5.0 as shown in Figure 6-45a. In this type of testing, the actual freestream Mach number is developed in the nozzle, and the entire inlet duct/engine combination is tested. This type of testing is costly since the full freestream stagnation pressure must be obtained, and a considerable excess facility mass flow must be provided over that mass flow which actually goes into the engine. Three different facility schemes were considered for free jet testing, and are represented by the schematic drawings in Figure 6-61.

The first method is the propulsion wind tunnel, which has a nozzle test section large enough to accept the inlet/engine combination at maximum angle of attack. Considerable nozzle height must be provided in order that sufficient room is left between the inlet and the ceiling and the exhaust nozzle and the floor of the test section to avoid interference effects. This method, although most satisfactory from a technical standpoint, requires the largest nozzle size and mass flow rate in comparison to the other two methods. As depicted in Figure 6-61, a test section size of 40 x 13 feet (12.2 x 4.0 m) is necessary.

The mass flows presented in the performance table of Section 6.3.6.1 must be multiplied by 4.7 for the test section size for this test section concept. The maximum mass flow is then 51,000 lbm/sec (23,200 kg/sec), and the maximum volume flow into the compressor plant 40,000,000 scfm (1,130,000 m^3/sec). The AEDC VKF compressor plant has a maximum volume flow of about 100,000 scfm (28,000 m^3/sec) and represents

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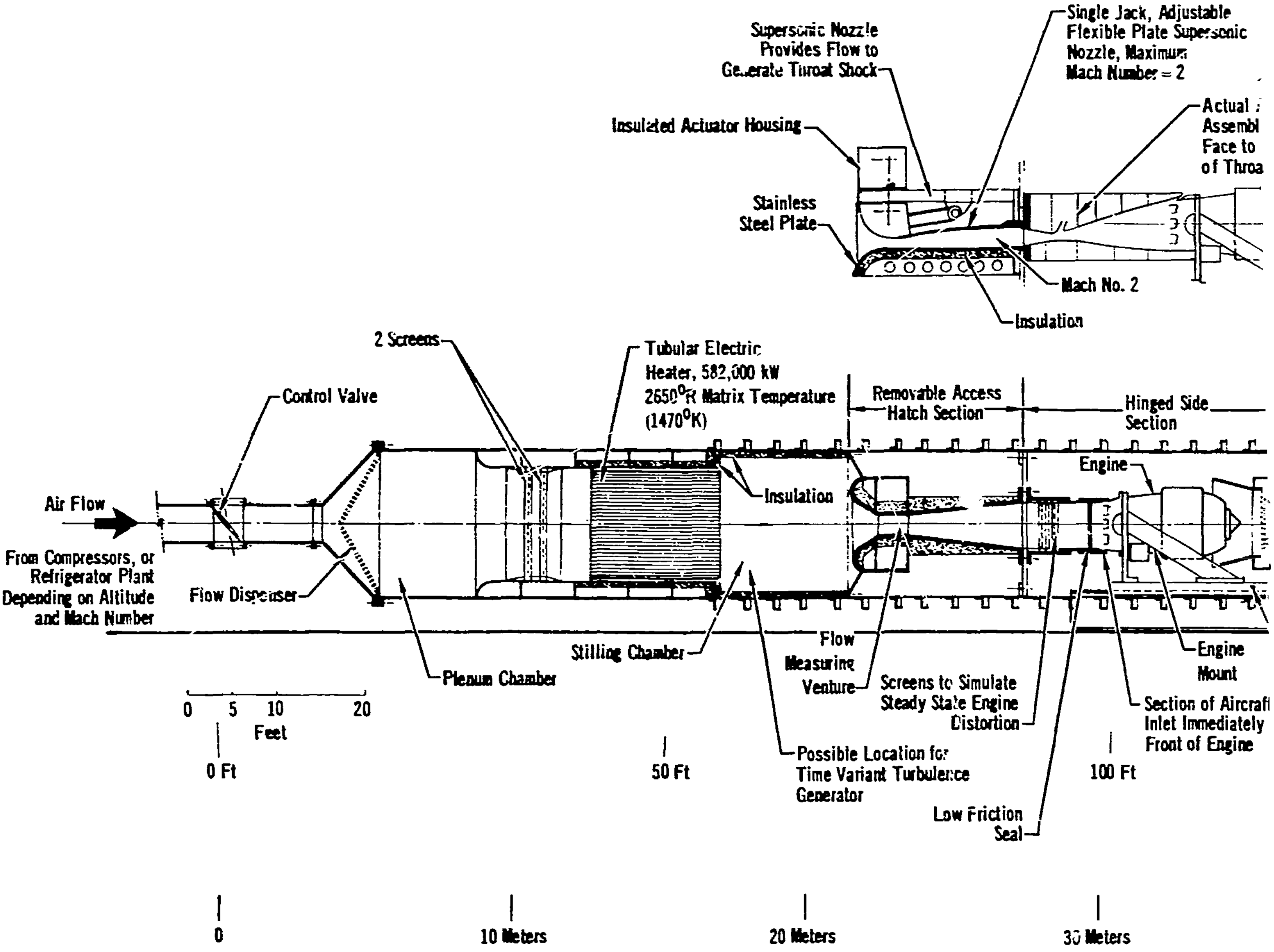
FIGURE 6-58
DIRECT CONNECT ENGINE TEST LEG FACILITY E20
(Identical to E6, in Figure 6-55)



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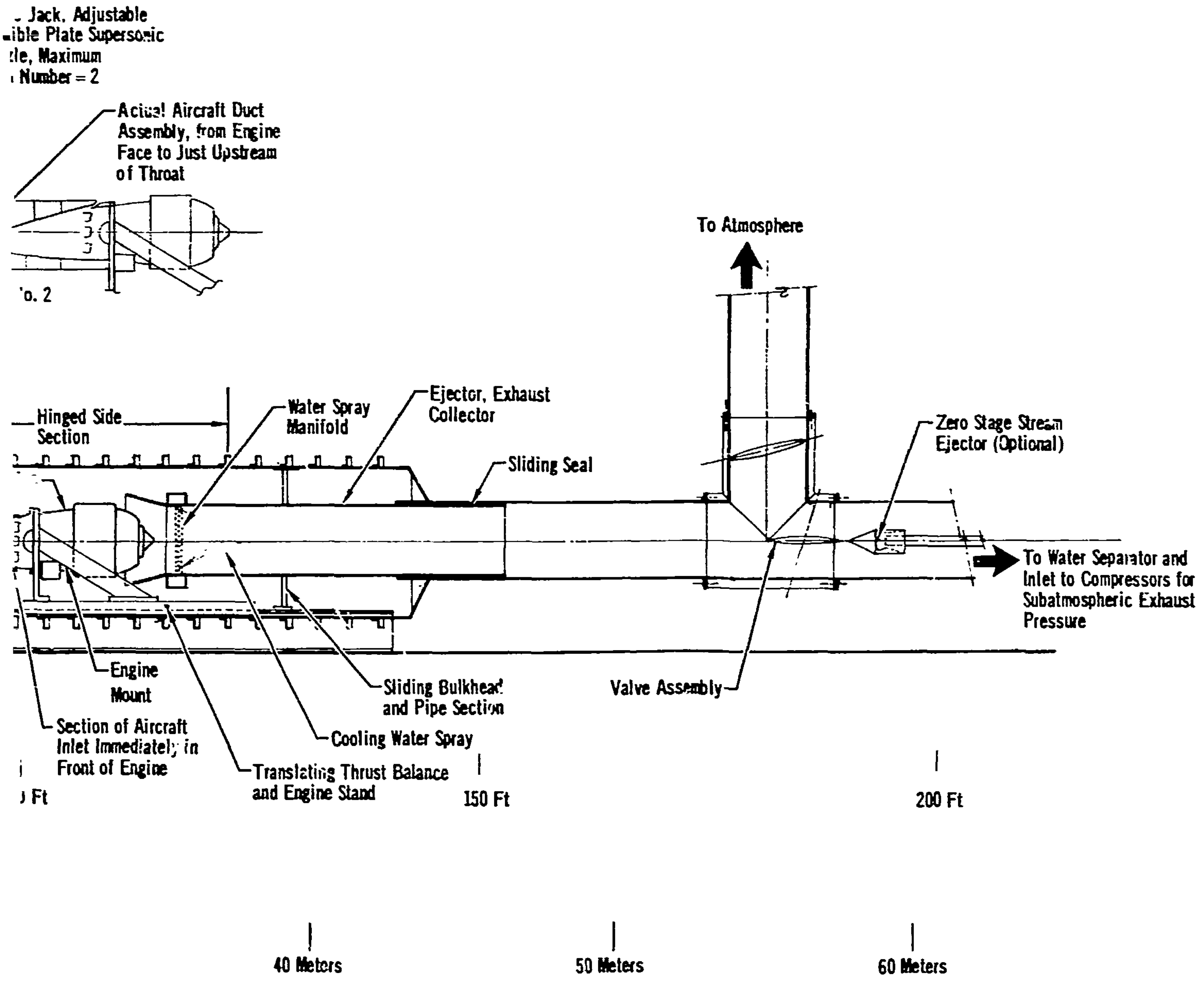

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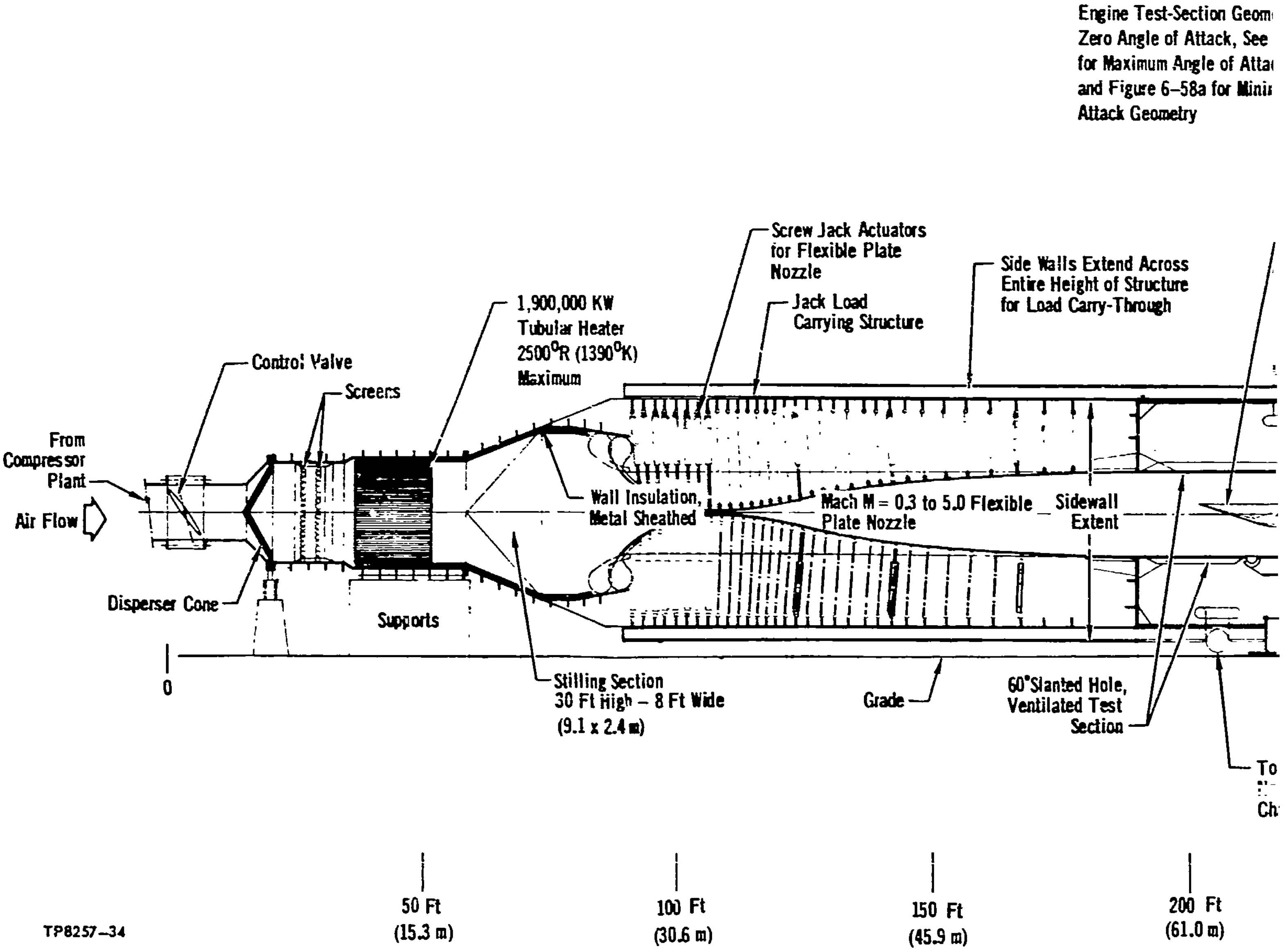

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FIGURE 6–59
FREE JET ENGINE TEST LEG, FACILITY E20

ction Geometry for
Attack, See Figure 6–58b
ngle of Attack Geometry,
58a for Minimum Angle of
y

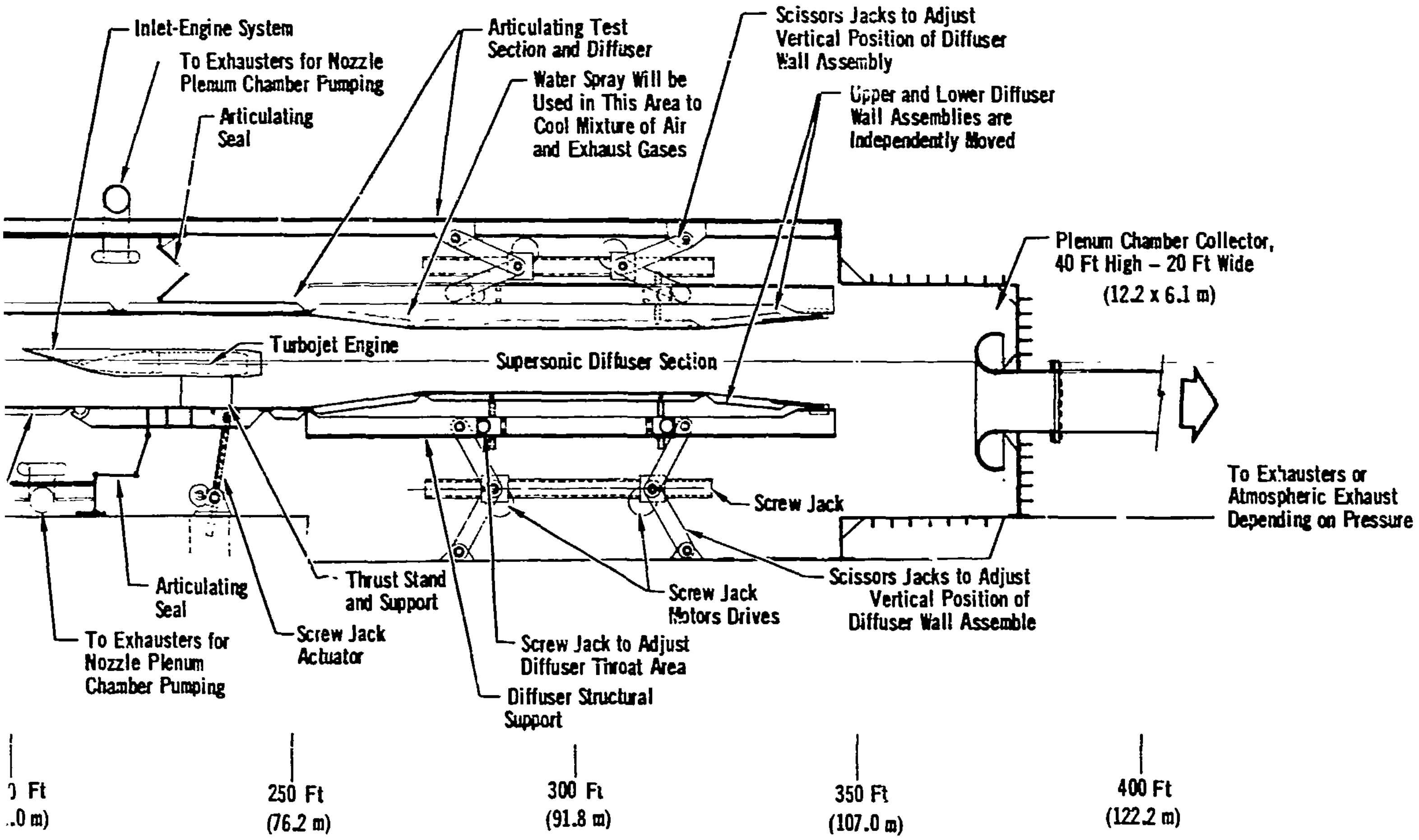
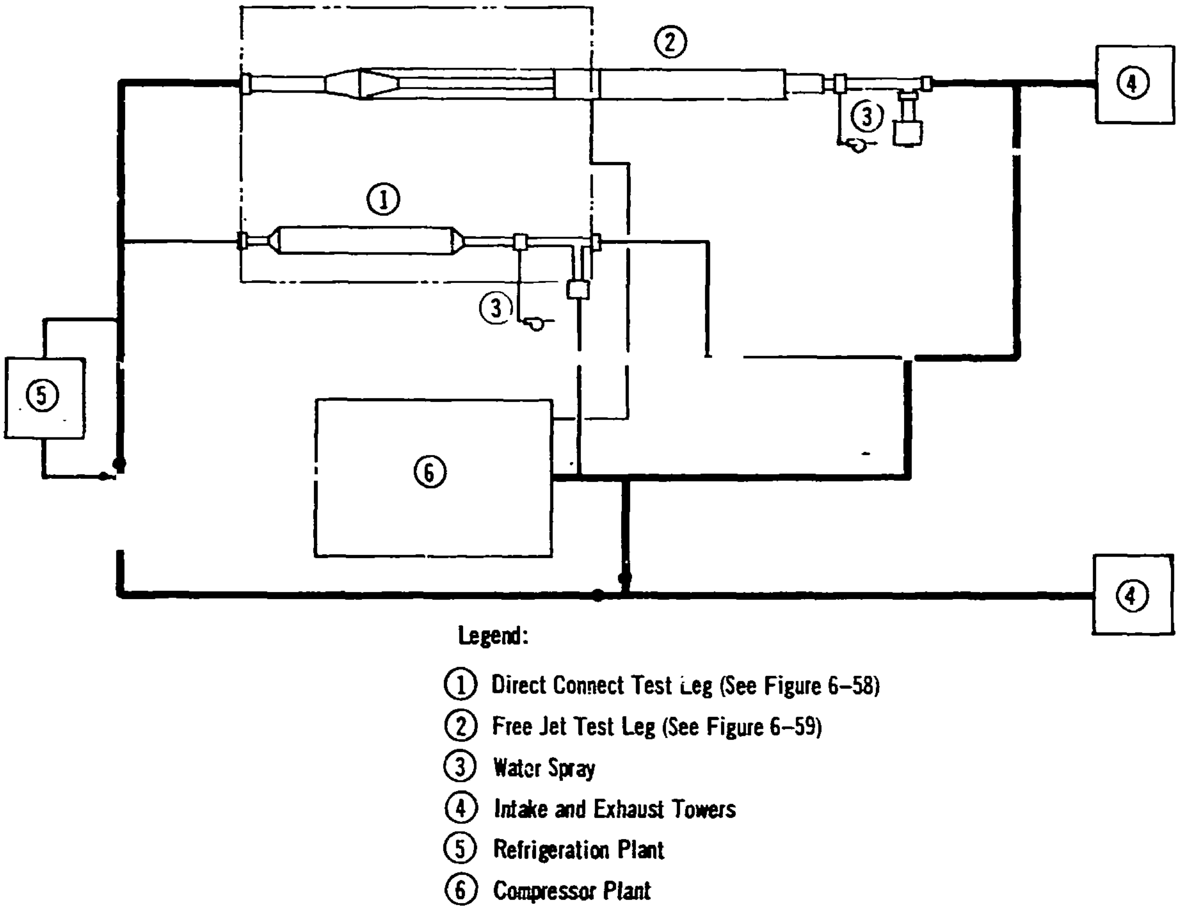


FIGURE 6-60
SCHEMATIC OF E20 TURBOMACHINERY
TEST FACILITY – DIRECT CONNECT LEG PLUS FREE JET TEST LEG



Legend:

① Direct Connect Test Leg (See Figure 6–58)
② Free Jet Test Leg (See Figure 6–59)
③ Water Spray
④ Intake and Exhaust Towers
⑤ Refrigeration Plant
⑥ Compressor Plant

a sizable plant in terms of wind tunnel compressor plants. Allis-Chalmers data shows that single machines up to 1,000,000 scfm (280,000 m^3/sec) have been built and are possible. However, estimation of the design and costs of the plant equipment needed to service this test section concept is a formidable task. For example, the electric heater for this concept would necessitate about a 10,000,000 kW input, which when combined with the estimated 20,000,000 kW required for the compressor plant so exceeds current technology that, even if the equipment could be defined, it is doubtful that a meaningful cost estimate can be obtained. In terms of the research value for this facility concept, such costs are not justified, and the concept was rejected.

The second method is a test cell where the inlet/engine is mounted on a fixed thrust stand and the nozzle is pitched, as depicted in Figure 6-61b. This method

FIGURE 61a
FREE JET FACILITY TEST SECTION ALTERNATE
(Propulsion Wind Tunnel)

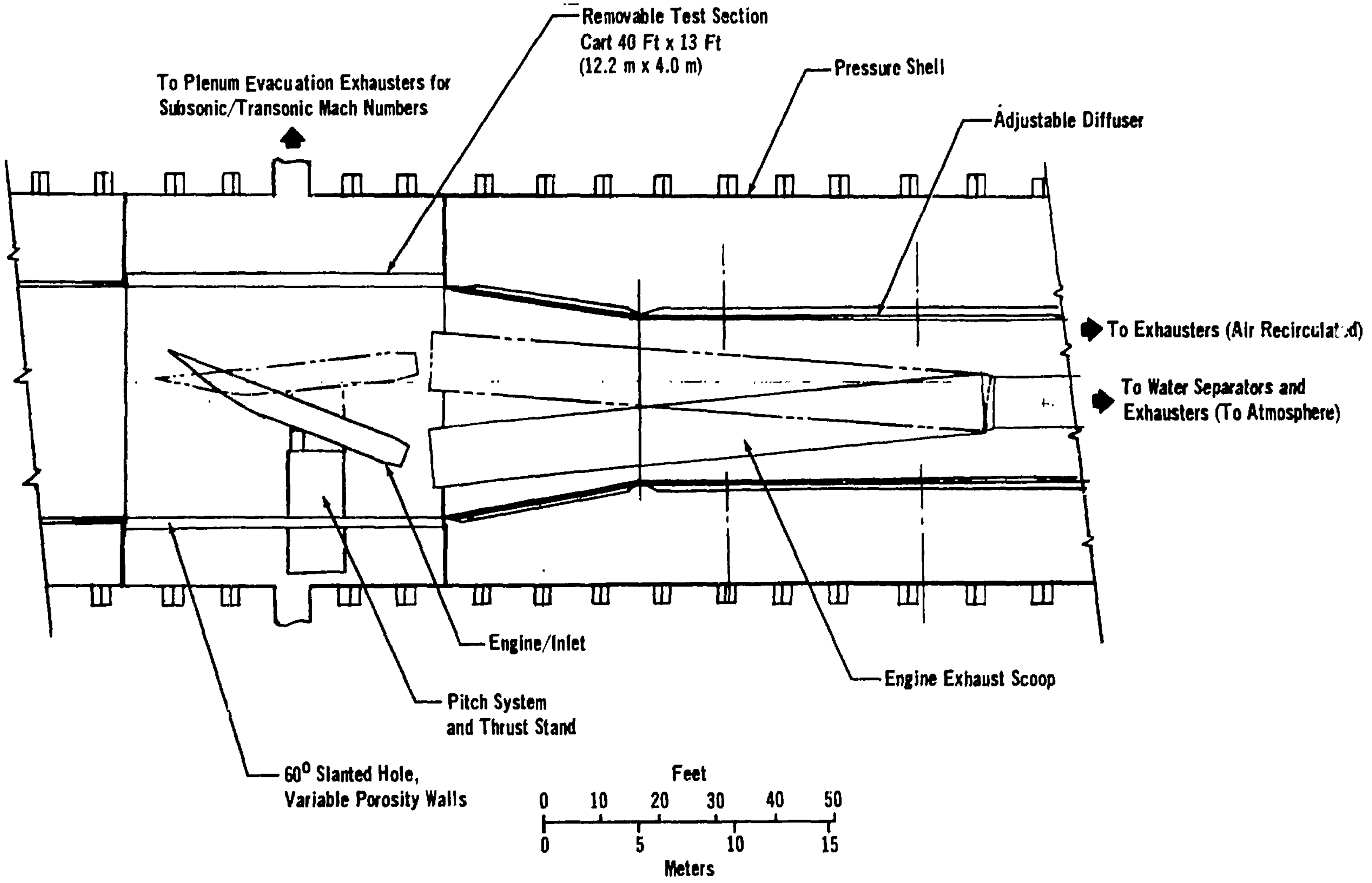


FIGURE 61b
FREE JET FACILITY TEST SECTION ALTERNATIVES (PITCHED NOZZLE)

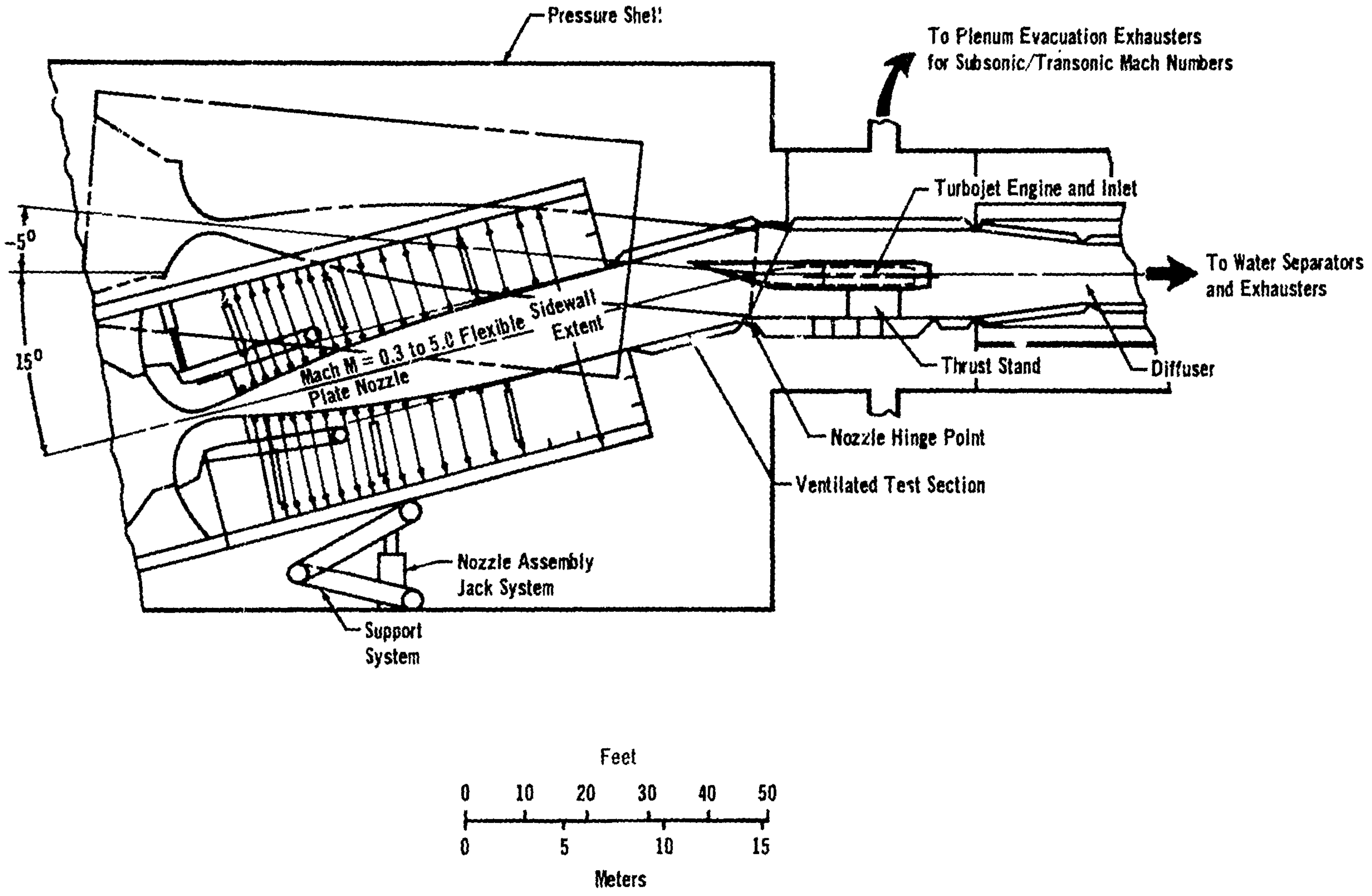
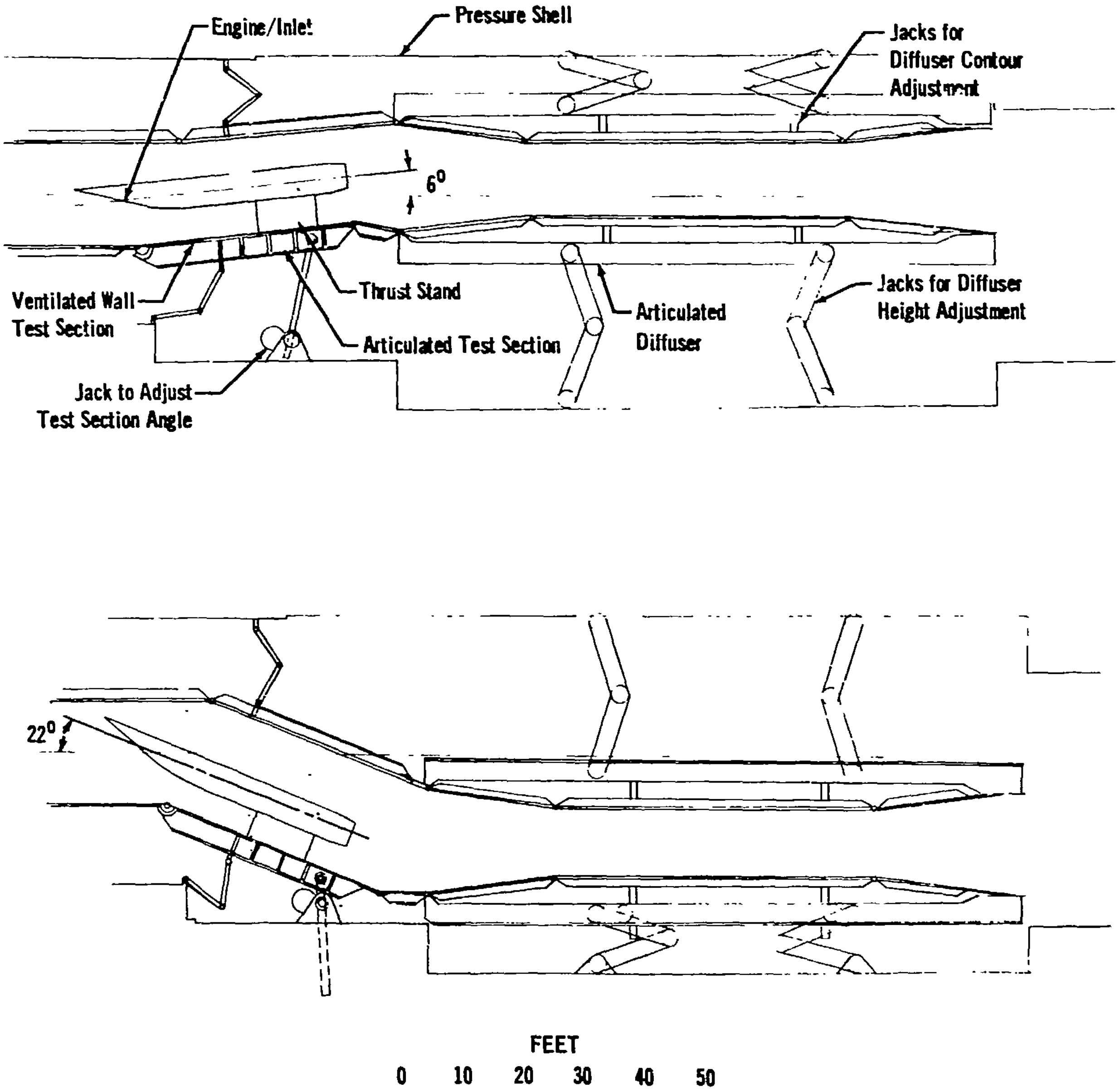


FIGURE 61c
FREE JET TEST SECTION ALTERNATIVES (PITCHED ENGINE AND TEST SECTION)



is used on small facilities, such as at APL and AEDC, with success and has an advantage in that the exhaust piping of the engine can be non-movable. In the case of E20, however, the large Mach range requires a very long and heavy flexible plate nozzle with water cooled walls. The weight and complexity of this system make it impractical to pitch the nozzle.

The pressurized plenum chamber around the nozzle which is some 90 feet (27.5 m) high and capable of withstanding 315 psia (217 N/cm^2) would present a major technical risk in terms of field fabrication, and meeting design specifications. The ventilated test section cannot be as effectively controlled, as in the previous fixed test section design, because of the nozzle motion, and transonic flow quality will be compromised. The dominating factor is the mechanical massiveness of the movable hardware, and the risk involved in the fabrication and operation of the facility. The mass flow is as presented in Section 6.3.6.1 for a test section 16 feet by 7 feet (4.9 m x 2.1 m). This concept was rejected because of the mechanical and fabrication problems.

The third method uses a large flexible plate water cooled nozzle, fixed in position. An inlet/engine model is mounted within a test section, whose ceiling and floor remain parallel while pitching with the inlet/engine. An articulated diffuser moves up and down with the test section and dumps the flow into a plenum chamber. A collector in the plenum chamber is connected to the exhaust piping. The top and bottom plates of the diffuser can move differentially with respect to each other, as well as together, so that optimum diffuser efficiency can be obtained at all Mach numbers, as depicted in Figure 6-61c. The nozzle contour changes, model and test section pitch, and diffuser position changes all occur while the facility is operating. The test section is ventilated for transonic Mach numbers, and is surrounded by a plenum chamber which is evacuated by an auxiliary evacuation system. The hinge points on the articulated test section are chosen so that expansion fans or compression waves emanating from the hinge points will have minimal effect on the inlet flow. These waves, and waves emanating from the aft test section hinges could, however, affect the exhaust nozzle flow. The nozzle size is 16 ft high (4.9 m) by 7 ft wide (2.1 m).

This concept is not utilized in any existing propulsion facility as are the previous two concepts. However, there are no existing facilities of the size and performance described in this section. Although a prototype scale model will be necessary to work out flow anomalies in the articulated test section concept, it appears to be a design which keeps the components and mechanisms to sizes and structural requirements consistent with current experience. For this reason, this concept was selected as the Phase II test section concept for the free jet leg. It minimized test section size for an operational engine, reduced the massiveness of the total facility, and provided components consistent with present field fabrication experience.

One other option was available, based on an analysis of the angle of attack of the aircraft at different flight path points. The maximum mass flow points occur at high dynamic pressures where maximum angles of attack cannot be flown because of the structural limitations of the aircraft. Theoretically, it should be possible to move the nozzle flexible plates closer to the centerline, consistent with the reduced angle of attack requirements, since less nozzle height is required. The facility mass flow could be correspondingly reduced. For example at a flight path point of Mach number 1.2 at sea level, the nozzle height for the articulated test section could be reduced from 16 feet (4.9 m) to 10.5 ft (3.2 m) allowing a 34% reduction in mass flow. A simplified analysis indicated that the complexity of providing translation as well as contour control to the nozzle actuation system, plus the additional actuator stroke increased the cost and technical risk in an already complicated test section configuration, negating the advantages of the reduced mass flow requirements. Application of this principle to the complete free jet concept would not have reduced the mass flow sufficiently to alter the conclusions concerning the feasibility of a facility based on this test section concept.

The nozzle sizes for the test section concepts were determined from the requirements for the three engines depicted in Figure 6-62. The angle of attack range assumed for each engine/inlet system was:

SST Type Turbojet	$-5^\circ \leq \alpha \leq 8^\circ$
Fighter Turbojet	$-5^\circ \leq \alpha \leq 22^\circ$
Turboramjet	$-5^\circ \leq \alpha \leq 15^\circ$

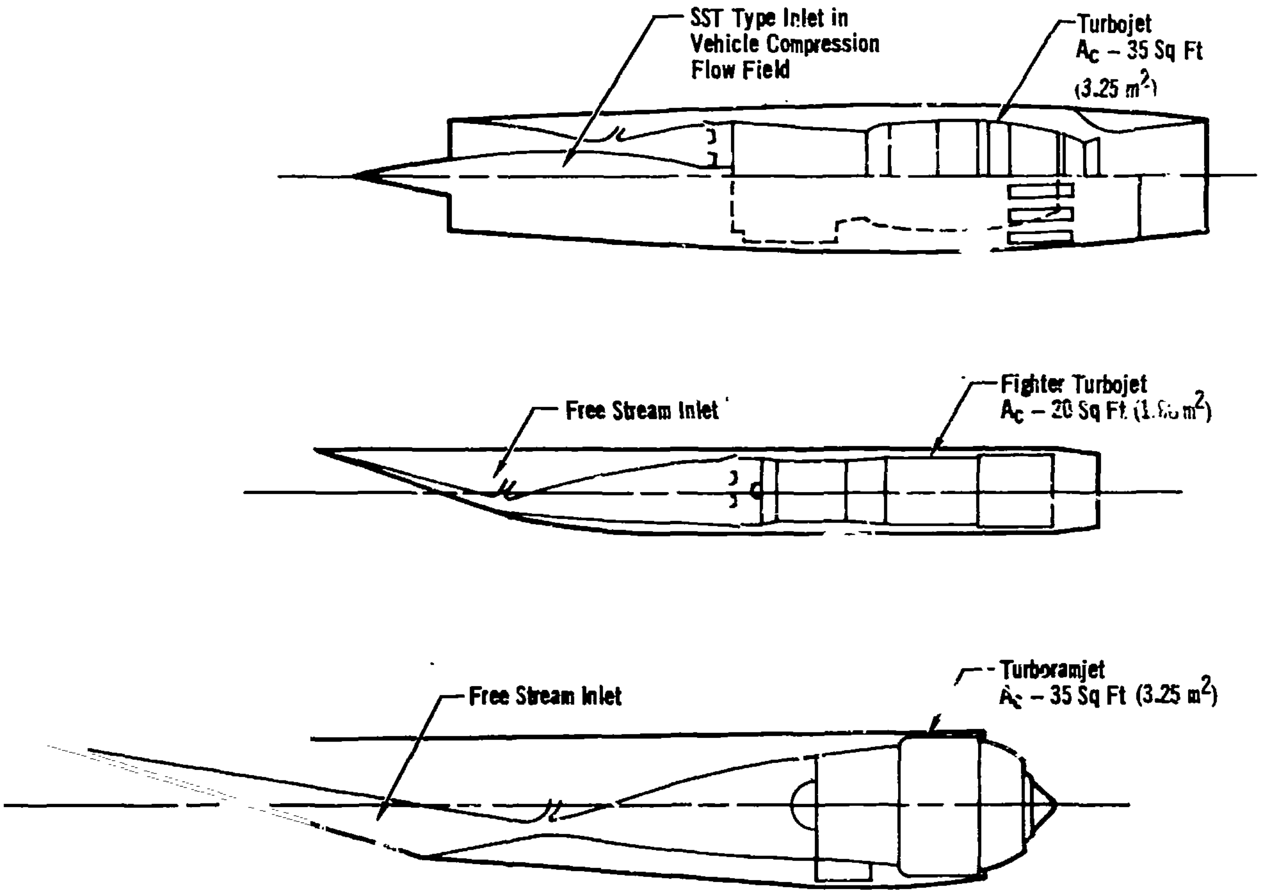
As discussed in Section 6.3.6, for the direct connect facility E6, the continuous air heater presents a serious design problem for this class of facility. The heater requirements were stringent enough for E6 with a maximum mass flow of 1300 lbm/sec (590 kg/sec). For the 10,870 lbm/sec (4925 kg/sec) required for the free jet leg, the heater system must be considered a limiting technical factor in accomplishing the performance as specified. A first stage combustion heater which would provide an inlet temperature to the electric heater on the order of 1800°R (1000°K) could substantially reduce the input power into the electric heater. Although the matrix materials problems are still present, the problems associated with supplying and routing the input power to the heater are reduced. This aspect will be further studied in Phase III.

In summary, the free jet test leg is capable of doing performance and PFRT tests on a continuous basis, and with full duplication of flight stagnation temperatures and pressures, over the Mach number range of 0.3 to 5.0. It is especially suited to testing the inlet/engine compatibility problems, using full scale actual inlets. The complexity of the mechanical test leg components, needed to minimize overall facility size and the compressor requirements, gives rise to several developmental problems, to be discussed in Section 6.3.7.3.

6.3.7.1 Specifications - The following table presents the physical and operating specifications of the E20 integrated turbomachinery test facility. The test leg description and test section performance refer only to the free jet test leg. Specifications of the direct connect leg are given in 6.3.6.1. System component specifications refer to the system components necessary to provide the mass flow and stagnation pressure and temperature of both test legs.

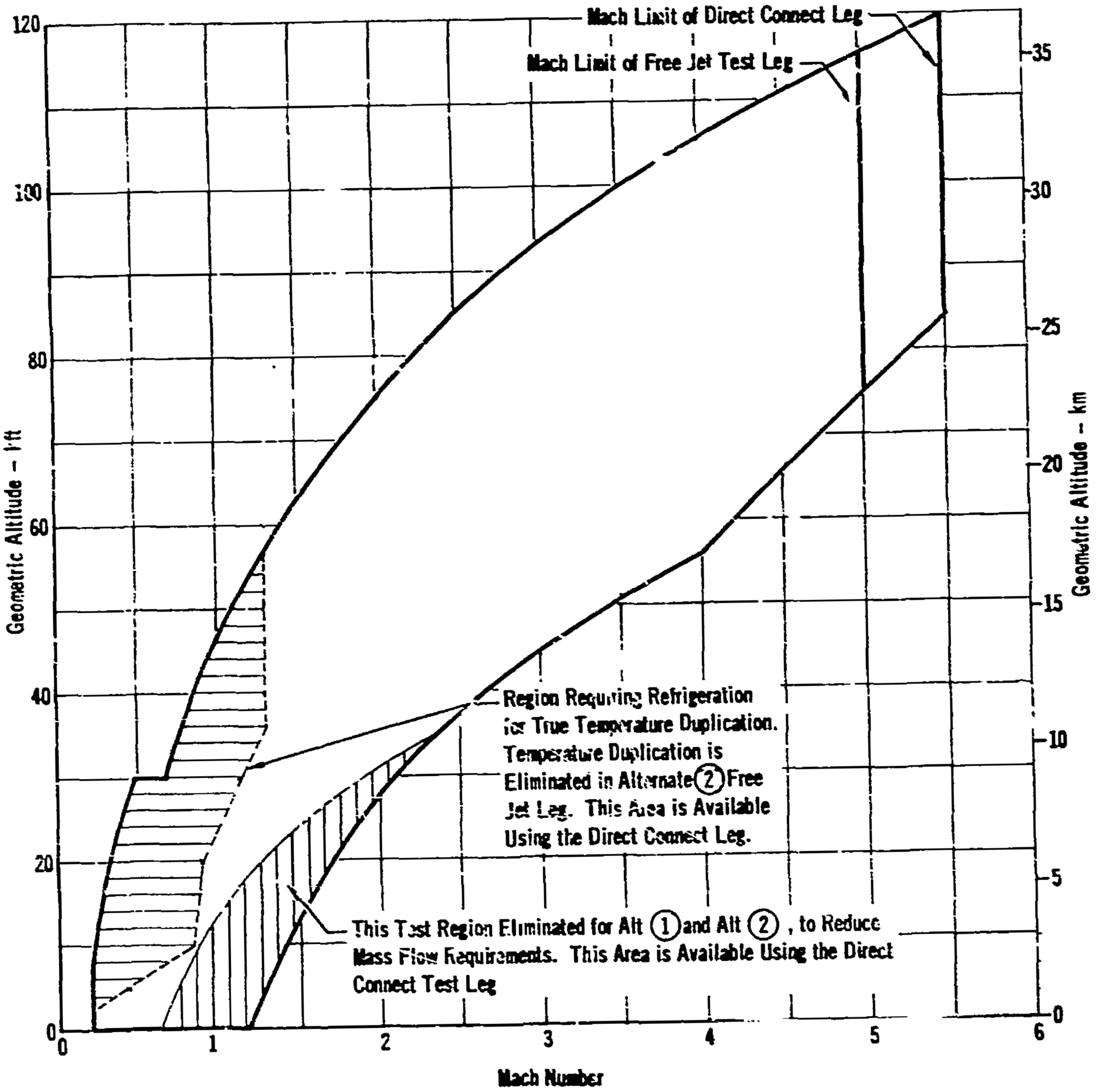
One of the major contributions of the free jet leg research capability will be in the area of engine/inlet compatability research. With the capability of complete temperature duplication to Mach number 5, time variant pressure and temperature distortions can be investigated, at actual engine and inlet operating temperatures. If this can be considered a major role for this facility, with much of the engine related research being accomplished in the direct connect leg, then some compromises can be made in the low speed portion of the performance envelope, reducing the maximum mass flow requirements. Figure 6-63 presents these compromises,

FIGURE 6-62
REPRESENTATIVE ENGINE/INLET ARRANGEMENTS



represented as Alternate 1 and 2 facility definitions. Alternate 1 reduces the maximum mass flow to 6000 lbm/sec (2720 kg/sec), eliminating some of the transonic, low altitude duplication capability. Since the time variant distortions generally are more important in the supersonic flight regime than in the transonic flight regime, this deletion should have little effect on the engine/inlet research capability. Alternate 2 adds to Alternate 1 the elimination of the temperature duplicated region at subsonic and transonic speeds requiring cooling of the air supply below 70°F (295°K). Elimination of flight duplicated temperature in this region should have a negligible effect on the overall research capability - the operating region will be available, but the air stagnation temperature will be too high for flight duplication. This will necessitate some adjustments in engine rpm to obtain scaled results. High angle of attacks associated with transonic high performance maneuvers would still be available for inlet research.

FIGURE 6-63
FLIGHT DUPLICATION REGIONS OF ENGINE TEST FACILITY E20



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The direct connect leg is presented in Figure 6-58, and the free jet leg, based on the articulated test section concept, in Figure 6-59. The articulated test section position corresponding to minimum and maximum angle of attack is shown in Figure 6-61. A schematic representation of the E20 facility complex is given in Figure 6-60.

- Test Leg Description (Free Jet)

Nozzle Dimensions:	Height = 16 ft (4.9 m) Width = 7 ft (2.1 m)
Maximum Inlet/Engine Length	= 45 ft (13.7 m)
Maximum Engine Thrust:	100,000 lb (444,800 N)
Mach Number Range:	0.3 to 5.0
Altitude Range:	0 to 116 kft (0 to 35.4 km)
Stagnation Pressure Range:	3 to 315 psia (2 to 217 N/cm^2)
Stagnation Temperature Range^2:	432 to 2350°F (340 to 1300°K)
Mass Flow Range^1:	286 to 10,870 lbm/sec (130 to 4930 kg/sec)
Run Time:	Continuous

- Test Section Performance

M	Altitude kft	(km)	P_c psia	(N/cm^2)	T_o^{2} °R	(°K)	$\dot{w}$^{1} lbm/sec	(kg/sec)
.3	0	(0)	15.65	(10.8)	528	(293)	2,720	(1230)
	18	(5.5)	7.81	(5.38)	462	(256)	1,458	(661)
.5	0	(0)	17.45	(12.0)	544	(302)	4,700	(2130)
	30	(9.15)	5.18	(3.56)	432	(240)	1,570	(712)
.7	0	(0)	20.8	(14.3)	568	(315)	6,720	(3050)
	31	(9.46)	5.8	(4.00)	450	(250)	2,020	(916)
1.0	0	(0)	27.85	(19.2)	622	(346)	9,630	(4370)
	48	(14.65)	3.38	(2.33)	468	(260)	1,458	(661)
1.2	0	(0)	35.6	(24.5)	668	(371)	10,870	(4925)
	55	(16.8)	3.22	(2.22)	505	(281)	1,230	(558)
1.7	21	(6.4)	32.0	(22.0)	700	(389)	8,070	(3660)
	68	(20.7)	3.53	(2.43)	616	(342)	896	(407)
2.0	27	(8.24)	39.1	(26.9)	760	(422)	7,170	(3250)
	75	(22.9)	4.03	(2.78)	710	(394)	762	(346)
2.5	37	(11.3)	53.8	(37.1)	880	(489)	5,820	(2640)
	85	(25.9)	5.5	(3.78)	900	(500)	605	(274)
3.0	44	(13.4)	82.7	(57.0)	1080	(600)	4,930	(2230)
	93	(28.4)	8.2	(5.65)	1120	(622)	493	(223)
3.5	51	(15.6)	126	(86.9)	1300	(722)	4,250	(1930)
	100	(30.5)	12.6	(8.69)	1350	(750)	426	(193)
4.0	56	(17.1)	201	(139)	1600	(890)	3,700	(1680)
	105	(32.0)	20.4	(14.1)	1650	(917)	370	(168)
4.5	65	(19.8)	256	(176)	1850	(1028)	3,300	(1500)
	111	(33.8)	30.5	(21.0)	2050	(1138)	321	(145)
5.0	75	(22.9)	315	(217)	2200	(1222)	2,970	(1350)
	116	(35.4)	48	(33.1)	2350	(1306)	286	(130)

[1] For Alternates, maximum mass flow equals 6000 lbm/sec (2720 kg/sec)

[2] For Alternate 2, no temperatures below 560°R (311°K) are available.

- System Component Specifications

Compressor Plant: (Frictional losses in distribution piping were calculated to find the minimum compressor pressure requirement at each test condition.)

		BASELINE	ALT. 1	ALT. 2
Maximum Inlet Flow	scfm	8,500,000	4,700,000	4,700,000
	(m^3/min)	(241,000)	(133,000)	(133,000)
Maximum Pressure	psia	315	315	315
	(N/cm^2)	(217)	(217)	(217)
Electric Heater				
Direct Connect Leg				
Max Power - kW		600,000	600,000	600,000
At Temp - °F		1900	1900	1900
(°C)		(1038)	(1038)	(1038)
Free Jet Leg				
Max Power - kW		1,900,000	1,900,000	1,900,000
At Temp - °F		1740	1740	1740
(°C)		(950)	(950)	(950)
Refrigeration				
Direct Connect Leg				
Capacity - Tons		2240	2240	2240
(kW)		(7880)	(7880)	(7880)
Free Jet Leg				
Capacity - Tons		15,300	-	-
(kW)		(53,800)	-	-

6.3.7.2 Facility Component and Cost Summary - Figure 6-64a shows a compilation of the costs estimated for each of the facility components. Estimates were made by the methods discussed in Section 6.1.

An overall view of the costs is presented by the "pie" charts, Figure 6-64b, which reveal graphically the relative proportions of each facility element to the total cost. The largest cost elements are those which are most amenable to better definition and cost estimation in Phase III. In this case, the largest cost is the compressor plant. Selection of either of the alternates cuts this cost in half and is recommended. Further definition of the compressor operating envelope, and consultation with compressor manufacturers in Phase III will produce a much firmer cost estimate on this very important facility component. The concept of the continuous

FIGURE 6-54a
E20 FACILITY COMPONENT AND COST SUMMARY

Facility Component		Cost Estimate $1000's		
		Baseline	Alt 1	Alt 2
1. DIRECT CONNECT ENGINE TEST LEG (Same as E6)	Sub Total	19,832	19,832	19,832
2. FREE JET ENGINE TEST LEG	Sub Total	54,492	54,492	54,492
2.1 Main Pressure Structure		5,372	5,372	5,372
2.2 Electric Heater		40,000	40,000	40,000
2.3 Flexible Nozzle Assembly (Sidewall Structure, Jack Reaction Structure, Electric Screw Jacks, Water Cooled Flexible Plates, Nozzle Seals).		4,300	4,300	4,300
2.4 Test Section and Diffuser Assembly (Sidewall Structure, Porous Wall Plates, Plenum Evacuation Piping and Valves, Thrust Stand, Articulated Test Section and Diffuser top and Bottom Plates, Dynamic Seals, Test Section Screw Jacks and Scissors Mechanism).		3,000	3,000	3,000
2.5 Engine Fuel System (Price included in Direct Connect Leg Cost).		-	-	-
2.6 Lab/Office/Control Building (Addition to Cost Required for Direct Connect Test Leg).		420	420	420
2.7 Facility Automatic Control System		400	400	400
2.8 Instrumentation and Data Acquisition System (Transducers, Amplifiers, Power Supplies, Analog/Digital Converter, Tape Recorder).		1,000	1,000	1,000
3. WATER SPRAY UNIT (Motors, Pumps, Piping, Spray Ring Manifolds, Water Separators for both Legs).		5,000	3,000	3,000
4. INTAKE AND EXHAUST TOWERS		3,060	1,840	1,840
5. REFRIGERATION PLANT		8,730	8,730	1,280

FIGURE 6-64a (Continued)
E20 FACILITY COMPONENT AND COST SUMMARY

6. COMPRESSOR PLANT Sub Total	497,352	269,764	269,764
6.1 Mechanical Components (Compressors, Intercoolers, Oil Filters, Air Dryers, Motors, Controls, Distribution Piping and Valves).	442,800	221,488	221,488
6.2 Electric Substation (Includes Power for Compressors and Electric Heaters).	54,552	48,276	48,276
Total	588,466	357,658	350,208
Contingency @ 10%	58,846	35,766	35,021
Facility Cost	647,312	393,424	385,229
A&E Fee @ 6%	38,800	23,700	23,100
MGT & Coord. Fee @ 4%	25,900	15,700	15,400
Grand Total	712,012	432,824	423,729

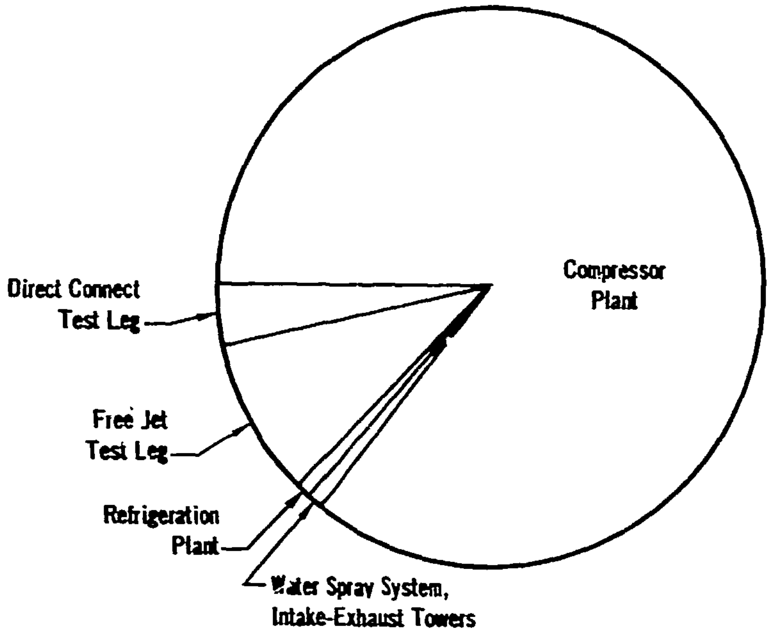
air heater has not been finalized so that the cost estimate is based on a number of assumptions from industrial sized heaters. Refinement of the concept and inquiry as to actual fabrication techniques with representative suppliers will probably result in an upward adjustment of these costs. As for E6, investigation of possible sites where integration of E20 with existing equipment could result in reduced compressor, refrigeration, or heating costs, is likely to result in reduced acquisition costs.

6.3.7.3 <u>Development Assessment</u> - So far as is known, the free jet leg is unlike any facility now operating or planned, and incorporates several difficult mechanical design problems. These problems are all related to the articulated test section and diffuser and should be investigated through prototype development before committment to a firm engineering design. Examples are:

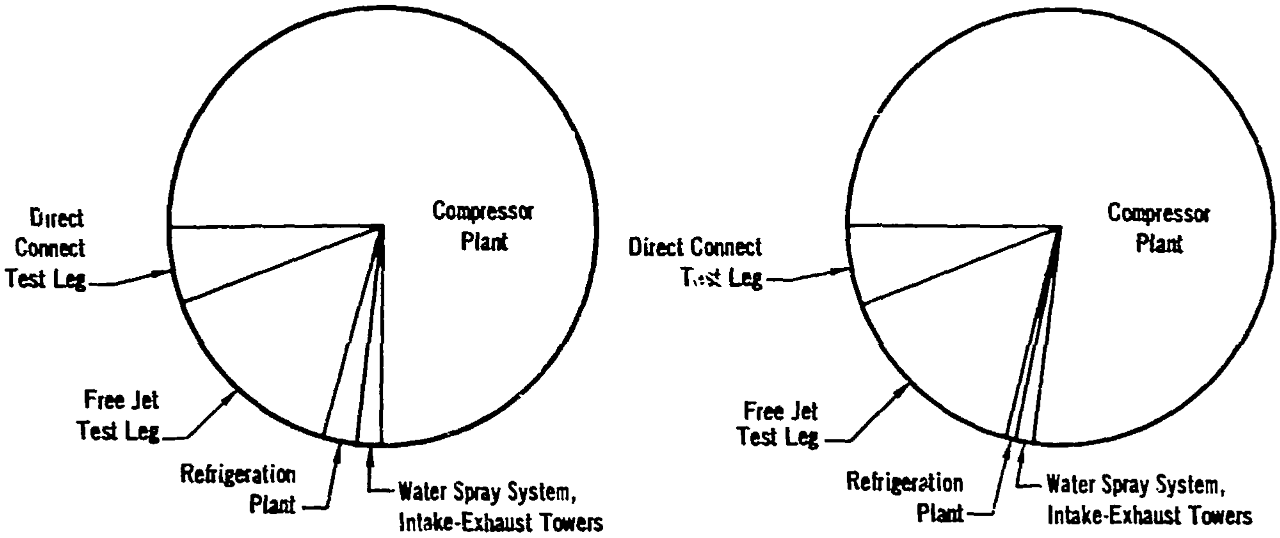
- o Investigation of transonic flow characteristics of the articulated test section.
- o Development of seal design for test section plenum chamber and diffuser plates.
- o Development of sidewall seals for nozzle, test section, and diffuser.
- o Investigation of pumping characteristics of plenum chamber collector when the diffuser is running off-center.
- o Design of water cooled flexible plate nozzle, including investigation of the possibility of using a simpler single jack, tapered plate concept.

The individual items comprising the articulated test section have a confidence level of 5 (as defined in Section 6.2.8.3) associated with them, however the assembled articulated test section would have a confidence level of 2, requiring scale model development. The compressor plant would be level 4, in that individual compo-

FIGURE 6–64b
DISTRIBUTION OF FACILITY COMPONENT COSTS – E20



Baseline



Alternate 1

Alternate 2

FIGURE 6–64c
E20 FACILITY SUMMARY
Operating Cost

Operating Costs – Dollars/Occupancy Hour	Baseline	Alternate 1	Alternate 2
Repair and Maintenance	10,740	6,607	6,472
Staffing	1,000	1,000	1,000
Power	13,220	11,730	11,648
Total	24,960	19,337	19,120

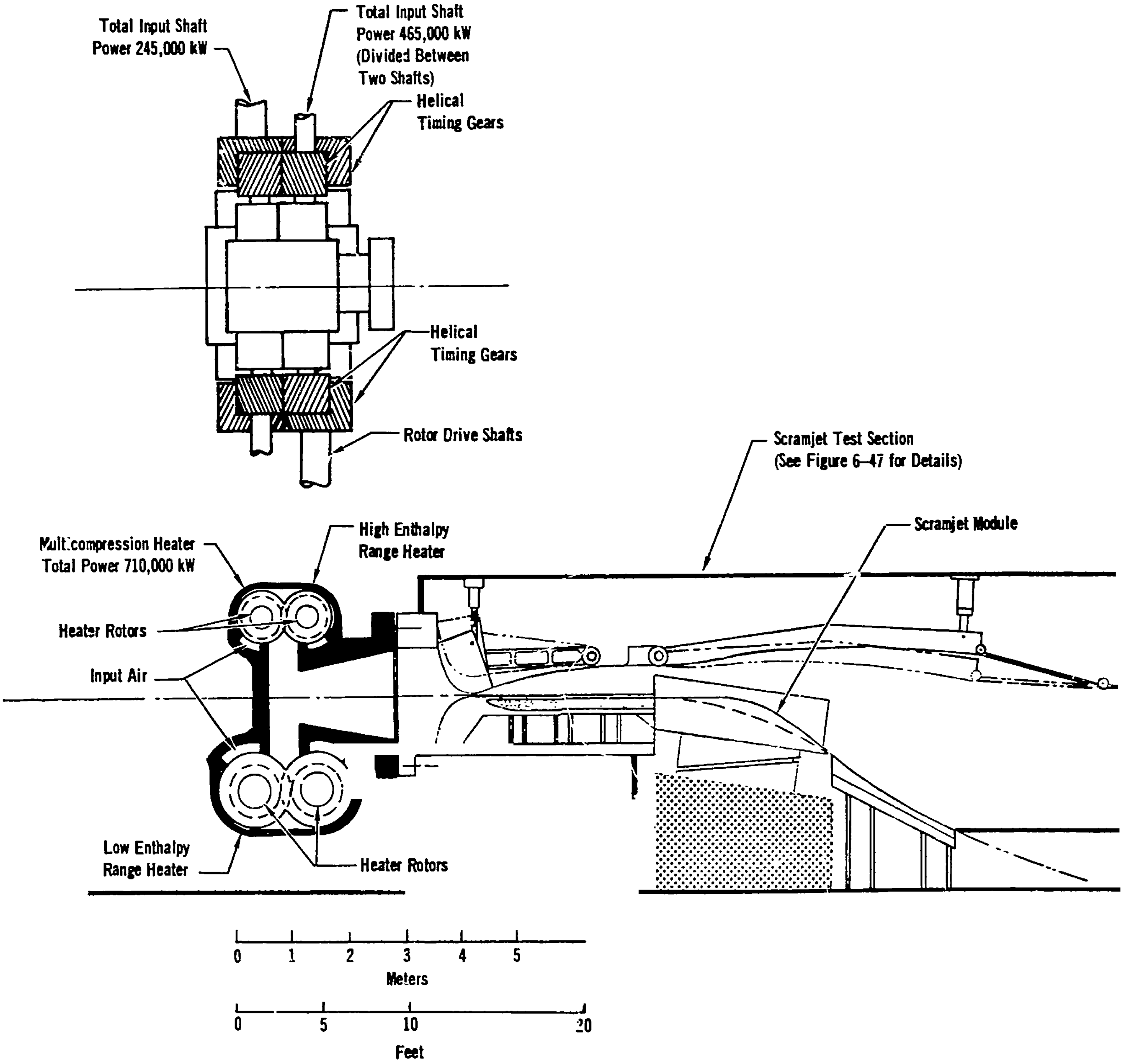
nents are or have been built but not integrated into a plant of this size. A significant time span must be allowed to permit balancing the compressors and valving at different test conditions. Consequently, the initial facility performance will probably be less than specified until the intricacies of the compressor operation matching are worked out. Despite its size, there seem to be no potential unsolvable problems associated with the compressor plant. The continuous air heater, on the other hand, is indicative of level 2. Large resistance, inductive, and combustion heaters have been developed and are in operation, however the heater for the E20 free jet leg represents an order of magnitude increase in input power over current sizes. This item is critical to the attainment of the duplicated flight temperatures necessary to develop high performance composite engines, and is probably the pacing item in terms of acquisition schedule and risk of not achieving the specified performance. A significant development program would probably be necessary by heater suppliers to arrive at a satisfactory design for final construction. The risk involved with the heater, and the cost of the overall facility compared to its increment in research value, requires an unfavorable assessment of the development of this type facility. The problems which could arise that would produce serious and costly delays, including failure to achieve specified performance, are numerous.

6.3.8 MULTIRECOMPRESSION HEATER SCRAMJET TEST FACILITY (E8) - This facility is designed to test scramjet engine and convertible scramjet engine modules, on a continuous basis, through the Mach number range of 3 to 12.5, and an altitude range of 45 to 160 kft to (13 to 49 km). A modified direct-connect test technique is used, testing engine modules up to 15 ft^2 (1.39 m^2) capture area. Air is the test medium, and is heated to the high stagnation temperatures required by a two stage multirecompression heater (MRCH). This is a mechanical heater concept which converts mechanical shaft power directly into thermal energy.

The test leg of the facility is designed on a modular basis, with the MRCH and a subsonic diffuser section installed in fixed locations. Engine testing is done by installing the scramjet engine test module and its connecting piping between these fixed locations, as shown in Figure 6-65. The pressure, temperature and flow rate provided by the heater can also be used for thermo/structural testing of full scale aircraft components or sections. This is accomplished by installing one of a set of water cooled aerodynamic nozzles, a test cabin containing the test specimen, and a diffuser adapter in place of the engine test module. This arrangement is shown in Figure 6-51. Longitudinal tracks are provided for axial translation of

FOLDOUT FRAME 1

FIGURE 6–65
MULTICOMPRESSION HEATER SCRAMJET ENGINE TEST FACILITY FOR A 15 SQ FT (1.39 m^2) CAPTURE AREA MODULE



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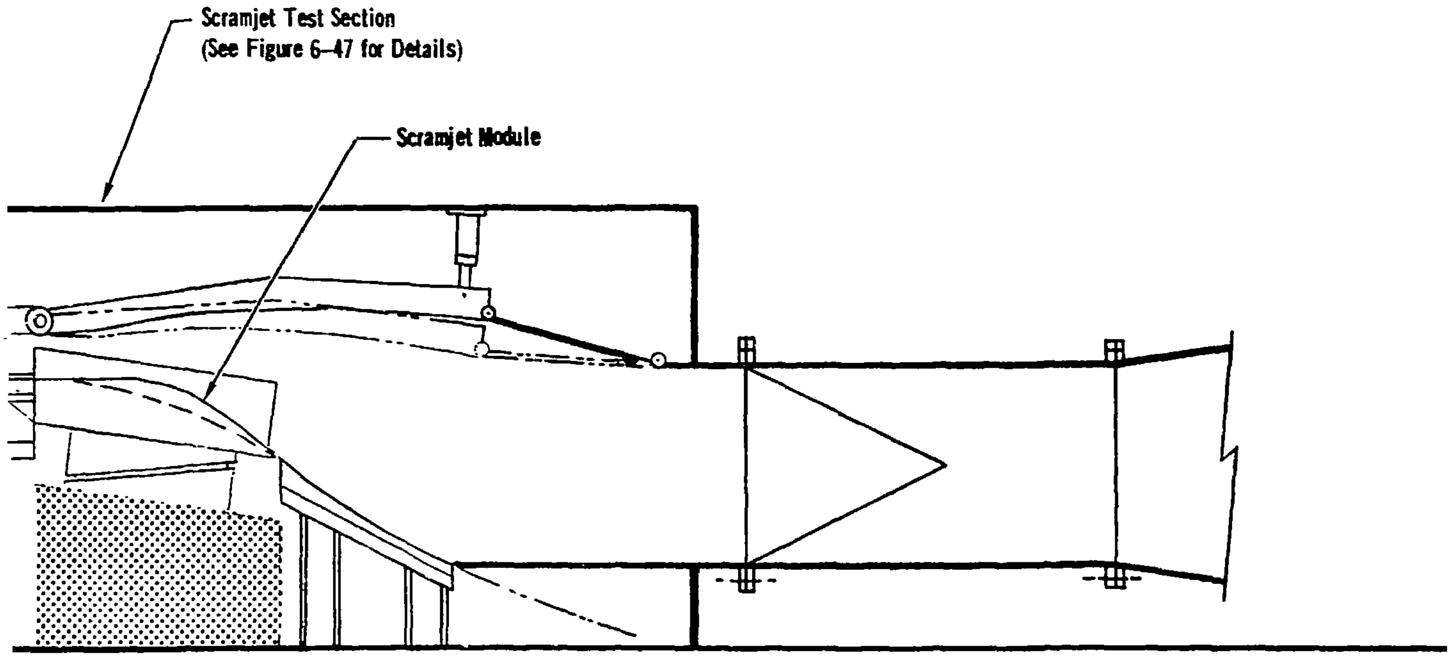
FOLDOUT FRAME 2

ENGINE TEST FACILITY
AREA MODULE



the engine test module and the nozzle test cabin, and lateral tracks are provided for moving the various components to set-up and storage areas.

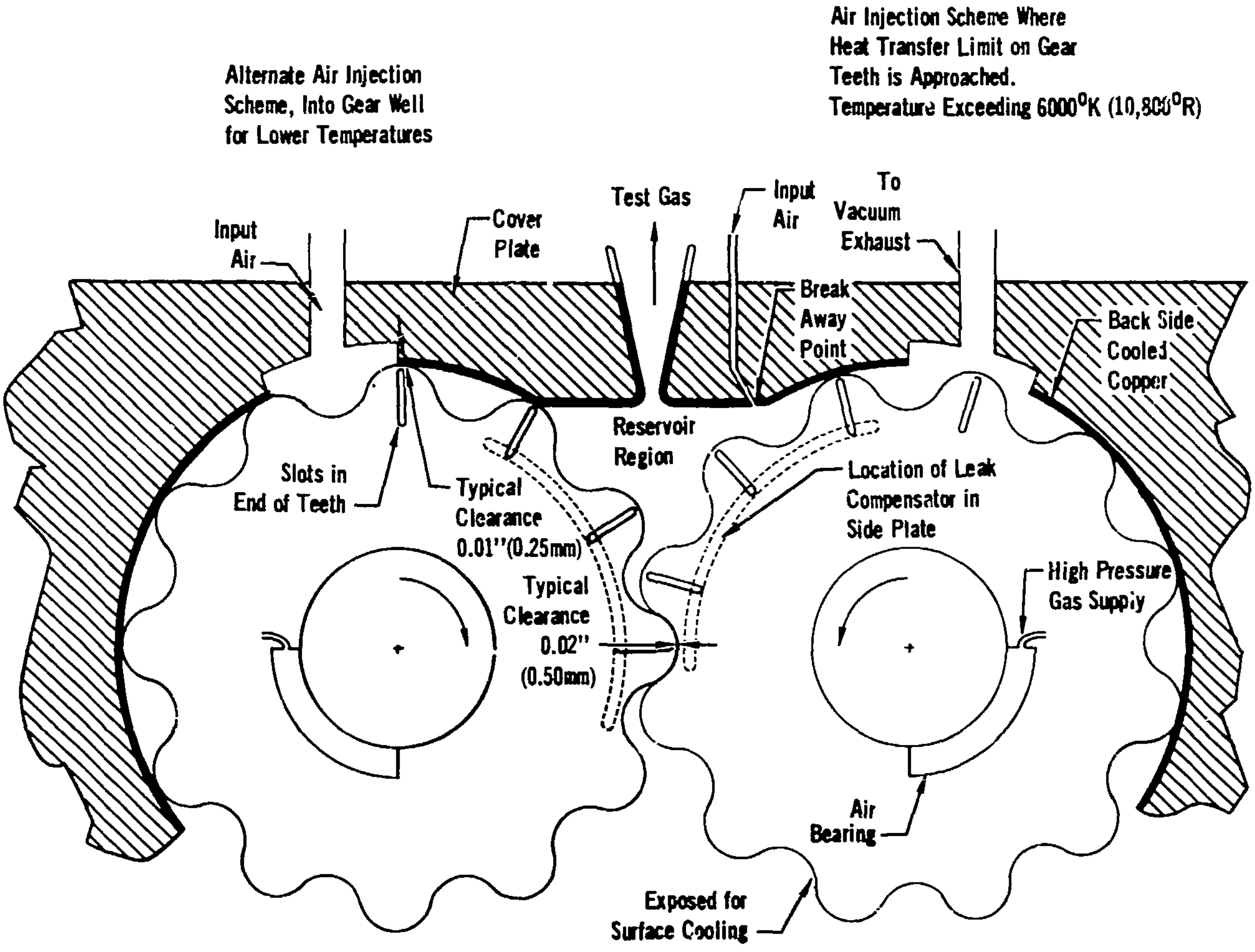
Details of the scramjet engine test section module are shown in Figures 6-47 and 6-48. A description of the philosophy of modified direct connect testing of scramjet and convertible scramjet engines along with descriptions of the unique mechanical details of the test section module are found in Section 6.3.2.

The dimensions of the aerodynamic nozzles which are used for thermo/structural testing are shown in Figure 6-49a. Estimates of the potential flow diameters are also shown in this figure. A description of the use of these nozzles for thermodynamic/structural testing is given in Section 6.3.4.

The multirecompression heater (MRCH), which is the high enthalpy air source, is the critical component of this facility, and represents a new concept in high enthalpy heaters.. The concept was developed by Roger Weatherston of the Cornell Aeronautical Laboratory, Buffalo, New York.

The MRCH is a mechanical device which converts shaft power directly into thermal energy. Heating is produced by rapid and cyclic successive adiabatic expansions and recompressions. This is accomplished by a device which is generically related to a gear pump but which differs in its basic principle of operation. The rotors of the MRCH are driven at high pitch line speeds to produce the thermodynamic heating action. The details of the heating process and derivation of the governing equations are given in Reference 16. Figure 6-66 shows the geometry of the heater and indicates two methods of input air injection to the heater. On the left side of the figure, the air is shown entering into a gear well. This method is used when the reservoir temperature is not high enough to require direct cooling of the gear teeth by the cool input air. Using this method, the required pressure of the incoming air is less than the reservoir stagnation pressure and the air compressor horsepower requirements are reduced. When stagnation temperatures are attained which require gear tooth cooling by the input air, the injection method shown on the right side of the figure is used. This method needs a higher air compressor horsepower because the input pressure needed is equal to the full reservoir stagnation pressure. The design used for E8 assumes the first method, gear well air injection, as stagnation temperatures are less than 6000°K. At temperatures greater than 6000°K, the gear tooth injection scheme would be necessary. The multirecompression heater is still a theoretical design, however there is physical evidence that in principle it will function as conceived. A Roots type blower with the inlet sealed corresponds to the concept of the MRCH, and in this configuration the output temperature of the gas will increase rapidly. The temperature of a sealed-inlet Roots blower can rise high enough to damage the machine if this situation is not quickly remedied. Mr. Weatherston has experimented with Roots blowers having sealed inlets and states that he was able to experimentally verify the equations in Reference 16, which predict the performance of the MRCH. Although very low power levels were used compared to those required for E8, at least some data exists verifying the principle of operation.

FIGURE 6-66
MULTIRECOMPRESSION HEATER CONCEPT, WITH SIDE PLATE REMOVED



The flight path chosen is represented in Figure 6-45c by the entire shaded area, and the maximum values correspond to:

$M_\infty \leq 1.2$	Z = sea level
$1.2 < M_\infty \leq 4$	q_∞ = 2000 psf (9.7 N/cm^2)
$4 < M_\infty \leq 6$	duct pressure < 150 psia (103 N/cm^2)
$6 < M_\infty \leq 8.5$	Z = 94,000 ft (28.7 km)
$1.5 < M_\infty$ 13	Materials temperature limits on vehicle compression side, based on upper surface temperature near $\alpha = 0°$

Determination of the dimensions and power requirements of the MRCH start with definition of the maximum mass flow and temperature requirements at each flight simulated Mach number.

ENGLISH UNITS

M_∞	Ho Btu/lbm	$\dot{w}_{ENG}$ lbm/sec	$\dot{w}_{NOZ}$ lbm/sec	$\dot{w}_{MRCH}$ lbm/sec	INPUT POWER kW	Po psia
3	263	200	340	343	49,000	84
4	430	180	306	311	93,400	191
5	590	140	238	254	118,000	280
6	845	110	187	206	153,000	353
7	1100	180	306	355	353,000	900
8	1330	208	354	453	552,000	1915
9	1640	175	298	328	511,000	4110
9.7	1800	135	239	265	440,000	7000
10	1830	122	208	236	422,000	8700
11	2150	102	174	205	438,000	12,000
12	2650	100	170	221	554,000	17,300
12.5	2850	103	175	238	684,000	22,000

S.I. UNITS

M_∞	Ho J/kg (x 10^6)	$\dot{w}_{ENG}$ kg/sec	$\dot{w}_{NOZ}$ kg/sec	$\dot{w}_{MRCH}$ kg/sec	INPUT POWER kW	Po N/cm^2
3	.633	91	154	156	49,000	58
4	1.00	81.6	139	141	93,400	132
5	1.37	63.5	108	115	118,000	193
6	1.96	49.9	85	94	153,000	243
7	2.55	81.6	139	161	353,000	620
8	3.08	94.5	161	205	552,000	1320
9	3.80	79.5	135	149	511,000	2830
9.7	4.17	61.3	108	120	440,000	4830
10	4.25	55.3	94	107	422,000	6000
11	4.98	46.3	79	93	438,000	8275
12	6.15	45.4	77	100	584,000	11,930
12.5	6.61	46.7	80	107	684,000	15,180

In this table, $\dot{w}_{ENG}$ is the mass flow required by the engine module, $\dot{w}_{NOZ}$ is the mass flow which goes through the engine and around three sides of the scramjet module, and $\dot{w}_{MRCH}$ is the total nozzle flow plus a heater leakage flow. The leakage flow is determined by minimum clearances possible between the rotor lobes, as determined by possible production tolerances and allowances for thermal expansion.

The actual maximum mass flow trajectory possible in a continuous facility is limited by the nozzle throat cooling. A parameter used by AEDC to reflect the maximum flow conditions which can be continuously run in water cooled nozzles is:

$$\sqrt{Po}\ Ho = 39,000$$

where Po is the stagnation pressure in atmospheres, and Ho is the stagnation enthalpy in Btu/lbm. This limitation is based on nozzle cooling data from AEDC and other facilities using high pressure air electric arc heaters as enthalpy sources. A graphic illustration of the throat cooling limit is shown in terms of stagnation pressure and temperature in Figure 6-67. Using this limitation restricts the mass flow at Mach numbers above 9.7 so that the line of maximum power is redefined as follows:

M	Ho Btu/lb	 (J/kg) (x 10^6)	$\dot{w}_{MRCH}$ lb/sec	 (kg/sec)	INPUT POWER kW	Po psia	 (N/cm^2)
3	273	(.633)	343	(156)	49,000	84	(58)
4	430	(1.000)	311	(141)	93,400	191	(132)
5	590	(1.37)	254	(115)	118,000	280	(193)
6	845	(1.95)	206	(94)	153,000	353	(243)
7	1100	(2.55)	355	(161)	353,000	900	(620)
8	1330	(3.08)	453	(206)	552,000	1915	(1320)
9	1640	(3.80)	328	(149)	511,000	4110	(2830)
9.7	1800	(4.17)	265	(120)	440,000	7000	(4830)
10	1850	(4.20)	188	(85)	325,000	6480	(4470)
11	2400	(5.57)	88	(40)	206,000	4660	(3215)
12	3200	(7.42)	44	(20)	142,000	3200	(2205)
12.5	3800	(8.82)	42	(19)	161,000	2800	(1930)

The conditions tabulated above were then used with the relationships developed in Reference 16, which relate the required power, increase in enthalpy, and pressure ratio to the geometric parameters of the MRCH.

The primary equation used in determining the operating speeds and geometry of the MRCH is:

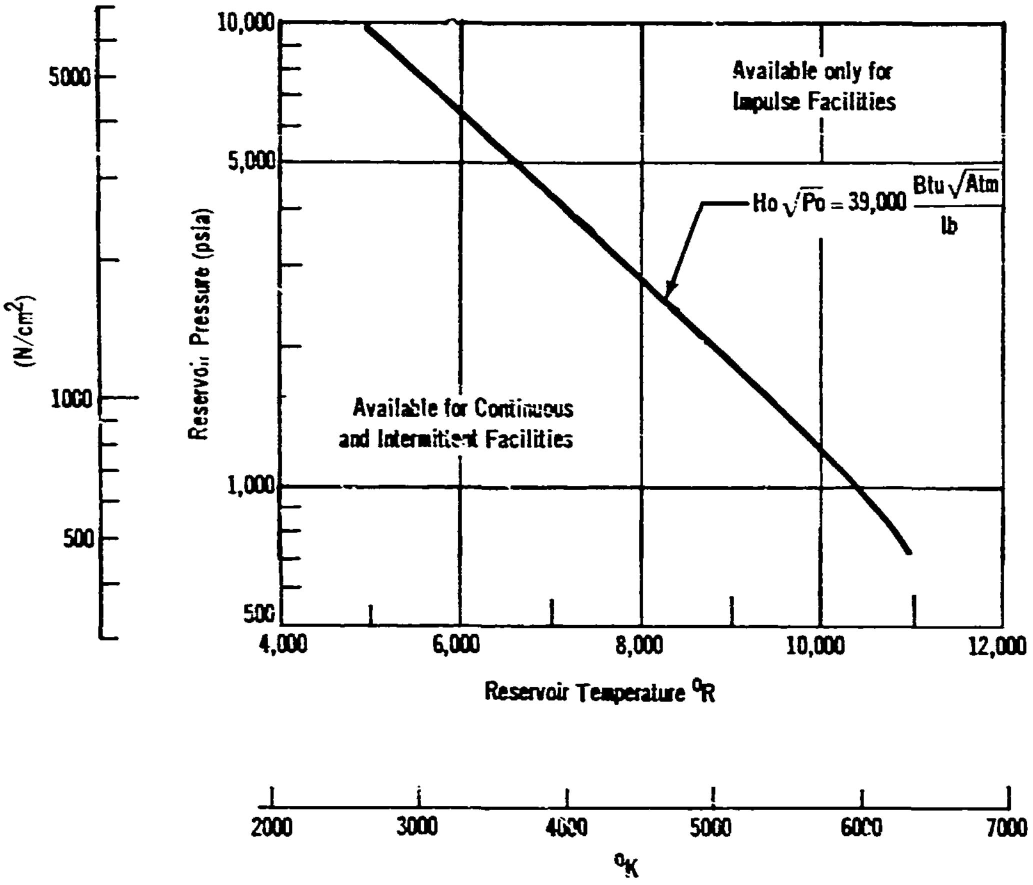
$$L = \frac{6480}{nD^2} \left[\frac{\Delta H \dot{w}}{P_R} \right] \qquad \text{(ft/sec)} \qquad 6.3\text{-}5$$

Where L = Pitch Line Velocity of Rotor Lobes (ft/sec)
D = Rotor Diameter (in)
n = Ratio of Rotor Length to its Diameter
ΔH = Increment of Enthalpy Added by Heater (Btu/lbm)
$\dot{w}$ = Heater Mass Flow (lbm/sec)
Pr = Compression ratio of Heater

Thus, for a fixed rotor geometry, (n, D), the range of pitch line velocities throughout the operating range of the facility is proportional to the factor $\Delta H\dot{w}/Pr$. This factor ranges from 556 at M = 3 to 42 at M = 12, a range of 13 to 1. For a single MRCH design, this produces a range of pitch line velocities (and rpm) of 13 to 1. A complicating factor arises because the minimum power required occurs at the highest L (and rpm), resulting in a very low torque requirement, while maximum power required occurs at a much lower rpm, such that required torque is very high.

Analysis of the power and torque requirements indicated that a single MRCH design for such a range of input power and pitch line velocities is not practical because of the contradictory torque/rpm characteristics, and because of the rpm range over which the power source must be continuously variable.

FIGURE 6–67
FACILITY RESERVOIR CONDITIONS CORRESPONDING TO THE BACKSIDE WATER COOLED THROAT HEATING LIMIT



A double MRCH design has been specified which minimizes these problems, although introducing an additional problem associated with shutting down one pair of rotors while the other pair continues to operate, as required above Mach number 8.5. The basic design consists of two sets of rotors, a large diameter (45.9 in.) (117 cm) low enthalpy range set and a small diameter (30.1 in.) (76 cm) high enthalpy range set. Both sets were sized using the guidelines obtained from the Philadelphia Gear Company for pitchline velocity:

L_{max} = 800 ft/sec (245 m/sec) intermittent operation
L_{max} = 600 ft/sec (183 m/sec) continuous operation
L_{min} = 200 ft/sec (61 m/sec)

The limitation of L_{min} = 200 at M = 12 established the size of the small diameter rotor set. The method of operation proposed is that both sets of rotors are used from M = 3 to 8.5, and that the small set takes over completely at that point. The large rotor set diameter was sized so that L = 800 at M = 3.

Figure 6-68 summarizes the operating characteristics of the double rotor set MRCH for the maximum mass flow trajectory.

FIGURE 6–68a MRCH OPERATING CHARACTERISTICS – ENGLISH UNITS

SMALL MACHINE							LARGE MACHINE				
M	$\frac{\dot{w}\Delta H}{Pr}$ $\frac{Btu}{sec}$	L $\frac{ft}{sec}$	$\dot{w}$ $\frac{lb}{sec}$	Power kW	Torque ft-lb	rpm	L $\frac{ft}{sec}$	$\dot{w}$ $\frac{lb}{sec}$	Power kW	Torque ft-lb	rpm
3	556	800	106	15.1	17,480	6090	800	237	33.9	59,800	4000
3.5	515	742	101	21.2	26,450	5650	742	225	47.3	90,000	3700
4	462	664	96	27	37,600	5060	664	215	66.4	141,500	3310
4.5	441	636	92	35.6	51,900	4830	636	207	79.4	176,700	3170
5	400	576	78	36.5	58,700	4380	576	176	71.5	175,800	2870
5.5	434	625	68	45	66,600	4760	625	152	101	228,500	3115
6	410	590	62	47	73,700	4490	590	204	106	254,000	2940
6.5	480	690	87	76.5	102,800	5250	690	203	186	381,000	3440
7	373	600	120	119	183,[illegible]	4570	505	235	234	655,000	2520
7.5	336	600	157	126	1[illegible],[illegible]00	4570	449	275	334	1,052,000	2240
8	273	600	208	253	39[illegible],[illegible]	4570	406	245	299	1,033,000	2040
8.5	189	600	300	406	627,000	4570	132	156	213	2,380,000	658
9	118	565	328	511	838,000	4300					
9.7	59.9	286	265	440	1,427,000	2175					
10	47.5	227	188	325	1,327,000	1728					
10.5	48.9	234	133	273	1,080,000	1780					
11	44.0	210	88	206	908,000	1600					
11.5	47.1	226	65	177	726,000	1720					
12	42.0	200	44	142	659,000	1520					
12.5	54.6	202	42	161	570,000	1990					

The dual rotor set MRCH concept is shown connected to the scramjet engine test module in Figure 6-65. The helical timing gears which are shown are necessary to ensure that the lobes of each rotor set do not contact each other. The timing gears do not carry full torque, but their design must accommodate the torque due to driver shaft rotational speed mismatch. Whatever type of prime mover is chosen for the MRCH must be provided with a servo control system which will maintain both shafts of each rotor set to very small tolerances of rotational speed and torque.

A very large amount of mechanical shaft power must be provided for each of the two rotor sets. As was discussed in Section 6.3.5, electric motors have a much lower power density in terms of power per square foot of floor area, compared to gas turbines. The use of both electric motors and gas turbines as power sources for the MRCH is shown in Figure 6-69. The top half of the figure shows a possible arrangement using a total of 10 gas turbine engines driving the MRCH through expansion turbines. The equivalent arrangement using synchronous electric motors is shown in the lower half of the figure. A total of 12 synchronous motors, each rated at 48,000 kW, is required. In order to arrange a suitable physical layout, an off-axis grouping is used, which requires 8 sets of 70,000 hp (52,000 kW) class right helical gears. These gears are nearly three times the capacity of the largest

FIGURE 6-68b MRCH OPERATING CHARACTERISTICS – S.I. UNITS

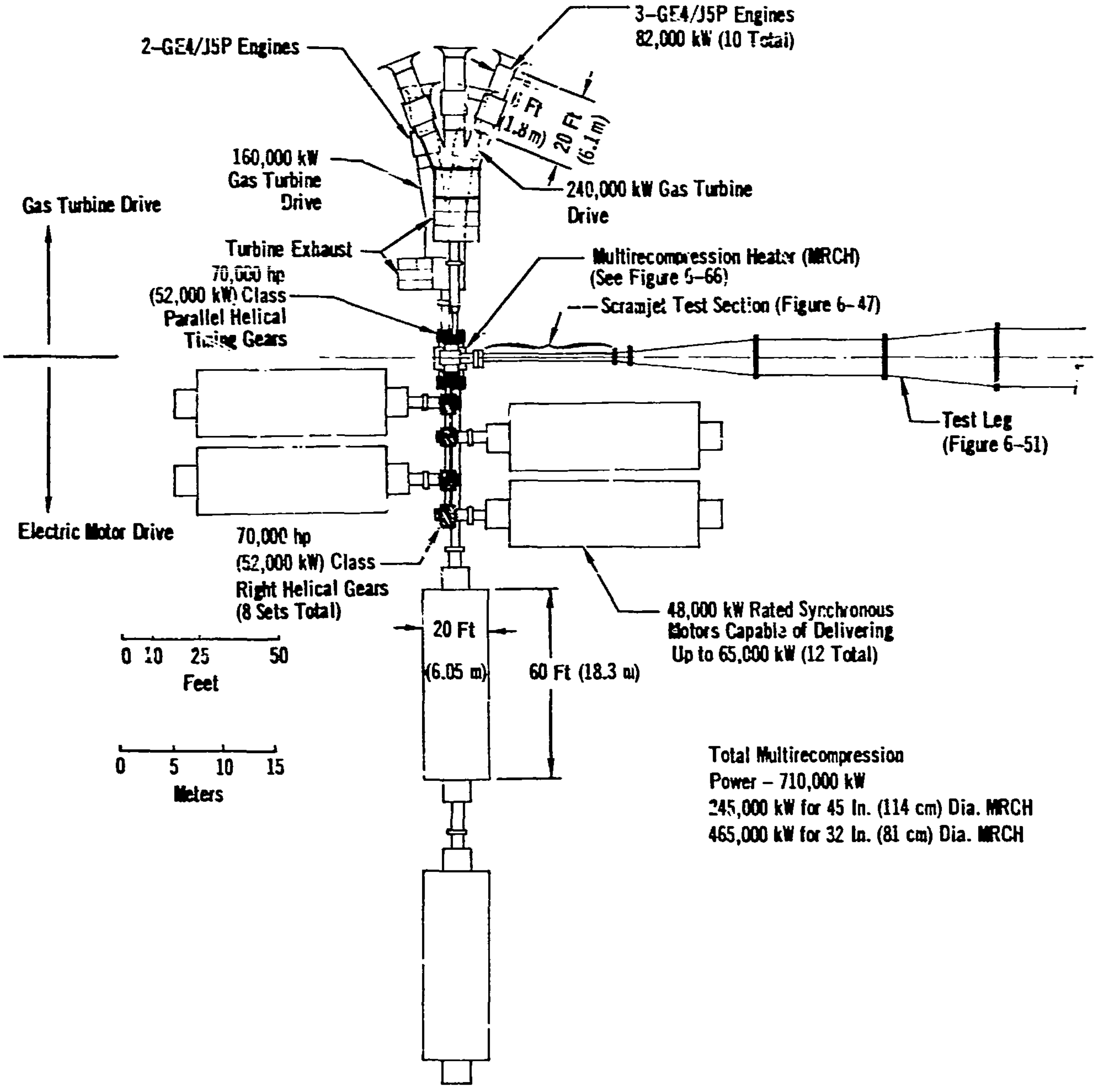
	SMALL MACHINE						LARGE MACHINE				
M	$\frac{\dot{w}\Delta H}{Pr}$ J/sec x 10^6	L $\frac{m}{sec}$	$\dot{w}$ $\frac{kg}{sec}$	Power kW	Torque m-N	rpm	L $\frac{m}{sec}$	$\dot{w}$ $\frac{kg}{sec}$	Power kW	Torque m-N	rpm
3	.586	244	48.1	15.1	23,680	6090	244	107	33.9	81,000	4000
3.5	.543	226	45.8	21.2	35,860	5650	226	104	47.3	122,000	3700
4	.487	202	43.6	27	51,000	5060	202	97.5	66.4	192,000	3310
4.5	.465	194	41.8	35.6	70,400	4830	194	94.0	79.4	239,500	3170
5	.422	175	35.4	36.5	79,500	4380	175	80.0	71.5	238,500	2870
5.5	.458	191	30.8	45	90,300	4760	191	69.0	101	310,000	3115
6	.432	180	28.2	47	100,000	4490	180	92.5	106	344,000	2940
6.5	.506	210	39.5	76.5	139,500	5250	210	92.1	186	517,000	3410
7	.393	183	54.5	119	249,000	4570	154	106.7	234	888,000	2520
7.5	.354	183	71.3	126	264,000	4570	137	124.8	334	1,427,000	2240
8	.288	183	94.5	253	530,000	4570	124	111.2	299	1,400,000	2040
8.5	.199	183	136.0	406	850,000	4570	40	70.8	213	3,230,000	658
9	.124	172	149	511	1,137,000	4300					
9.7	.063	87	120	440	1,935,000	2175					
10	.050	69	85.4	325	1,800,000	1728					
10.5	.052	71	60.3	273	1,465,000	1780					
11	.046	64	40.0	206	1,230,000	1600					
11.5	.049	69	29.5	177	985,000	1720					
12	.044	61	20.0	142	907,000	1520					
12.5	.057	62	19.0	161	773,000	1990					

such gears currently manufactured (reference Section 6.3.5), and represent a serious technical limitation at this time. Philadelphia Gear Company would not attempt to estimate projected costs for these gears, so the costs estimated here (grouped in the electric motor drive system costs) were extrapolated from current prices on the basis of power transmission capability.

The magnitude of the total required installed power of this facility as it is specified is so large that there was no value in determining the effect on cost of increasing the test section size. A study of this nature is presented for the Hybrid Heater Scramjet Test Facility (E9). Future studies regarding the use of the MRCH concept should concentrate on refining the concept to minimize the required power or on using the MRCH to augment other heater types which themselves are less expensive but generally do not produce pure air as the test medium, as does the MRCH.

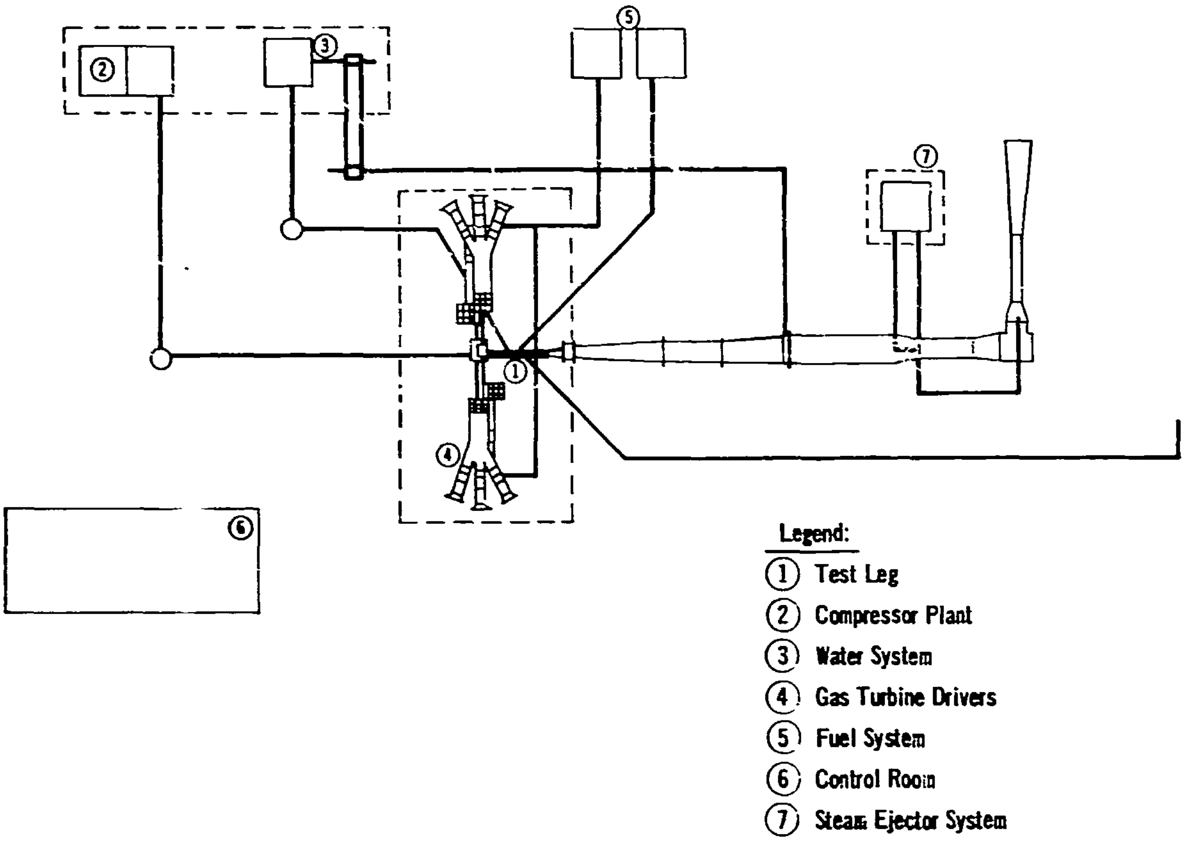
The baseline facility concept for E8 has been chosen as the MRCH, powered by gas turbine drivers, and sized for a 15 ft^2 (1.39 m^2) scramjet engine test module capture area. For cost comparison, the alternate concept is identical to the baseline, with the exception that power for the MRCH is provided by synchronous electric motors. The baseline concept is illustrated in Figure 6-70, and the alternate concept as shown in Figure 6-71, both of which show a simplified schematic drawing of the entire facility with auxiliary systems.

FIGURE 6-69
ALTERNATIVE DRIVE ARRANGEMENTS FOR SCRAMJET TEST FACILITY E8, BASELINE, 15 SQ FT (1.39 m^2) CAPTURE AREA



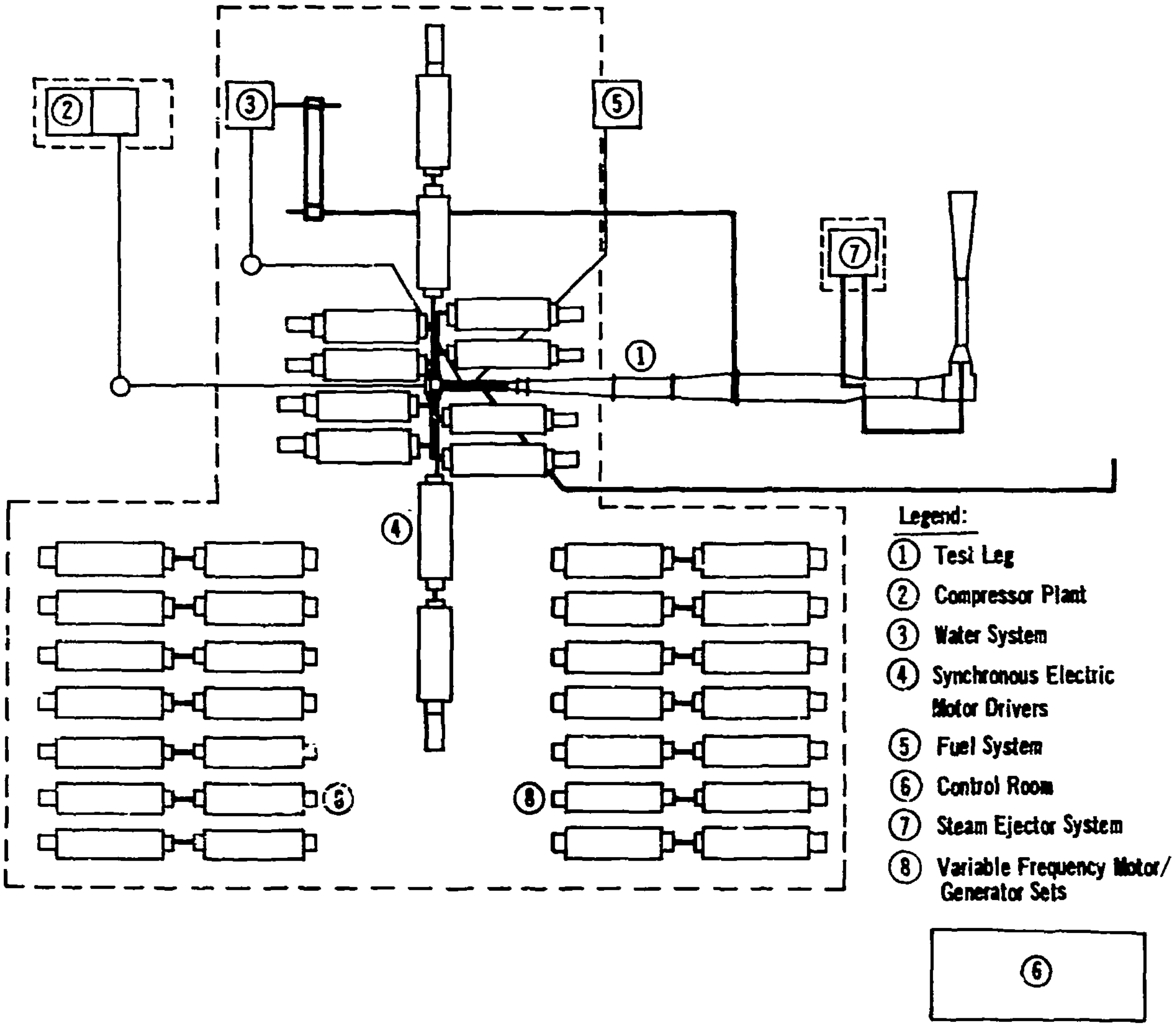
Note: Not shown are a 72,000 kW variable frequency generator, and wound rotor motor, motor generator set for each 65,000 kW synchronous motor.

FIGURE 6-70
SCHEMATIC LAYOUT OF E8 SCRAMJET ENGINE TEST BASELINE FACILITY
(Multicompression Heater Driven by Gas Turbines)



6.3.8.1 Specifications - The following table presents the mechanical specifications of the [illegible] compression heater scramjet test facility. Heater operating conditions [illegible] in the previous section for the maximum mass flow limit line. The f[illegible] operate to the minimum mass flow line indicated in Figure 6-[illegible] are the same for both the baseline definition, powered by g[illegible] the alternate, which is powered by synchronous electric m[illegible]

FIGURE 6-71
SCHEMATIC LAYOUT OF E8 SCRAMJET ENGINE TEST ALTERNATE FACILITY
(Multirecompression Heater Powered by Electric Motors)



- Engine Test Leg Description

SJ/CSJ Engine Capture Area	15 ft^2 (1.39 m^2)
Nozzle Geometric Area	3.45 ft^2 (.32 m^2)
Module Cowl Area	2.65 ft^2 (.246 m^2)
Flight Mach Number Range	3 to 12.5
Altitude Range	45 to 160 kft (13.7 to 49 km)
Stagnation Pressure Range	10 to 7000 psia (6.8 to 4830 N/cm^2)
Stagnation Temperature Range	110 to 9500°R (610 to 5300°K)
Mass Flow Limit (Nozzle)	354 lbm/sec (160 kg/sec)
Run Time	Continuous

- Thermo/Structural Test Leg Description

Flow Parameters	Same as Above

Aerodynamic Nozzles

Design Mach Number	Length ft (m)	Diameter ft (m)	Constant Velocity Core ft (m)
6	21.7 (6.6)	4.8 (1.46)	3.68 (1.12)
9	41.7 (12.7)	8.9 (2.71)	6.08 (1.85)
10	54.1 (16.5)	10.83 (3.3)	7.30 (2.21)
12	63.3 (19.3)	15.32 (4.67)	7.41 (2.26)

- Air Compressor Description

Maximum Inlet Volumetric Flow	358,000 scfm (10,130 m^3/min)
Maximum Pressure:	275 psi (190 N/cm^2)

NOTE: Only moderate pressures are provided by the air compressor, since with gear well air inlet, the MRCH does most of the compression.

6.3.8.2 Facility Component and Cost Summary - Figure 6-72 shows a compilation of the costs estimated for each of the facility components. Estimates were made by the methods discussed in Section 6.1.

The tabulated cost estimates show that the alternate facility would cost approximately 50% more than the baseline facility for acquisition, and would cost twice as much as the baseline facility to operate. The only difference between

FIGURE 6-72a
E8 FACILITY COMPONENT AND COST SUMMARY

	FACILITY COMPONENT	COST ESTIMATE $1000's	
		Baseline	Alternate
1.	Test Leg Sub Total	21,294	16,000
1.1	Multi Recompression Heater Assembly (casing; high enthalpy rotors, timing gears, shafting & couplings; low enthalpy rotors, timing gears, shafting & couplings)	16,000	16,000
1.2	Engine Module Test Section Assy. (Pressure enclosure, heater attachment fixture, water cooled throat block, nozzle hinge arm, flexible plate and side plates, adjustment jack & fixed block hot wall structure, fixed contour adjustable nozzle plate, thrust stand & balance, replaceable engine expansion nozzle, hinged diffuser entrance ramp, transition section).	3,000	3,000
1.3	Aerodynamic Nozzle Adaptation (water cooled throat assemblies (4), water cooled nozzles (4), test cabin assembly, diffuser throat sections and adapters.)	1,170	1,170
1.4	Test Module Bed & Transfer Tracks	178	178
1.5	Facility Enclosure	946	9,460
2.	Compressor Plant Sub Total	35,729	54,729
2.1	Mechanical Components (compressors, intercoolers, oil filters, air dryers, motors, controls, distribution piping).	32,145	32,145
2.2	Electric Substation (for compressor motors and, for the alternate, for MRCH drive)	3,584	22,584
3.	Water Cooling System (pumps, heat exchanger, piping & valves)	1,000	1,000
4a.	Gas Turbine Drive System (baseline facility) (GE4/J5P gas turbines (10), 250,000 kW power turbines (2), 160,000 kW power turbines (2) turbine intake & exhaust towers)	80,000	—
4b.	Electric Motor Drive System (alternate facility) (65,000 kW synchronous motors (12), 2500 kW wound rotor starting motors (8), 5000 kW wound rotor starting motors (2), MG sets (12)	—	126,000

FIGURE 6-72a (Continued)
E8 FACILITY COMPONENT AND COST SUMMARY

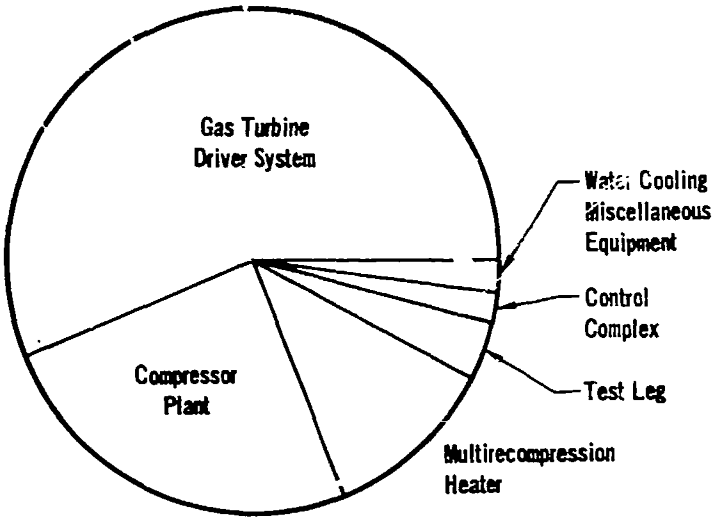
5. Fuel System - LH_2 distribution & control	71	71
6. Control Complex Sub Total	2,900	2,900
6.1 Lab/Office/Control Building	1,400	1,400
6.2 Automatic Facility Control System	400	400
6.3 Instrumentation & Data Acquisition System (transducers, amplifiers, power supply, analog/digital connecter, tape recorders, closed circuit TV)	1,100	1,100
7. Steam Ejector	1,165	1,165
Total	142,159	208,159
Contingency @ 10%	14,216	20,816
Facility Cost	156,375	228,975
A & E Fee @ 6%	9,380	13,738
Mgt. & Coord. Fee @	6,250	9,159
Grand Total	172,005	251,872

these versions is the method of driving the multirecompression heater. It may be seen that the power cost is the largest of the operating costs, and from the baseline system "pie" chart, is the largest facility acquisition cost. Clearly, within the limitations of the simple cost estimating procedures used in Phase II, the gas turbine drive is by far the most economical and would be preferred.

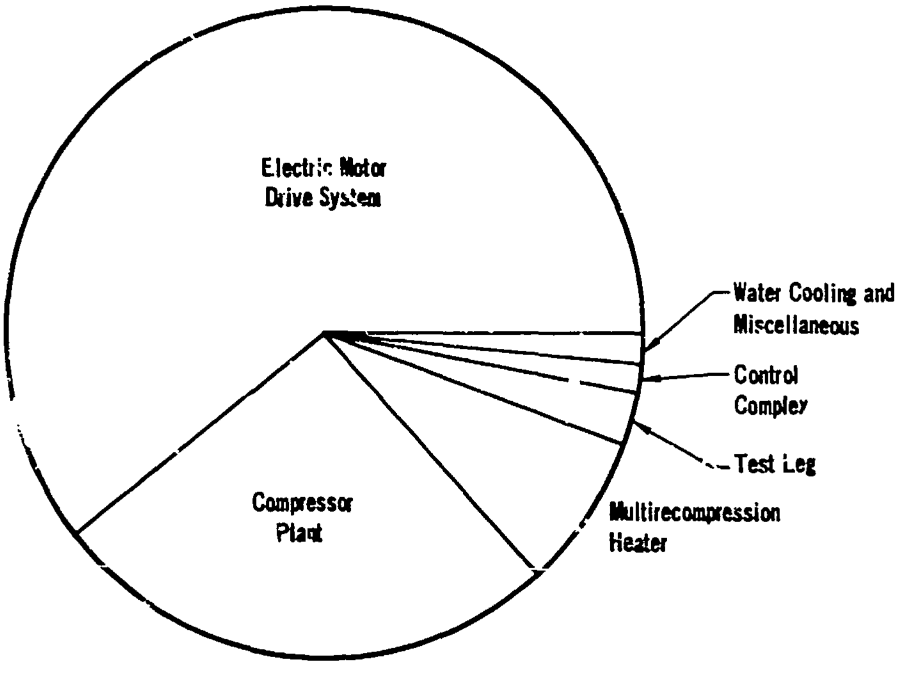
The "pie" chart shows again the characteristic of high pressure and high temperature continuous facilities that the equipment needed to provide the flow is much more costly than the actual test leg, and indicates that to improve the quality of the cost estimates the main effort must be to refine in detail the facility flow and pressure requirements, and translate these into very complete auxiliary equipment specifications.

6.3.8.3 Development Assessment - The components of the test leg, that is, the aerodynamic nozzles, test cabin, and diffuser components, are basically of conventional size and design and have the highest confidence level of 5. The scramjet test section does incorporate a combination of aerodynamic devices such as the single jack flexible nozzle, the uncooled refractory metal nozzle wall, and the fixed contour nozzle for tailoring of engine exhaust conditions, which have never been used in this combination to date and therefore has been given a confidence level of 2.

FIGURE 6–72b
DISTRIBUTION OF FACILITY COMPONENT COSTS – E8



Baseline



Alternate

FIGURE 6-72c
E8 OPERATING COST SUMMARY

Operating Costs – Dollars/Occupancy Hour	Baseline	Alternate
Repair and Maintenance	2,052	5,341
Staffing	1,000	1,000
Power	3,260	6,600
Total	6,312	12,941

scramjet module which is installed in the test section will be identical in configuration, materials, and construction to the engine which it represents, and will have the same design and development problems as the engine. These problems will probably be associated with materials and the cryogenic regenerative cooling system. If actual engine structures are not being evaluated, performance data can be obtained using water cooled copper boiler-plate engine modules would have a higher confidence level.

The multirecompression heater has many development problems which will have to be solved before the concept can be considered operational. At this time, the concept is purely analytical, the only experimental data available having been done on a very small scale and at low enthalpy and pressure, its confidence level is very low, approximately 1 on the scale defined in Section 6.2.8.3. A three phase development program is needed to make the MRCH concept operational:

Phase I - Theory verification on a 1 percent model of the full scale version, intermittently operating, with maximum mass flow of 4 lb/sec (1.8 kg/sec). A flywheel can be used to store energy and reduce the power required to about 600 kW. A single rotor design would be used first to verify the thermodynamic cycle and establish practical efficiencies. At a later stage, a dual rotor MRCH would be used to solve the problems associated with operating two sets of rotors at different speeds and powers and with bringing the larger rotor set to rest while the small, high energy set is running without overheating the stopped rotors.

Phase II - Operational development of a continuous operating, dual rotor MRCH at 10 percent of the full scale size. This machine would have a mass flow of about 40 lb/sec (18 kg/sec) and have a total installed power of 60,000 kW. The prime mover selected for the full scale facility would be used. The main goals of this development phase would be investigation of the dynamic response of the system, development of a precise control system for the dual rotors, and mechanical development of the MRCH components for continuous operation.

Phase III - Operational checkout of the full scale MRCH and integration with the total facility system is performed in this phase. Having successfully developed a 10 percent scale operating model in Phases I and II, the problems encountered in this phase are those associated with installing and integrating any large scale system whose operating principles have been proved, and a confidence level of 4 would be expected.

No serious design effort should be contemplated on any facility concept using an MRCH without having successfully completed a development program similar to that described, for without such confirmation of theory and the solution of practical operating problems, the MRCH concept is, by definition, a confidence level of one device.

Many of the expected problems are related to the basic definition of the facility, with its large range of mass flow and enthalpy conditions dictating the use of a dual rotor. The design of a small diameter, single rotor-set heater for the Mach 9 to 12 range would probably be much easier and might be considered as an interim step in the development of E8. Adaptation of this small heater as an adjunct to the combustion heater of E9 should be considered as a long range addition to that facility's capability.

6.3.9 HYBRID HEATER SCRAMJET ENGINE TEST FACILITY (E9) - This facility is designed to test scramjet engine and convertible scramjet engine modules, on a continuous basis, through the flight Mach number range of 3 to 9 and altitudes from 45 to 145 kft (13.7 to 44.2 km). A modified direct connect test technique is used, testing engine modules equivalent to up to 15 ft^2 (1.39 m^2) capture area. Two versions of this facility are proposed, differing physically only in the type of heater used.

The baseline definition uses a dual mode of operation. A combustion heater which burns carbon monoxide, air, and oxygen is the steady state heater, and provides vitiated air to the engine module on a continuous basis. This heater combination is shown in Figure 6-73. The combustion heater is used to run the engine module up to cruise conditions and perform long term PFRT endurance tests on the engine. The other mode of operation is provided by a zirconia storage heater which is used to provide heated air, on a blowdown cycle, to the engine for pure air performance testing. The duration of the air blowdown cycle is up to 60 sec. This dual mode operational concept is critical to the entire test philosophy of the E9 facility, since the combustion heater will be used to duplicate a real-time test trajectory, heating the materials and structure of the engine module identically to the flight case, using vitiated air. This avoids the thermal shock to the scramjet module materials that would occur if a given test point was suddenly established in a blowdown facility. With the engine already running at flight duplicated conditions in vitiated air at a given test point, the heated air blowdown cycle is established with no change in test conditions except for the gas composition. A schematic of the hybrid heater system is shown in Figure 6-74.

The alternate facility definition uses an inductively heated graphite matrix heater, which continuously heats nitrogen. A plenum chamber is used to mix the heated nitrogen with oxygen in order to approximate the chemical composition of air. This heater arrangement is used throughout the entire test, no blowdown capability being provided. A further addition to testing capability could be added by providing nitrous oxide injection to the plenum section for higher temperature vitiated air testing. This should be considered as a far-term facility improvement and will not be discussed further. The graphite heater is shown in Figure 6-75, and a schematic of the facility equipped with the graphite heater is shown in Figure 6-76.

The test leg of this facility is designed on a modular basis, with the heater and a fixed diffuser installed in a fixed location. Engine testing is done by installing the scramjet engine test module and its connecting piping. This arrangement is shown in Figure 6-50. The pressure, temperature, and flow rate produced by the heater can also be used for the thermo/structural testing of full scale aircraft components or sections. This is done by installing one of a set of water-cooled nozzles, a test cabin containing the test specimen, and a diffuser adapter in place of the engine test module. This arrangement is shown in Figure 6-51. Longitudinal tracks are provided for axial translation of the engine test module and the nozzle test cabin, and lateral tracks are provided for moving the various components to set-up and storage areas.

Details of the scramjet engine test section module are shown in Figures 6-47a, 6-47b, and 6-48. A description of the philosophy of modified direct-connect testing of scram and convertible scramjet engines, along with descriptions of the unique

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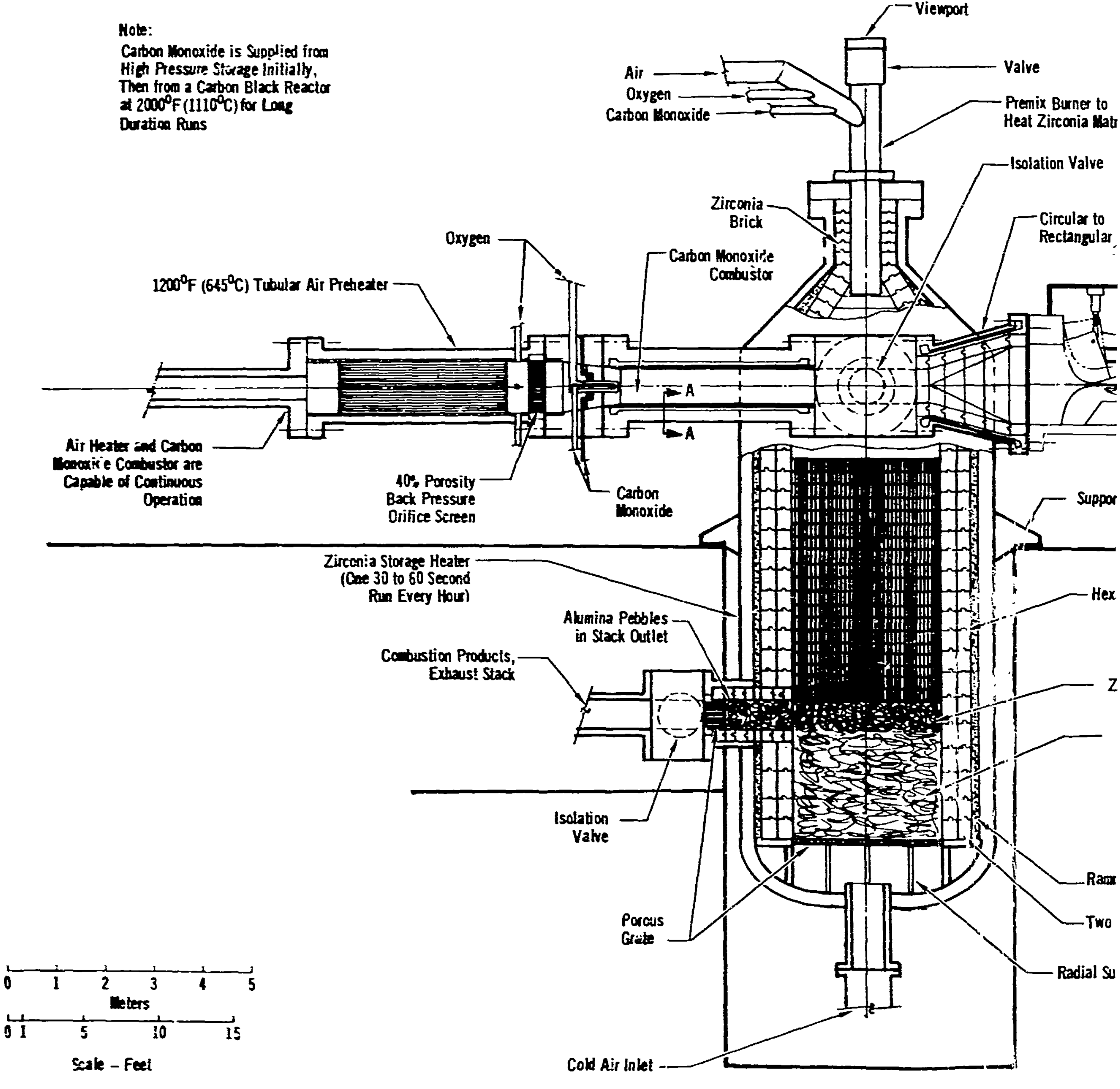
FOLDOUT FRAME 1

FIGURE 6–73
E9, HYBRID COMBUSTION/STORAGE HEATER SCRAMJET ENGINE TEST FACILITY


Note:
Carbon Monoxide is Supplied from High Pressure Storage Initially, Then from a Carbon Black Reactor at 2000°F (1110°C) for Long Duration Runs

FOLDOUT FRAME 2

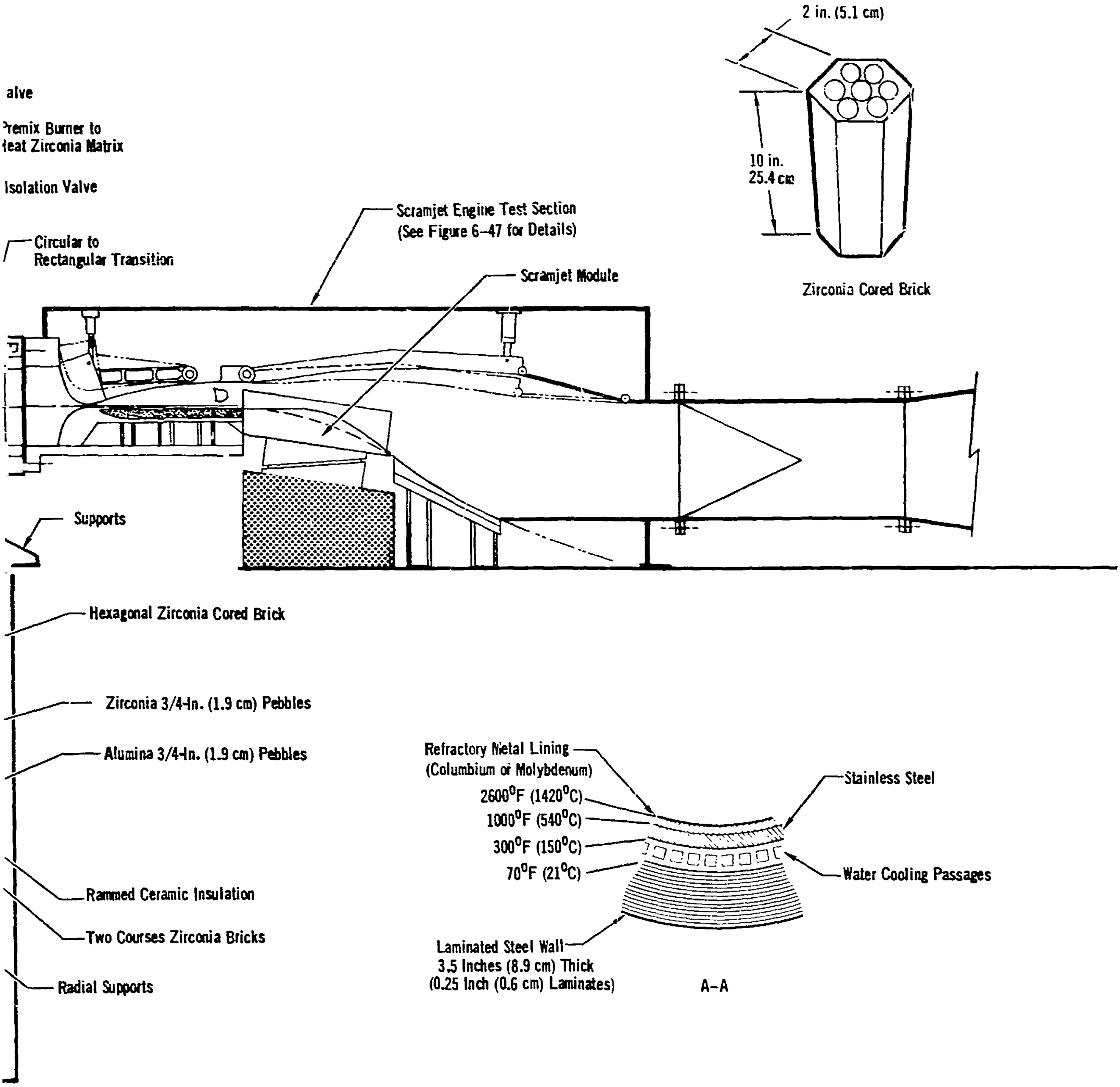
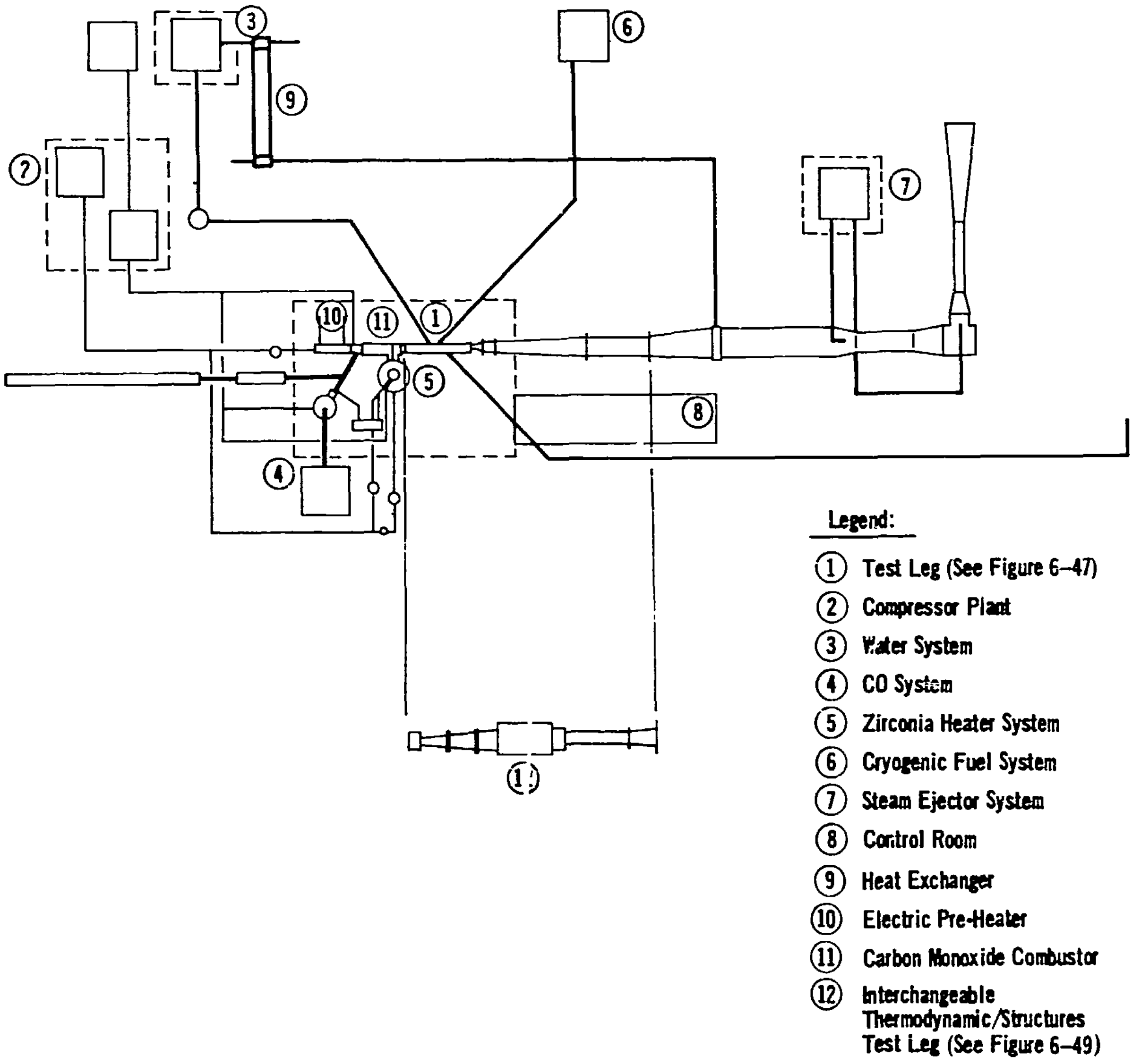


FIGURE 6-74
SCHEMATIC LAYOUT OF E9 SCRAMJET ENGINE TEST BASELINE FACILITY
(Carbon Monoxide Continuous Heater and Zirconia Pebble Bed Heater
For Intermittent Performance Testing)



Legend:

① Test Leg (See Figure 6-47)
② Compressor Plant
③ Water System
④ CO System
⑤ Zirconia Heater System
⑥ Cryogenic Fuel System
⑦ Steam Ejector System
⑧ Control Room
⑨ Heat Exchanger
⑩ Electric Pre-Heater
⑪ Carbon Monoxide Combustor
⑫ Interchangeable Thermodynamic/Structures Test Leg (See Figure 6-49)

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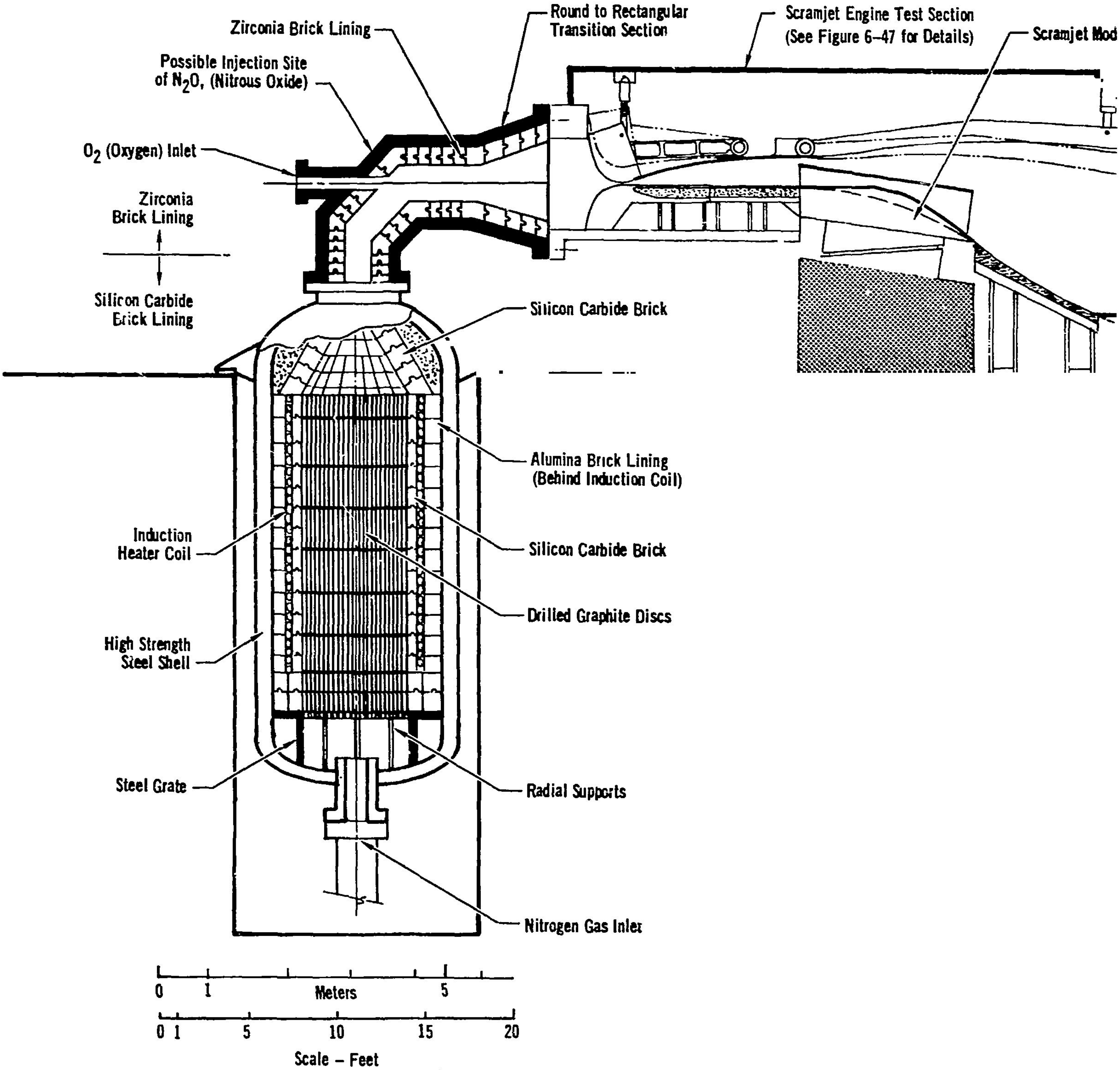
FOLDOUT FRAME 1

FIGURE 6-75
E9 ALTERNATE, INDUCTIVELY HEATED GRAPHITE SCRAMJET ENGINE TEST FACILITY



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FOLDOUT FRAME 2

970

JET ENGINE TEST FACILITY

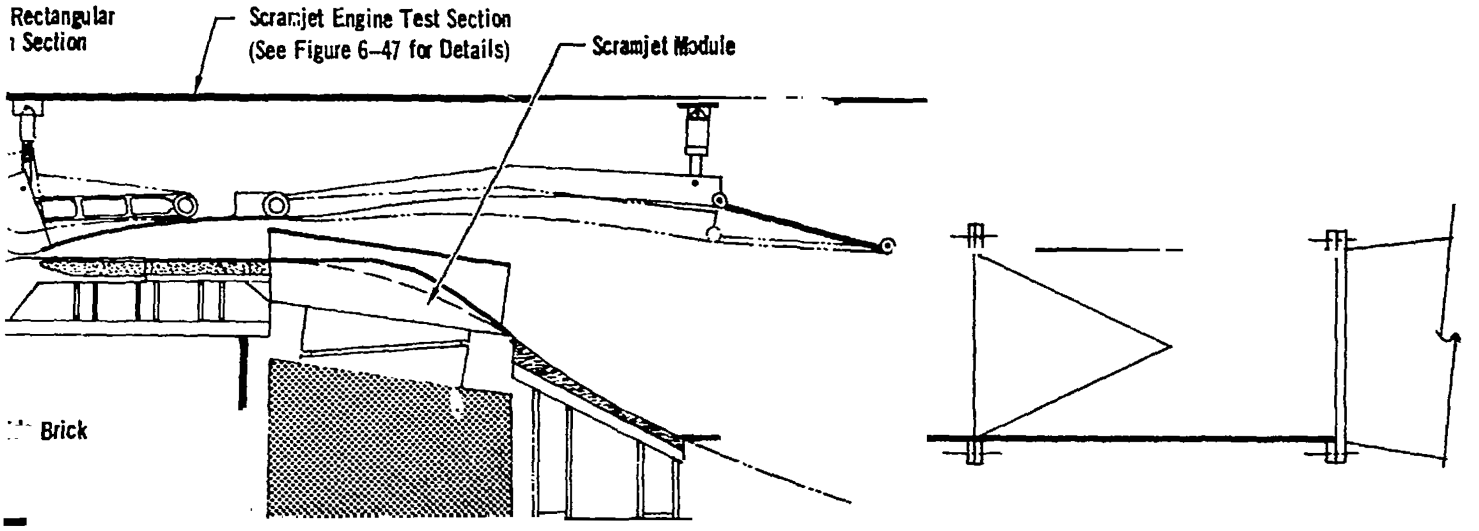
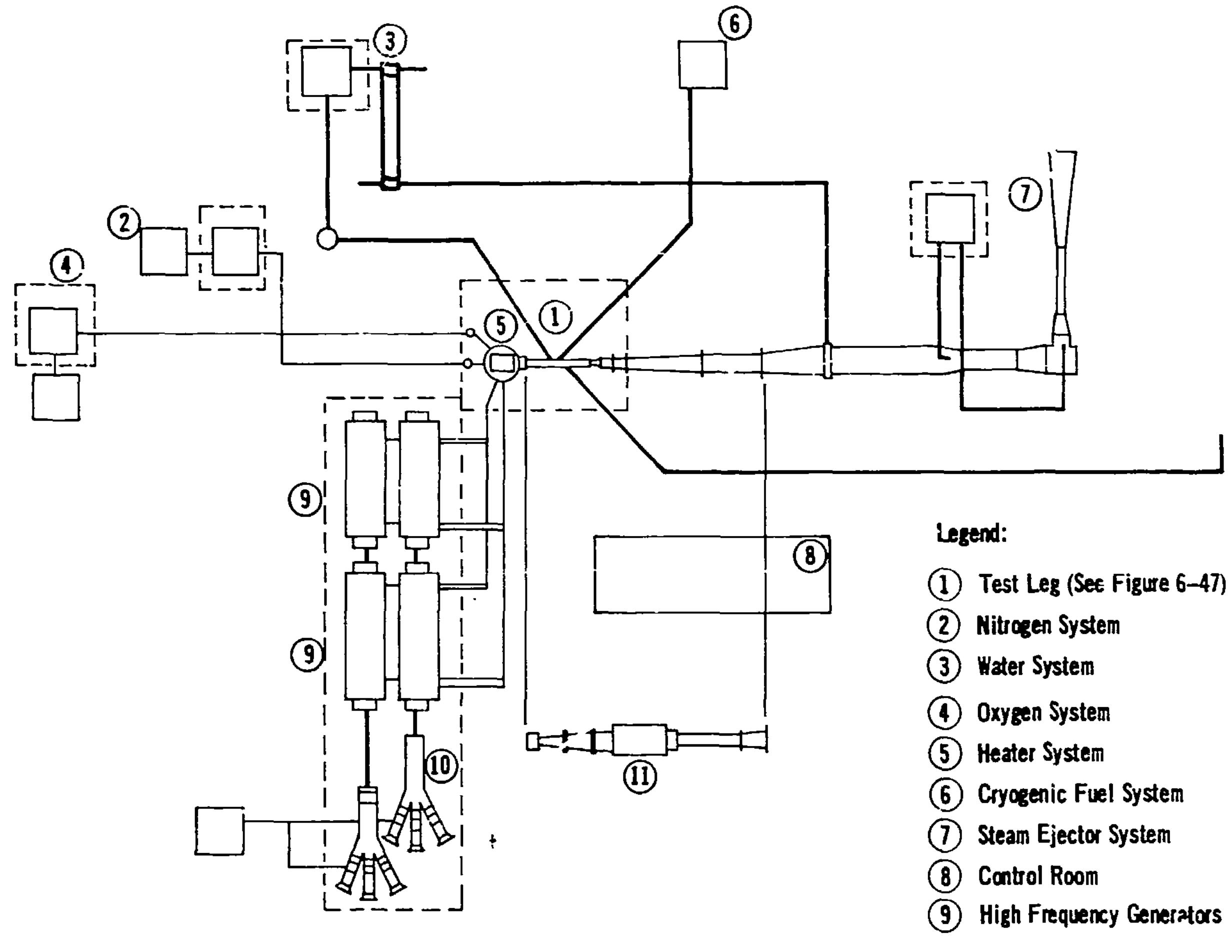


FIGURE 6-76
SCHEMATIC LAYOUT OF E9 SCRAMJET ENGINE TEST ALTERNATE FACILITY
(Graphite Induction Heater)



Legend:

① Test Leg (See Figure 6-47)
② Nitrogen System
③ Water System
④ Oxygen System
⑤ Heater System
⑥ Cryogenic Fuel System
⑦ Steam Ejector System
⑧ Control Room
⑨ High Frequency Generators
⑩ Gas Turbine Drive
⑪ Interchangeable Thermodynamic/ Structures Test Leg (See Figure 6-49)

mechanical details of the test section module are found in Section 6.3.3.

The dimensions of the aerodynamic nozzles which are used for thermo/structural testing are shown in Figure 6-49a. Estimates of the potential flow core diameters are also shown in this figure. A description of the use of these nozzles is given in Section 6.3.4.

The hybrid heater system, consisting of the carbon monoxide combustion chamber for steady state running and the zirconia heater for intermittent operation with air is a new concept. The air heater is of conventional design except that it is heated by a CO-Air-O_2 burner. The carbon monoxide combustion chamber is sufficiently unique to warrant a rather lengthy explanation.

The concept of a non-hydrocarbon combustion process was conceived of in Phase I because of a desire to have a test gas entirely free of water vapor in order to avoid deleterious effects on scramjet engine refractory materials. The idea used for Phase I was that of combustion of carbon which had been ground to a suitable size. The Cabot Corporation, Boston, Mass., has given much thought to the problem of producing, grinding, and burning carbon in the quantities required for the facility. Although direct combustion of carbon has the potential of very high flame temperature, the problems involved in supplying finely ground carbon at the flow rates required have led to a different concept. The main problem is grinding large quantities of carbon. The Sturdavant Mill Co., a producer of vortex-type carbon grinders, have current designs which can grind 8-10 lb of carbon per second, which is orders-of-magnitude less than required.

The new fuel concept used in Phase II was proposed by Cabot Corp. Figure 6-73 shows some details of the combustor and Figure 6-74, the facility schematic, indicates the relationships of all the facility components.

Basically, the new concept is the direct combustion of carbon monoxide, air, and oxygen for all facility temperatures above 2500°R (1390°K). An electric air pre-heater, which is needed for the combustion process anyway, is used alone for temperatures less than the lower combustion limit. The carbon monoxide is produced in a CO reactor. The reactor is a shell filled with pelletized carbon black. The temperature of the carbon black is raised initially with an auxilliary burner and when the critical temperature is attained, oxygen is flowed into the burner from the bottom. A continuous, self-sustaining reaction is attained, and pelletized carbon black and oxygen are supplied in the correct proportions to replace the hot carbon monoxide being produced.

The carbon monoxide thus manufactured is burned with heated air, and oxygen, in the combustion chamber during the combustion cycle to produce vitiated air. A small amount of carbon monoxide is also used to supply the burner of the zirconia pebble bed during its heating cycle. A carbon monoxide heat exchanger and accumulator is provided to cool and store some of the CO when the facility mass flow requires less CO than is being produced in the reactor. This stored carbon monoxide is then used during peak facility CO consumption to augment the steady state CO production.

The facility maximum mass flow limit line is bounded by the P_o = 3000 psi line (2070 N/cm^2) and the T_o = 6000°R line (3330°K). Figure 6-77 shows the facility stagnation conditions and the total mass flow based on those limits.

FIGURE 6-77 MAXIMUM FACILITY OPERATING CONDITIONS – E9

M_∞	P_0 psia	P_0 (N/cm^2)	T_0 °R	T_0 (°K)	$\dot{W}_{Total}$ lbm/sec	$\dot{W}_{Total}$ (kg/sec)
3	84	(58)	1060	(600)	340	(154)
3.5	126	(87)	1400	(777)	323	(147)
4	191	(132)	1710	(950)	306	(139)
4.5	247	(171)	1980	(1100)	289	(131)
5	280	(193)	2280	(1270)	238	(108)
5.5	318	(219)	2800	(1556)	204	(93)
6	353	(243)	3150	(1750)	187	(85)
6.5	518	(357)	3610	(2010)	255	(116)
7	900	(620)	3960	(2200)	306	(139)
7.5	1300	(896)	4400	(2445)	340	(154)
8	1915	(1320)	4700	(2610)	354	(161)
8.5	3000	(2070)	5100	(2830)	357	(162)
9	3000	(2070)	5700	(3165)	248	(113)
9.5	3000	(2070)	6000	(3330)	139	(63)
10	3000	(2070)	6000	(3330)	116	(53)

Combustion tables were calculated by Cabot Corp. using the Naval Ordnance Test Station Propellant Evaluation Computer Program which presents the input constituents required and the chemical composition of the combustion products as a function of flame temperature. The results of these calculations are shown in Figure 6-78 and 6-79. The relative proportions of input constituents used in the computer calculations were chosen to produce a molar fraction of molecular oxygen in the combustion products identical to that in free air. This was done by assuming a simplified model for the reaction. This model is illustrated below for a generalized hydrocarbon fuel:

$$\underset{\text{(fuel)}}{C_m H_n O_p} + a\,\underset{\text{(air)}}{(.788476\ N_2 + .211524\ O_2)} + \underset{\text{(oxygen)}}{b\ O_2} \rightarrow$$

$$\frac{n}{2} H_2O + m\ CO_2 + c\ O_2 + .788476\ a\ N_2 \qquad 6.3\text{-}6$$

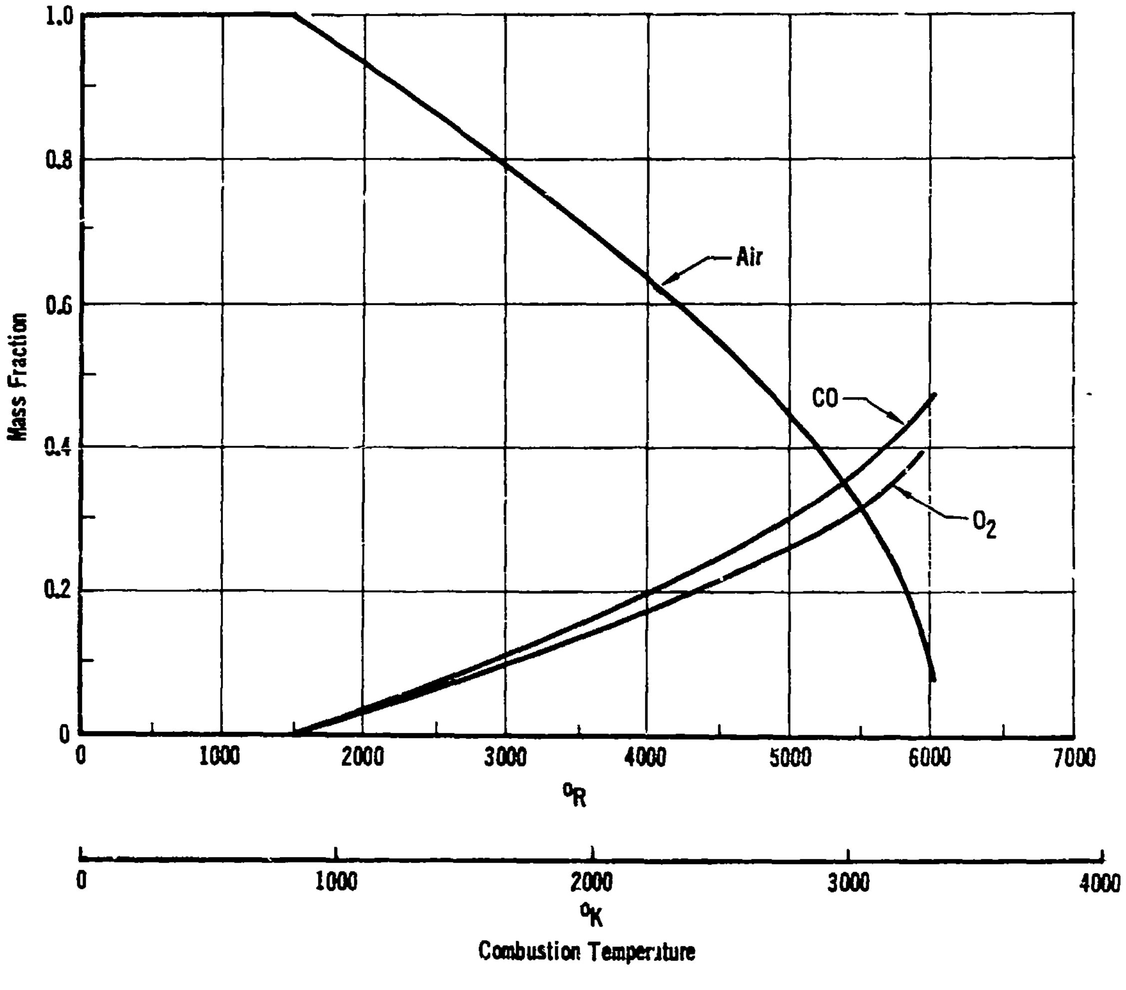
The subscripts m, n, p, define the chemical composition of the fuel and a and b define the amounts of air and oxygen volumetric inputs. Solving equation 6.3-6 for the oxygen balance gives:

$$\frac{p}{2} + .211524\ a + b = \frac{n}{4} + m + c \qquad 6.3\text{-}7$$

Letting y equal the concentration of molecular oxygen in the combustion products, equation 6.3-7 is expressed:

$$y = \frac{c}{\frac{n}{2} + m + c + .788476\ a} \qquad 6.3\text{-}8$$

FIGURE 6-78 MASS FRACTIONS OF INPUT CONSTITUENTS AS A FUNCTION OF TEMPERATURE FOR CARBON MONOXIDE-AIR-OXYGEN COMBUSTION PROCESS



Equations 6.3-7 and 6.3-8 can now be solved for c

$$c = \frac{p}{2} + .211524\ a + b - \frac{n}{4} - m \qquad 6.3\text{-}9$$

and

$$c = \frac{y\ (\frac{n}{2} + m + .788476\ a)}{1-y} \qquad 6.3\text{-}10$$

Solving equations 6.3-9 and 6.3-10 simultaneously for b, the volumetric fraction of the input oxygen,

$$b = n\left[\frac{(1 + y)}{4(1-y)}\right] + m\left[\frac{1}{1-y}\right] + a\left[\frac{.788476y}{1-y} - .211524\right] - \frac{p}{2} \qquad 6.3\text{-}11$$

This result is general, for any fuel and any concentration (y) of oxygen in the combustion products. For the combustion products desired for engine testing, y is equal to the free air concentration of oxygen, which is .211524, the coefficient of a is 0, and the interesting result is that the amount of input oxygen required is a straight function of the composition of the fuel used.

$$b = .384135\ n + 1.268269\ m - .500\ p, \qquad 6.3\text{-}12$$

and the fuel/oxygen ratio is constant for all flame temperatures. This result is shown below for various fuels:

FUEL	CHEMICAL COMP.	m	n	p	b = O_2/FUEL RATIO
Pure Carbon	C	1	0	0	1.268269
Carbon Black	C_8H	8	1	0	10.53029
Carbon Monoxide	CO	1	0	1	.76827
Propane	C_3H_8	3	8	0	6.87789
Methane	CH_4	1	4	0	2.80481

For carbon monoxide, .76827 moles of O_2 for every mole of fuel were used in the NOTS computer program with varying amounts of air. The resulting flame temperature and chemical constitution of the products as shown in Figure 6-79 were obtained. This program uses a more sophisticated combustion model than the simple one developed here, with constituents such as CO, NO, NO_2, and C included. The formation of these products causes the results to deviate slightly from the constant y = .211524, but it is seen that it is quite possible to attain an essentially constant free oxygen content for engine testing.

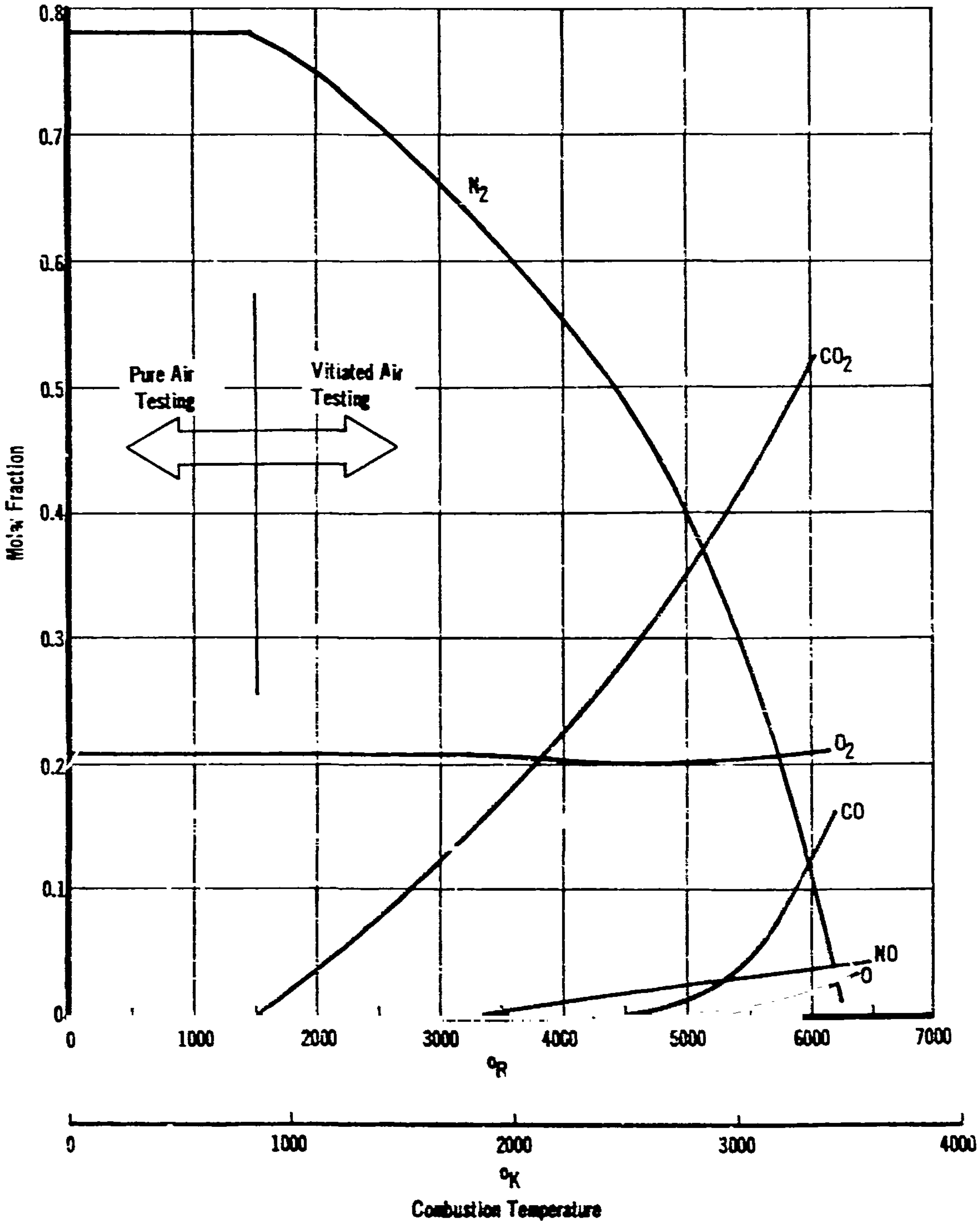
The graphite heater specified as the alternate heater type is sized to provide the same mass flow schedule as the combustion heater baseline facility. The heater is used to provide nitrogen at temperatures up to 5000°R (2780°K), which is mixed with oxygen to provide the correct air composition for engine testing. The heater design is based on the NASA Lewis Plumbrook facility heater, but requires approximately 210 times the power of the NASA heater. Operation is continuous rather than intermittent. A gas turbine power plant is provided for the induction coils which is independent of all other facility power sources, and which runs at a constant output frequency. This heater was included as an alternate primarily to provide a direct cost comparison between a combustion process and an electric heater as a continuous, high enthalpy source for scramjet testing.

6.3.9.1 <u>Specifications</u> - The following table presents the mechanical specifications of the E9 hybrid heater scramjet engine test facility. Heater operating conditions have been given in the previous section for the maximum mass flow limit line. The facility will also operate to the minimum mass flow line indicated in Figure 6-45c.

- <u>Engine Test Leg Description</u>

SJ/CSJ Engine Capture Area	15 ft (1.39 m^2)
Nozzle Geometric Area	3.45 ft^2 (
Module Cowl Area	2.65 ft
Flight Mach Number Range	3 to 10 (9 for alternate)

FIGURE 6-79
PRODUCTS OF COMBUSTION AS A FUNCTION OF TEMPERATURE FOR CARBON MONOXIDE – AIR – OXYGEN COMBUSTOR



Altitude Range	45 to 145 kft (13.7 to 44.2 km)
Stagnation Pressure Limit	3000 psia (2070 N/cm^2)

Stagnation Temperature Range

Baseline -	Continuous Flow	1080 to 6000°R (600 to 3330°K)
	Intermittent (Air)	1080 to 4500°R (600 to 2500°K)
Alternate -		1080 to 4000°R (600 to 2224°K)

Mass Flow Limit	357 lbm/sec (162 kg/sec)
Run Time	Continuous for vitiated air from combustion heater and for the alternate heater, 60 sec for the baseline blowdown cycle.

- o <u>Thermo/Structural Test Leg Description</u>

Flow Parameters	Same as above

Aerodynamic Nozzles

Design Mach Number	Length ft	(m)	Diameter ft	(m)	Potential Core ft	(m)
6	21.7	(6.6)	4.8	(1.46)	3.68	(1.12)
9	41.7	(12.7)	8.9	(2.71)	6.08	(1.85)
10	54.1	(16.50	10.83	(3.3)	7.3	(2.21)
12	63.3	(19.3)	15.32	(4.67)	7.41	(2.26

- o <u>Compressor Description</u>

Baseline Facility - Steady state air compressor capacity is 287,000 scfm (8125 m^3/min) at 6000 psia (4130 N/cm^2)

Alternate Facility - Steady state nitrogen compressor capacity is 224,000 scfm (6330 m^3/min) at 6000 psia (4130 N/cm^2)

Steady state oxygen compressor capacity is 53,200 scfm (1790 m^3/min) at 6000 psia (4130 N/cm^2)

- o <u>Electric Heater Description</u>

Baseline Facility - Electric preheater max. power is 100,000 kW.

Alternate Facility - Graphite induction heater max. power is 630,000 kW.

6.3.9.2 <u>Facility Component and Cost Summary</u> - Figure 6-80a shows a compilation of the costs estimated for each of the facility components. Estimates were made by the methods discussed in Section 6.1.

FIGURE 6-80a
E9 FACILITY COMPONENT AND COST SUMMARY

Facility Component	Cost Estimate $1000's	
	Baseline	Alternate
1. TEST LEG Sub Total	4,821	5,768
1.1 Engine Module Test Section Assembly (Same as in E8)	3,000	3,000
1.2 Aerodynamic Nozzle Adaptation (Same as in E8)	1,170	1,170
1.3 Test Module Bed and Transfer Tracks	178	178
1.4 Facility Enclosure	473	1,420
2. COMPRESSOR PLANT (Baseline Facility) Sub Total	37,926	3,000
2.1 Mechanical Components (Air Compressor, LO_2 Pump, LO_2 Gasifier and Accumulator, Motors, Piping and Valves, Air Storage Tank, LO_2 Storage).	35,280	-
2.2 Electric Substation (For Compressor Motors, Pump Motors, Electric Heaters).	2,646	3,000
3. WATER COOLING SYSTEM (Pumps, Heat Exchanger, Piping and Valves).	1,000	1,000
4. CARBON MONOXIDE SYSTEM (Baseline Facility) a. (CO Reactor, Pelletized Carbon Black Storage and Transfer, CO Accumulator, Electric Preheater, Combustion Chamber, Piping and Control Valves.)	7,000	-
5. ZIRCONIA HEATER SYSTEM (Baseline Facility) a. (Pressure Shell, Refractory Lining, Alumina/Zirconia Matrix, CO-Air-O_2 Burner.)	4,000	-
6. FUEL SYSTEM - LH_2 DISTRIBUTION AND CONTROL	71	71

FIGURE 6-80a (Continued)
E9 FACILITY COMPONENT AND COST SUMMARY

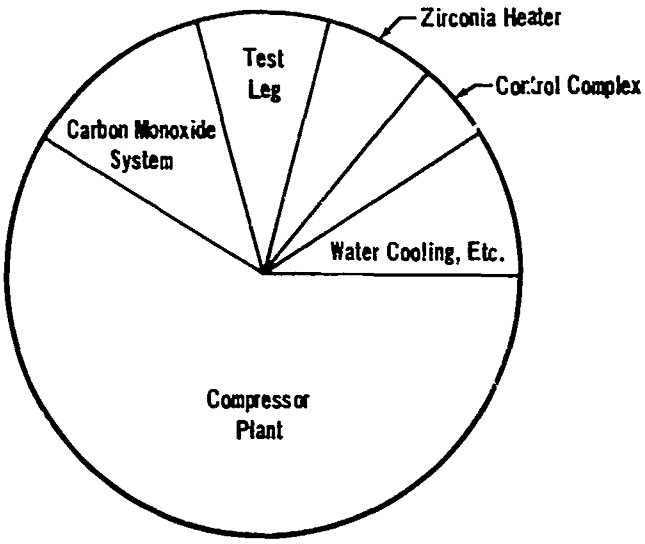
7. STEAM EJECTOR SYSTEM	1,165	1,165
8. CONTROL COMPLEX Sub Total	2,900	2,900
8.1 Lab/Office/Control Building	1,400	1,400
8.2 Automatic Facility Control System	400	400
8.3 Instrumentation and Data Acquisition System (Transducers, Amplifiers, Power Supply, Analog/Digital Converter, Tape Recorder, Closed Circuit TV).	1,100	1,100
2. NITROGEN SYSTEM (Alternate Facility)	-	28,497
b. (LN_2 Storage, LN_2 Pump, Gasifier, Compressor, Motors, Piping and Valves).	-	
4. OXYGEN SYSTEM (Alternate Facility)	-	7,141
b. (LO_2 Storage, Pump, Gasifier, Compressor, Motors, Piping and Valves).		
5. GRAPHITE ELECTRIC INDUCTION HEATER (Alternate Facility)	-	2,000
b. (Heater, High Frequency Generators, Gas Turbines, Power Turbines).		
Total	58,883	51,542
Contingency @ 10%	5,888	5,154
Facility Total	64,771	56,696
A&E Fee @ 6%	3,885	3,400
MGT & Coord. Fee @ 4%	2,590	2,270
Grand Total	71,246	62,366

The tabulated cost estimates show that the baseline facility would cost approximately 11% more than the alternate facility but would cost 54% less than the alternate facility to operate. The main difference in operating costs is in the consumables required. These are the carbon black pellets and liquid oxygen needed for the manufacture of carbon monoxide for the baseline facility, and the liquid nitrogen and liquid oxygen needed for the alternate facility. The fact that the baseline facility uses mostly air rather than purchased gases accounts for the difference.

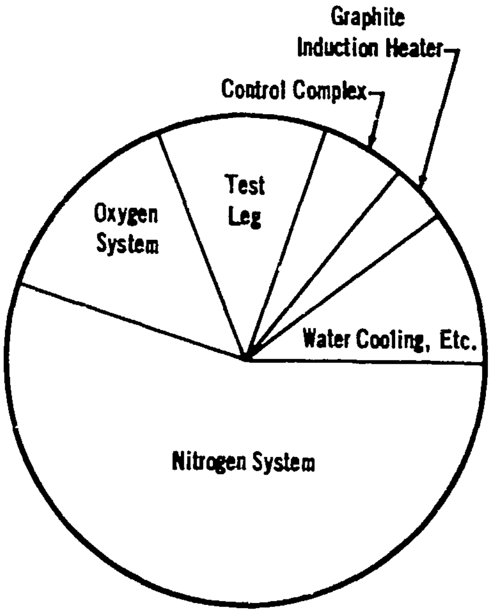
The "pie" chart presented for the baseline facility, Figure 6-80b, shows the characteristic high compressor costs for continuous high pressure facilities as well as the high cost of equipment for manufacturing the carbon monoxide. These two items account for more than 75% of the total acquisition cost, and also indicate that better definition of the technical requirements of these two items will have major impact on estimates of the total facility cost. Also apparent is the appreciable cost reduction that could be achieved by integrating the E9 facility compressor plant with existing-flow facilities.

Figure 6-81 is included to show the effect of increasing engine module capture area on the estimated component and total costs. This is done only for the baseline heater. Although the 15 ft^2 (1.39 m^2) module size is recommended for inclusion in Phase III, these computations give a good idea of what impact on cost any size increase will have. This information, combined with the improvement in research value for increased size, will help to define the most effective test section size.

FIGURE 6-80b
DISTRIBUTION OF FACILITY COMPONENT COSTS - E9



Baseline



Alternate

FIGURE 6-80c
E9 FACILITY OPERATING COST SUMMARY

Operating Costs – Dollars/Occupancy Hour	Baseline	Alternate
Repair and Maintenance	1,068	935
Staffing	1,000	1,000
Power and Consumables	3,600	10,400
Total	5,668	12,335

FIGURE 6-81
EFFECT OF ENGINE MODULE AREA ON COMPONENT COST
E9 Facility

FACILITY COMPONENT	COST ESTIMATE $1000's		
	A_c=15 Ft^2 (1.39 m^2)	A_c=45 Ft^2 (4.18 m^2)	A_c=90 Ft^2 (8.37 m^2)
1. Test Leg	4,821	25,069	68,458
2. Compressor Plant	37,926	128,948	265,482
3. Water Cooling System	1,000	3,500	7,200
4. Carbon Monoxide System (CO reactor, pelletized carbon black storage and transfer, co-accumulator, electric preheater, combustion chamber, piping and control valves)	7,000	35,000	97,300
5. Zirconia Heater System (Pressure shell, refractory lining, Alumina/Zirconia matrix, CO-AIR-O_2 burner)			
1 Baseline Heater	4,000		
3 Baseline Heaters		14,000	
3 2X Baseline Heaters			33,600
6. Fuel System (LH_2 Distribution & Control)	71	210	426
7. Steam Ejector System	1,165	3,844	7,806
8. Control Complex	2,900	3,500	4,800
TOTAL	58,883	189,002	485,072
Contingency @ 10%	5,888	18,900	48,507
Facility Total	64,771	207,902	533,579
A&E Fee @ 6%	3,886	12,474	32,015
MGT & Coord. Fee @ 4%	2,591	8,316	21,343
Grand Total	71,248	228,692	586,937
Cost/A_c	4,750	5,090	6,510

6.3.9.3 Development Assessment - The test leg components of this facility are identical to those of the E8 facility, and all comments regarding the development assessment given in Section 6.3.8.4 to those components apply to E9.

The heater concept developed for the baseline facility definition has never been applied to a facility of this type or size. The high pressure combustion chamber and air preheater should be developed through scale model prototype testing in order to determine the proper geometry, design of injection nozzles, flame stabilizers, and safety devices to ensure smooth, stable and complete combustion throughout the wide range of flow rates, pressures, and combustion temperatures required by the facility. Prior to this scale model development work, these components must be assigned a confidence level of 3. The carbon monoxide used in the combustion process is provided by a carbon monoxide reactor system. This reactor is a high pressure version of an atmospheric CO reactor currently operated by Cabot Corporation in Ashtabula, Ohio, which manufactures about 2 lb (1 kg) of CO per second. The reactor system required for E9 will have to generate from 75 to 100 lb/sec (34 to 45 kg/sec) on a steady basis. The exact value depends on the size of the accumulator provided for peak transient flow rates. A confidence level of 4 is appropriate for the reactor system in view of the size disparity between existing systems and the required system.

The heater required for the alternate facility definition is the graphite induction heater used to heat nitrogen on a continuous basis. The only such application of a graphite heater for engine testing is the intermittent storage-type heater used by the NASA Lewis Plumbrook facility. The E9 heater requires 210 times the power of the NASA heater and passes about 30 percent greater mass flow. The E9 heater shell must withstand 3000 psi (2070 N/cm^2) compared to the maximum pressure of 1200 psia available in the NASA facility. The NASA heater is not without its problems at this time, two of which are non-uniform heating of the drilled graphite discs which comprise the thermal matrix, and power supply instability and surge problems. The latter problem is partially caused by interaction of the four 750 kW power supplies with the base power system. This particular problem area would probably not exist for the E9 alternate heater if the heater power was provided by a gas turbine generator power pack which is completely independent of any external power system, as contemplated. Design of the E9 heater is made extremely difficult, however, by the tremendous power required (630,000 kW) and the continuous heating cycle required. Without a scale model prototype development program, the confidence level must be assessed as about 2. This level can be raised to 4 prior to construction of the full scale heater if a heater development program is conducted. Such a program might use the Plumbrook heater to solve the problems already observed there. A first step would be the installation of an adequate gas turbine generator power supply as mentioned. The final step of development using this heater would be its gradual development as a continuous heater. This phase might require installation of additional compressor capacity to permit continuous running at mass flows around 100 lb/sec (45 kg/sec). Successful solution of operational difficulties of the heater on this scale would give a high degree of confidence to the design of the full scale heater for E9.

In summary, the most critical development problem areas for the E9 facility occur in the heater design, regardless of which concept is used, prototype development being essential before a committment to a final design is made.

6.3.10 EVALUATION AND CONCLUSIONS - The turbo machinery facilities require the greatest expenditure of funds to acquire a broad capability of any facilities in this study. The baseline integrated direct connect/free jet facility (E20) costs over 700 million dollars. Compromising the facility's flight duplication capability at transonic Mach numbers by reducing the total mass flow requirements from 11,000 lb/sec (5000 kg/sec) to 6000 lb/sec (2700 kg/sec) reduces the cost to about $400 million. Alternate 1 is simply the reduction in the mass flow, while alternate 2 is reduction of the mass flow as well as elimination of the high altitude transonic refrigeration requirements. Although this is quite an expensive facility it provides a very essential inlet/engine research capability up to Mach 5 at flight duplicated conditions. This far exceeds the capability of existing facilities to evaluate time variant pressure and thermal distortions on inlet-engine matching research. At first glance it would appear that E6 alone would be the best choice, but a major reason for carrying this facility into Phase III would be the economics of integrating the total facility into existing facilities. The direct connect leg, which is E6 when considered independently, is really an upgraded T-1 facility at AEDC. By using the existing compressor plant, exhausters, and heaters a new leg would be required plus second stage compressors, and heater. This would reduce the total cost of E6 to about $35 to 40 million. The free jet leg and its compressor plant cost about $310 million, with the compressor plant amounting to 75% of this figure, hopefully this could be substantially reduced to bring the cost of the facility integrated into AEDC on the order of $250 million. This is only about twice the cost of the proposed Large Engine Test Facility would have only a direct connect capability, and provides substantially more research capability. A reasonable question is why is there a need for such a massive facility for research. The reason is that the ability to research the problems associated with an entire full scale engine was rated very high; and in order to provide basic research on a long life, high Mach number engine of a size applicable to the potential operational hypersonic aircraft, such a facility capability will certainly be required. The basic question for Phase III is, can it be done economically, and if not, what are the alternatives, including providing only the direct connect capability. The facility research value is presented graphically in Figure 6-82, and tabulated in Figure 6-83.

The scramjet facility baseline was based on an engine module with 15 ft^2 (1.39 m^2) capture area. This represented about the smallest size module which could yield meaningful data for the operational hypersonic aircraft (see Section 6.3.3). This size was a subscale module (from 1/4 to 1/6 full scale) for the operational vehicle but a near full scale size for the research aircraft. There is an increase in research value as the module size increases (Figure 6-84) but diminishing value per investment dollar above 15 ft^2 (1.39 m^2) capture area. A major factor determining facility capability is the investment required to attain that capability. For facility E8, there is no meaningful cost estimate that could be made in Phase II because its mechanical drive system so exceeds current capability. For E9 however, the hardware developed at Cabot Corporation, proposed for the AEDC TRIPLETEE, and in operation at the NASA Ames 3.5 foot hypersonic tunnel, provided a reasonable base from which increased capability could be projected. Figure 6-85 presents the cost of attaining a given level of research capability as a function of acquisition costs. Based on hardware considerations it appears that an initial capability of 15 ft^2 (1.39 m^2) capture area could be provided on a near term basis (1975). This could be increased to 45 ft^2 (4.19 m^2) in another five years at only a 10% greater cost per unit module area as operational experience and hardware capability increase. The recommended Phase III facility is therefore E9 baseline. E9 alternate which is a continuous running version of the NASA Lewis inductively heated, graphite storage heater at Plumbrook, has less temperature capability and very much higher operating costs .

The multirecompression heater offers the capability to increase the flight duplication capability from Mach 9 to Mach 12 (see Figure 6-45c), but suffers from extreme mechanical problems regarding the prime mover power and control requirements as well as being an undeveloped facility concept. A logical extension of E9 baseline would be to incorporate a small high enthalpy multirecompression heater into the E9 facility at some later date for the 15 ft^2 (1.39 m^2) capture area module to enlarge the Mach number range in which pure air testing can be obtained. The recommendation is then to carry the E8 facility into Phase III for further refinement, as a complete facility, and evaluate the aspects of integrating it into E9 as a growth potential of far term capability (1980-1985).

FIGURE 6-82
EVALUATION OF ENGINE RESEARCH FACILITIES (TURBOMACHINERY)

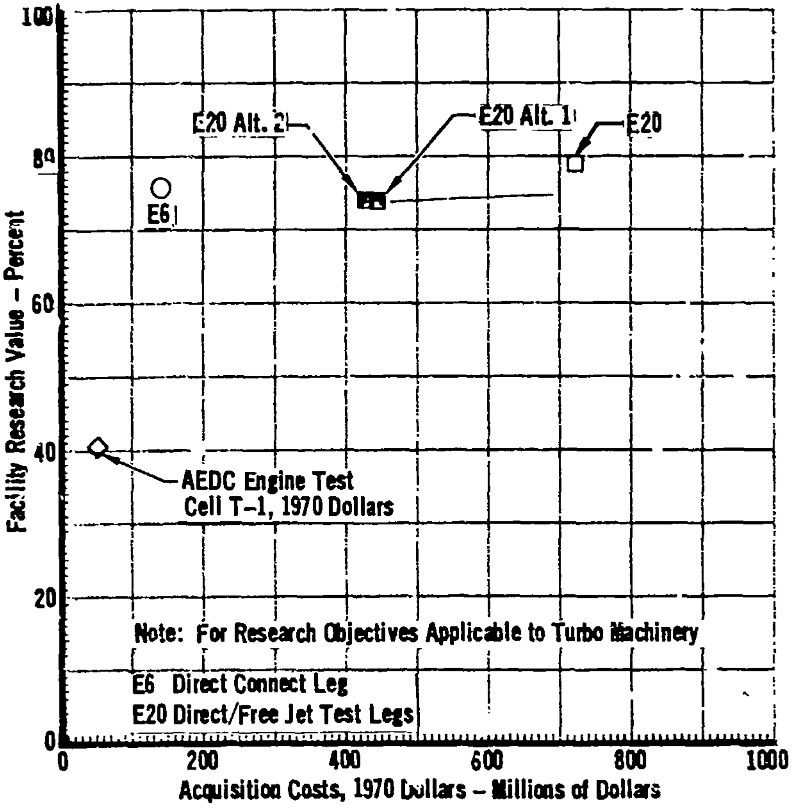


FIGURE 6–83
FACILITY EVALUATION (ENGINE, TURBOMACHINERY)

Facility	Average Research Value (Percent)	Acquisition Cost (Millions of Dollars)	Remarks
E6	75	114.5	Direct Connect Only
E20	79	712.0	Free Jet and Direct Connect
E20 Alt 1	78	432.8	
E20 Alt 2	78	423.7	Deletes regions best accomplished by E6 leg, and retains capability most necessary for inlet/engine research

Turbo Machinery
Research Objectives

FIGURE 6–84
COMPARISON OF SCRAMJET ENGINE MODULE SIZE WITH RESEARCH VALUE

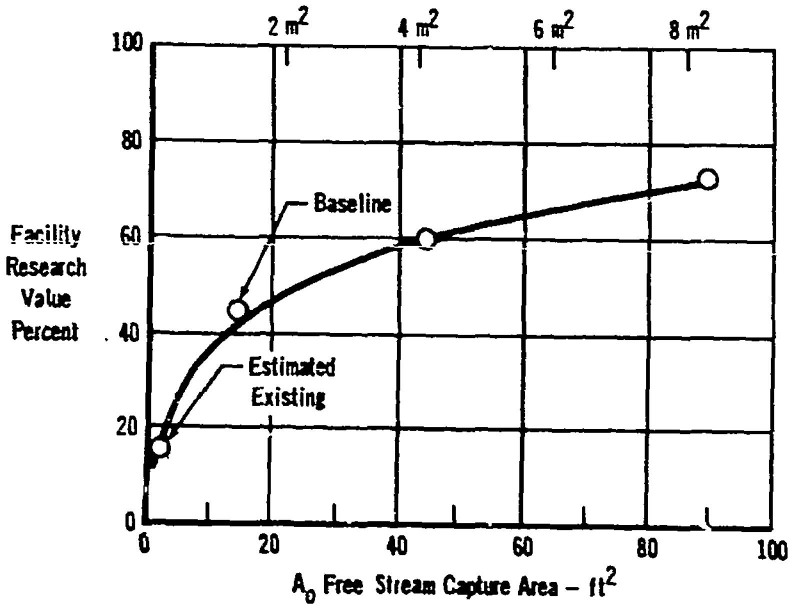
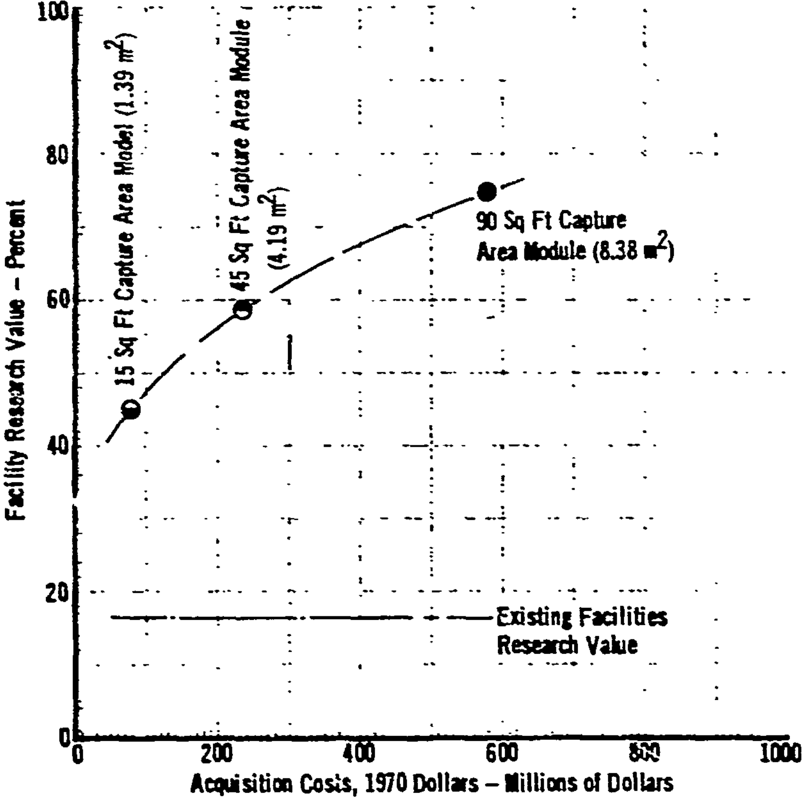


FIGURE 6–85
EVALUATION OF THE RESEARCH CAPABILITY OF A SCRAMJET ENGINE RESEARCH FACILITY AS A FUNCTION OF FREE STREAM CAPTURE AREA AND ACQUISITION COSTS

FOR ENGINE RESEARCH FACILITY E9



For research objectives applicable to scramjet research.

FIGURE 6-86
FACILITY EVALUATION
(Engine, Scramjet)

Facility	A_c Ft^2 (m^2)	Average Research Value (Percent)	Acquisition Cost (Millions of Dollars)	Remarks
E9	15(1.39) 45(4.17) 90(8.34)	45 59 75	71.2 228.7 386.9	Near Term, Based on Current Technology
E9 Alternate	15	40	62.4	Limited Temperature, very High Operating Costs
E8	15	48	172.0	Requires Considerable Development, Far Term
E8 Alternate	15	48	251.9	Beyond Technology in Electrical/Mechanical Drives

For Research Objectives Applicable to Scramjet Research

6.4 STRUCTURAL RESEARCH FACILITIES

6.4.1 DESIGN CRITERIA - The S2 Structural Research Facility was synthesized to establish and verify the thermal, structural, dynamic, and acoustic responses of the complete full-scale airframe of an operational vehicle and to demonstrate the vehicle design life operating in thermal, mechanical, acoustic, and pressure environments similar to those experienced in flight. The methodology used in selecting the facility requirements is shown in Figure 6-87. The baseline facility was chosen as that facility which could perform all test environments on a major section of the full scale vehicle in both time and magnitude.

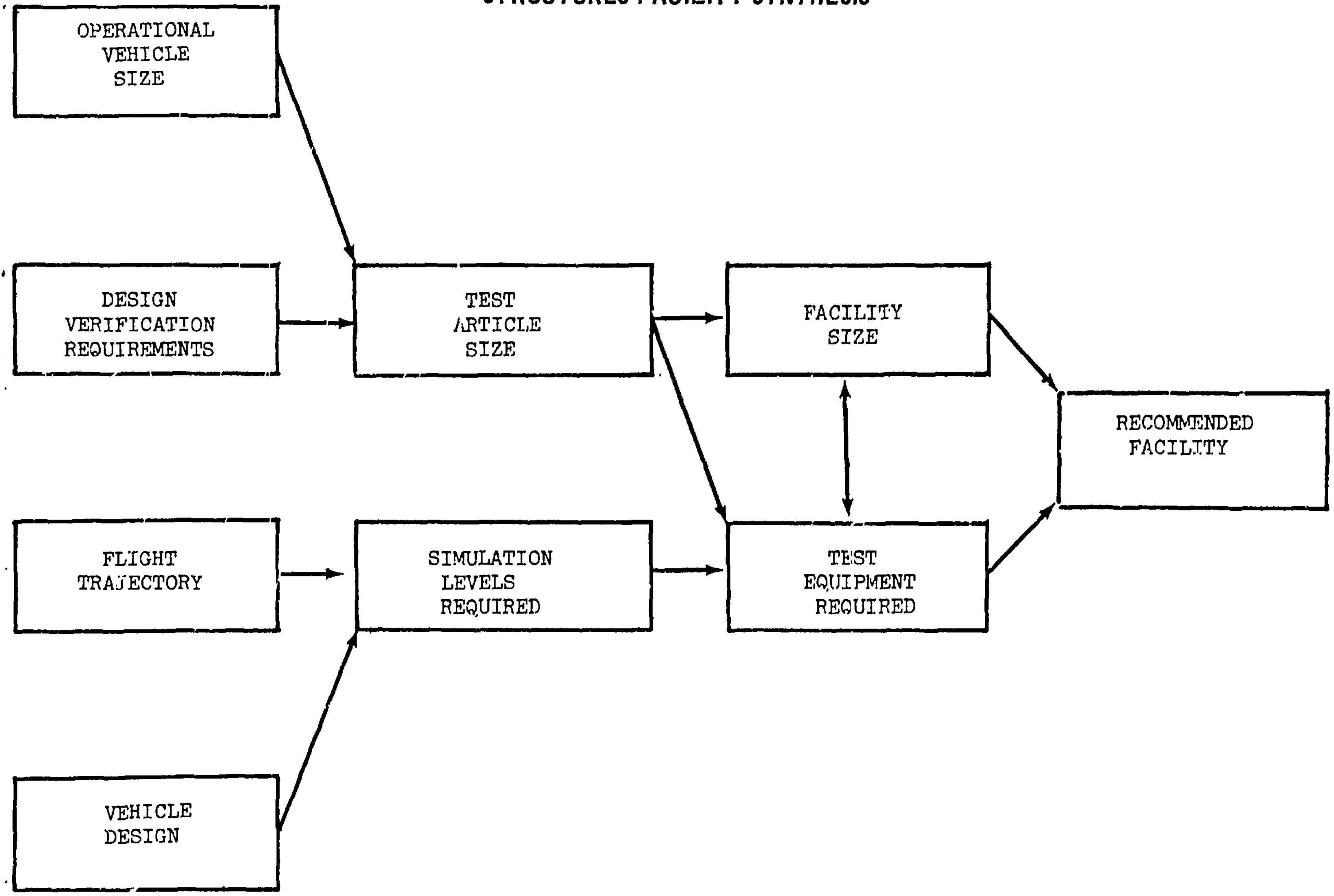
All test systems were designed to simulate the most severe parameter or environment encountered by any of the proposed operational vehicles. Each system was designed to be as adaptable and flexible as possible such that a wide variety of different test specimens and vehicles could be tested in the facility. The equipment chosen only indicates a tentative selection, based on an assumed test article and on assumed structural test requirements.

Where possible, off-the-shelf equipment was chosen, and, except where indicated, the equipment available can perform the required testing. The number of units of test equipment required was determined by scaling present aerospace structural tests. The number of units chosen for each test article was selected only as a reasonable appropriate number to determine costs.

6.4.2 PARAMETRIC STUDIES - Parametric studies were conducted to determine facility requirements, to show the impact of individual test parameters on cost, to show how the facility capability is affected by parametric variations, to determine the feasibility of various testing methods, and to identify the primary considerations in choosing a reasonable Structural Research Facility. The test parameters were studied by determining the facility requirements necessary to simulate flight environments in both time and magnitude, isolating the prime factors that most affect capability and cost, developing curves that show facility capability versus cost, and by analyzing the facility requirements and formulating conclusions so the facility specifications can be chosen.

A preliminary analysis of the Structural Research Facility indicated the most important parameters were: test article size, altitude simulation requirements, thermal simulation requirements, dynamic vibration excitation methods, thermal-acoustic testing, mechanical loading systems, and refrigeration requirements. These parameters were chosen because they appeared to be the parameters that had the major influence on facility design and cost.

FIGURE 6–87
STRUCTURES FACILITY SYNTHESIS



6.4.2.1 Test Article Size - In Phase I, the major section of the full scale operational vehicle was chosen as the baseline test article size. Any facility that was capable of testing a major section of the full scale operational vehicle could test a component of the full vehicle, and could also test any full scale research vehicle used in the acquisition of knowledge leading to production of an operational vehicle.

The magnitude of the cost of full scale vehicle testing forces structural testing to be conducted on as small a test article as possible. The test philosophy evolving from advanced large vehicle programs such as the SST and Concorde indicate that where feasible, ultimate strength verification and airworthiness testing will be done on component or major section size test articles. Thermal fatigue life verification must be performed on larger test articles because of unknown structural interactions, but major section size test articles are considered to be of sufficient size such that these interactions are not critical over a large portion of the area being tested.

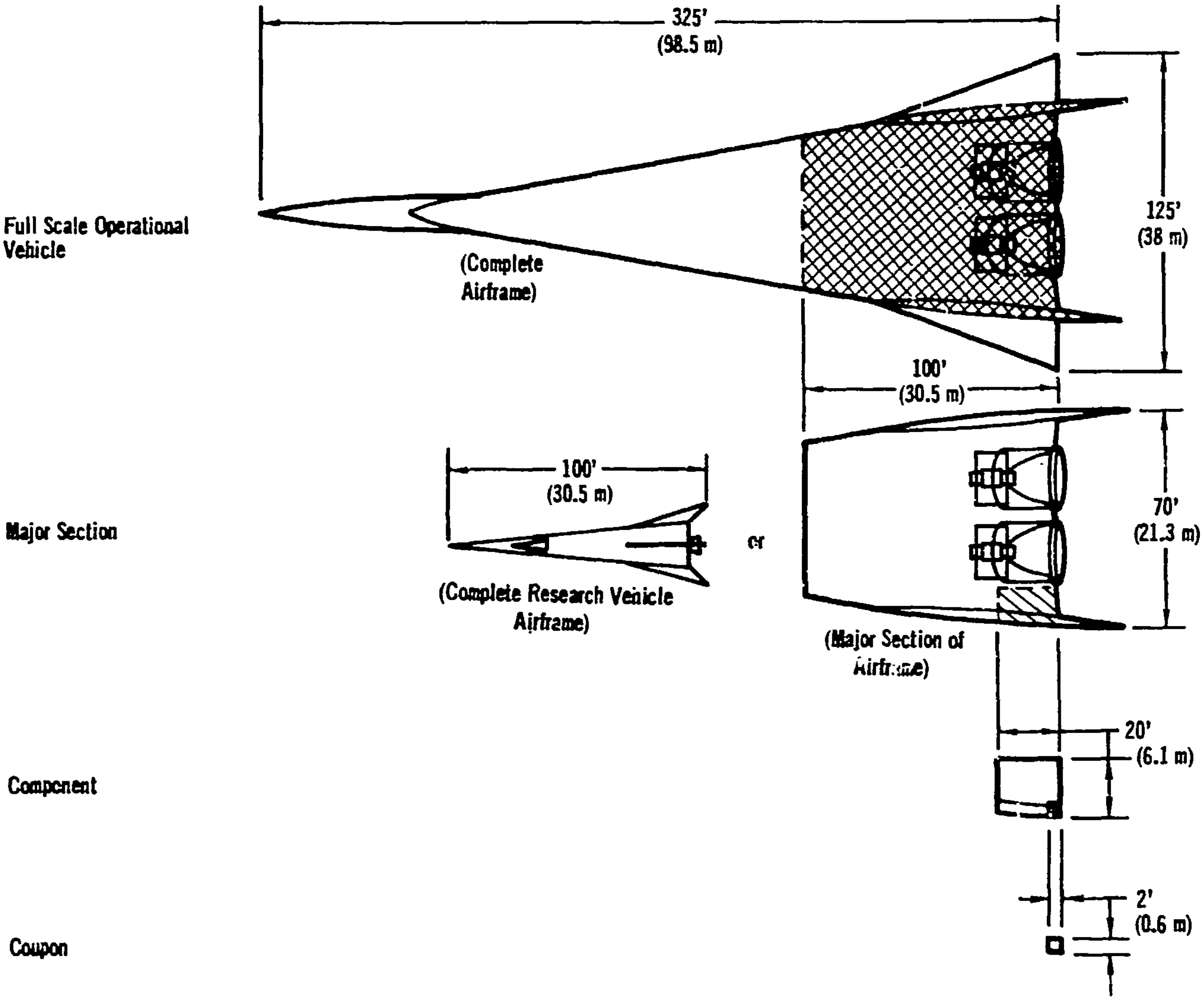
The advantages of testing smaller test articles include smaller facility requirements, lesser amounts of equipment, savings in test time, and less time to manufacture test specimens. Even with full scale vehicle testing, not all test objectives can be met with a single test, a series of tests being necessary to accomplish all desired test objectives. With small component testing, many tests may be performed concurrently to complete the entire verification program in a shorter time.

Three sizes of test articles, full-scale operational vehicle, major section, and component, were considered in this study and are shown in Figure 6-88, and each test article is described in Figure 6-89. All the test articles are of full scale construction such that all actual dimensions are identical to the flight vehicle, the only difference being the portion of the full scale vehicle included in the specimen. The major section test article is similar in size to a typical research vehicle so the complete full scale research vehicle could be structurally verified in the major section sized Structural Test Facility. The cost of the S2 facility for different test article sizes is presented in Figure 6-90. The costs of the structural facility were based on the assumption that all simulation levels would be applied on each test article, the only difference being the size of the test article.

In any structural test using specimen sizes other than the complete structure, sacrifices in test verification confidence levels must be made because unknown structural, thermal, and dynamic interactions of the entire vehicle are not present. The environmental levels most affected by reducing the specimen size are thermal and mechanical vibration because of the importance of edge conditions and structural response. Thermal fatigue testing must be done on test sections at least as large as a major section because of unknown structural and thermal interactions that cannot be simulated in a smaller component.

In the component ultimate strength verification approach, two different sizes of test articles may be considered; those of small size to determine the structural characteristics of a local area once a critical section is located,

FIGURE 6-88
TEST ARTICLE SIZE



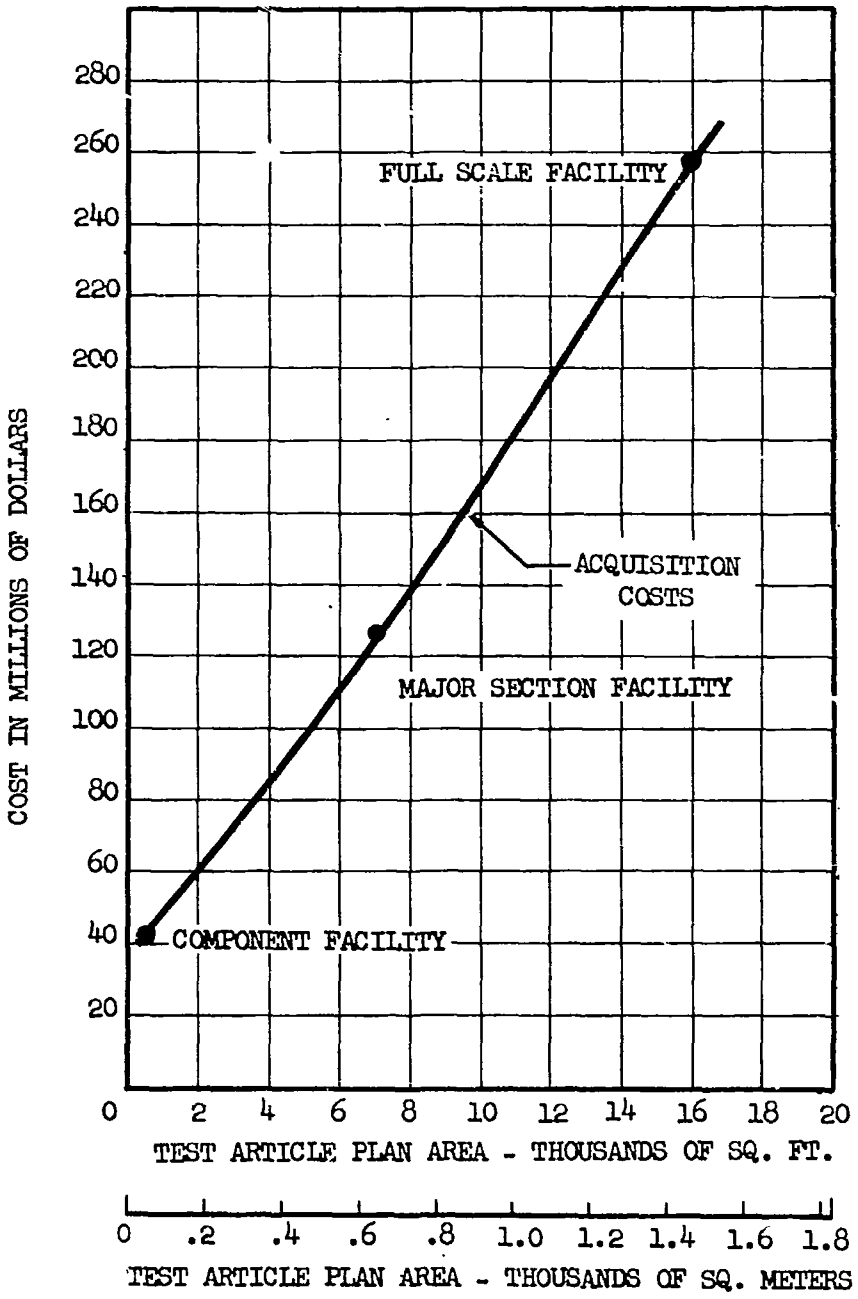
and larger components which evaluate the structural performance of a major section of the structure to reliably locate critical areas. The larger components are approximately 50 percent larger in gross size and 2 to 3 times larger in test areas than the smaller components.

A literature survey was conducted to technically verify the concept of testing major section or component size test specimens rather than full scale test articles. A technical analysis which determines the advisability of thermally testing component-sized test articles as opposed to complete vehicle testing is presented in Reference (8). Therein, an analytical investigation was performed

FIGURE 6–89
TEST ARTICLE DESCRIPTION

Parameter	Units		Coupon		Component		Major Section		Full-Scale Vehicle	
Length	ft	m	2	.6	20	6.1	100	30.5	325	98.5
Width	ft	m	2	.6	20	6.1	70	21.3	125	38
Height	ft	m	2	.6	20	6.1	30	9.1	90	27.5
Volume	ft^3	m^3	8	.16	6000	198	45,000	2830	150,000	4950
Plan Area	ft^2	m^2	2	.2	400	36	7000	465	16,000	1487
Surface Area	ft^2	m^2	8	.8	2500	332	15,000	1392	41,000	3810
Weight	lb	kg	100	45	40,000	18,100	566,000	22,600	1,025,000	465,000
Max. Avg. Test Surface Load	lb/ft^2	N/m^2	2500	1,193,000	2500	1,193,000	2500	1,193,000	2500	1,193,000
Max. Altitude	ft	m	150,000	45,800	150,000	45,800	150,000	45,800	150,000	45,800
Max. Nose Cap Temp.	°F	°C	3500	1930	3500	1930	3500	1930	3500	1930
Max. Leading Edge Temp.	°F	°C	3000	1670	3000	1670	3000	1670	3000	1670
Avg. Lower Body Temp.	°F	°C	2600	1440	2600	1440	2600	1440	2600	1440
Avg. Upper Body Temp.	°F	°C	1600	880	1600	880	1600	880	1600	880

FIGURE 6-90
DYNAMIC STRUCTURAL EVALUATION FACILITY ACQUISITION COST AS RELATED TO TEST ARTICLE PLAN AREA



to determine the optimum size test article that is required to simulate the flight temperatures and thermal stresses experienced by the complete vehicle.

A typical wing box structure of a Mach 4 vehicle, as shown in Figures 6-91 and 6-92, was studied to show the effect of specimen size on thermal gradients and thermal stresses. Figure 6-93 shows the effects of varying the heated portion of the specimen on the temperature of an interior point (Node 1) of the structure. It was determined that satisfactory simulation of temperatures could be attained at any interior point if the heated length extends in both directions at least 3 or 4 times the specimen cross-sectional depth and width. The effects of internal radiation were found to be a prime mode of heat transfer in the Mach 4 structure because internal radiation reflecting surfaces were not provided. The size of the test article is dependent on the area required to develop the internal radiation shape factors.

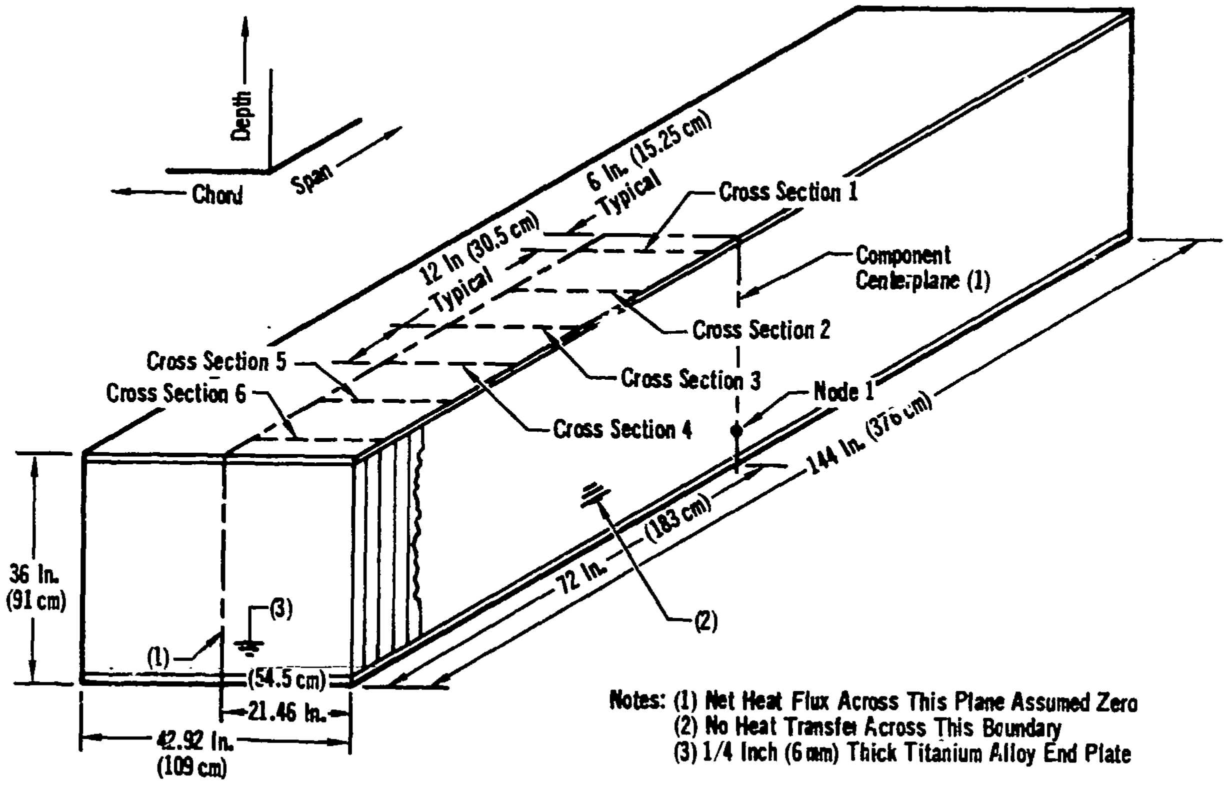
The above analysis concluded that the results for the wing cross-section of the Mach 4 vehicle are generally applicable to a Mach 12 vehicle, except that smaller specimen sizes can be used. The effect of internal radiation is not the driving factor in determining the required test article size for a Mach 12 vehicle because an active thermal protection system will probably be used and radiation reflectors will be provided. Figure 6-94 and 6-95 show typical areas of Mach 4 and Mach 12 airframes that may be considered as test specimens and the area that must be heated.

If structural boundary conditions are ignored and the thermal distribution for the Mach 4 wing box as shown in Figure 6-93 are assumed, the thermal stresses in the wing box at Node 1, as shown in Figure 6-96 , were found to be larger than those experienced when the entire vehicle is heated. This increase in thermal stress is due to increased thermal gradients in the smaller test articles. If the test specimen length is 3 to 4 times the cross-sectional depth, a good approximation of thermal stresses is present at the component centerplane, but thermal stresses at the ends of the specimen can exceed the nominal thermal stresses by approximately 50 percent. It is nevertheless possible to achieve valid thermal stress test results in relatively small test articles if provisions are incorporated in the test article to accommodate the higher thermal stresses expected at the specimen boundaries.

It is concluded that reproduction of full scale vehicle temperature distributions and thermal stresses in a major section is sufficiently accurate to permit the satisfactory demonstration of ultimate vehicle strength.

In mechanical vibration testing, where the response of the entire vehicle structure is required, component or major section testing may not be feasible unless the boundary conditions are known. An alternate testing method may be feasible where geometrically scaled flexible models are used as test specimens. The laws of similitude show that many structural characteristics may be achieved by proportional scaling, but other characteristics are governed by non-linear relations and therefore not geometrically scalable. Due to physical size limitations of material thicknesses and fastener sizes, the smallest feasible model size is thought to be approximately 1/5 scale. Reference (2) states that satisfactory results were obtained in determining the dynamic characteristics of the Titan III vehicle by using a 1/5 scale model. However, the MCAIR Structures and Dynamics

FIGURE 6-91
WING BOX COMPONENT IDEALIZATION MACH 3-4 VEHICLE

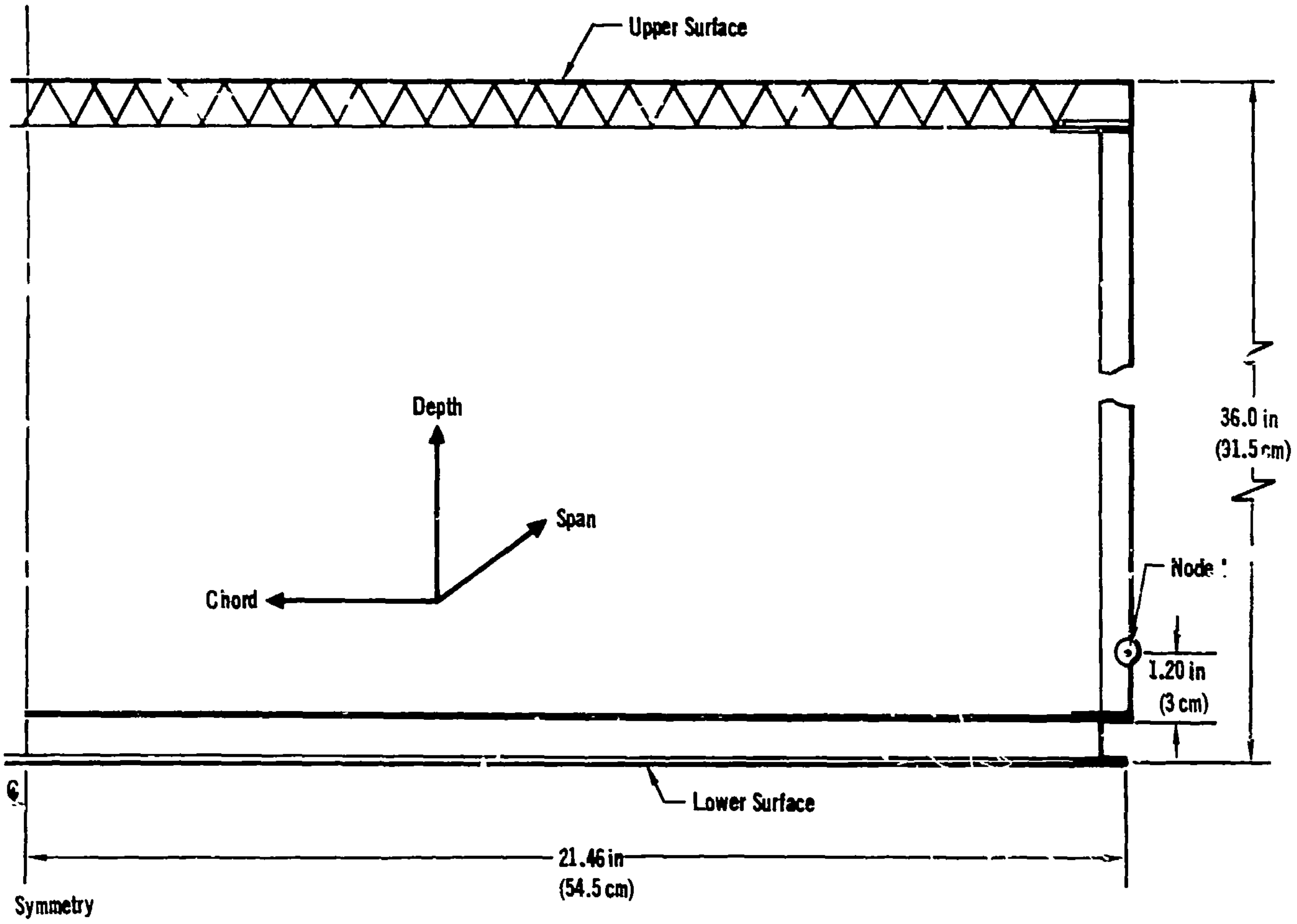


Notes: (1) Net Heat Flux Across This Plane Assumed Zero
(2) No Heat Transfer Across This Boundary
(3) 1/4 Inch (6 mm) Thick Titanium Alloy End Plate

Laboratories reported that acoustic testing of a 1/10 flexible scale model of the Voyager spacecraft installed in the upper stage of a 1/10 scale model of the S 1V-B indicated that the acoustic response of the configuration could be accurately determined. Specimen fabrication costs will increase if scale models are used because of special tooling and manufacturing costs. The determination of whether model testing should be used will depend on the vehicle being tested and its complexity.

A minimum fatigue life must be incorporated in the design of any hypersonic airframe for the environments in which the vehicle will operate. For a hypersonic vehicle, the effects of thermally induced stresses are additive to mechanical stress such that the important fatigue condition is that of thermal fatigue. Thermal fatigue research dictates that large sections of the complete structural airframe are necessary as a test specimen because unknown structural interactions have a major influence on thermal gradients, crack initiation, and the residual structural strength present when fatigue cracks appear. Thermal fatigue testing will involve months or years until sufficient load and temperature cycles are applied to the specimen to verify the fatigue life of the airframe component, even if testing is conducted on an accelerated basis. Proper test scheduling will

FIGURE 6-92
WING-BOX COMPONENT CROSS SECTION MACH 4.0 VEHICLE



allow the entire structural test facility to be used for the larger thermal fatigue test specimens after the ultimate structural strength verification test programs have been completed on component size test articles.

All of the structural test objectives can be accomplished using either component, major section, or geometrically scaled models, and it was concluded that full scale vehicle testing is not required to accomplish the Research Objectives.

It is concluded that structural test specimens need not include the complete vehicle, but in order to verify ultimate strength, fatigue life, and airworthiness, test articles as large as major sections must be tested. Dynamic and acoustic response determinations may be conducted on geometrically scaled models. The cost summary (Figure 6-107) shows that for all test article sizes, the cost of the facility is primarily determined by the quantity of test equipment required to test the respective test articles. The most efficient structural research facility would be one that incorporates a building complex large enough to test a complete

FIGURE 6–93
TEMPERATURE AT NODE I FOR VARIOUS HEATED LENGTHS MACH 4 VEHICLE

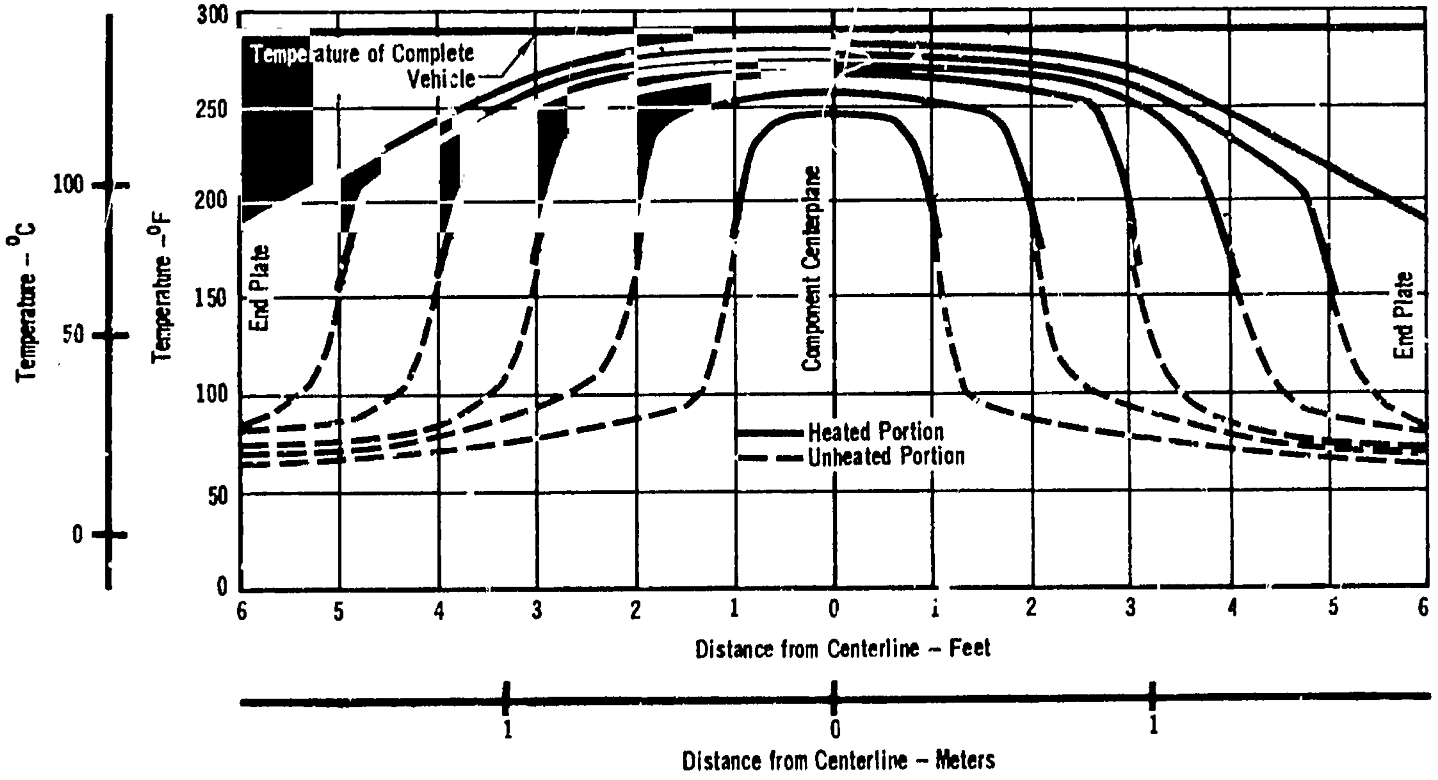


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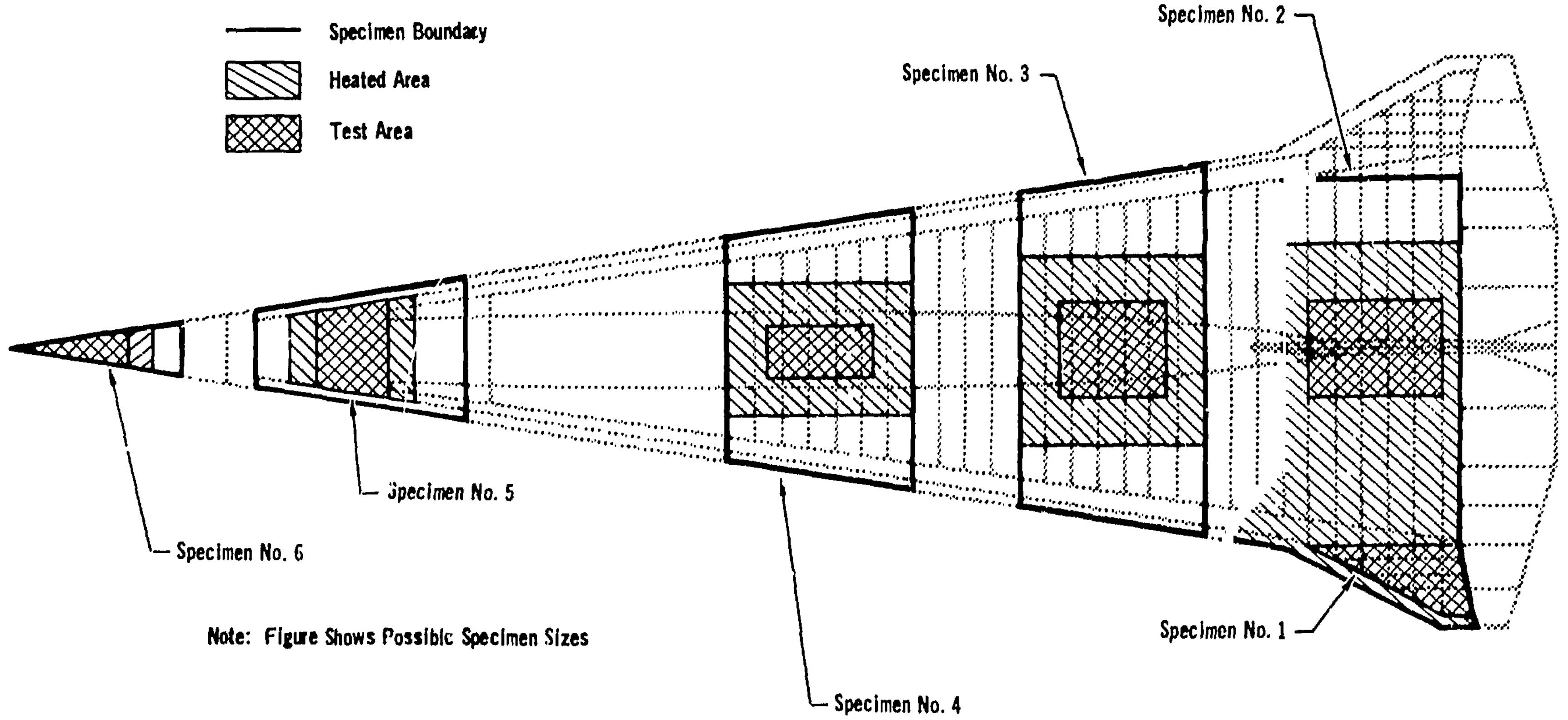
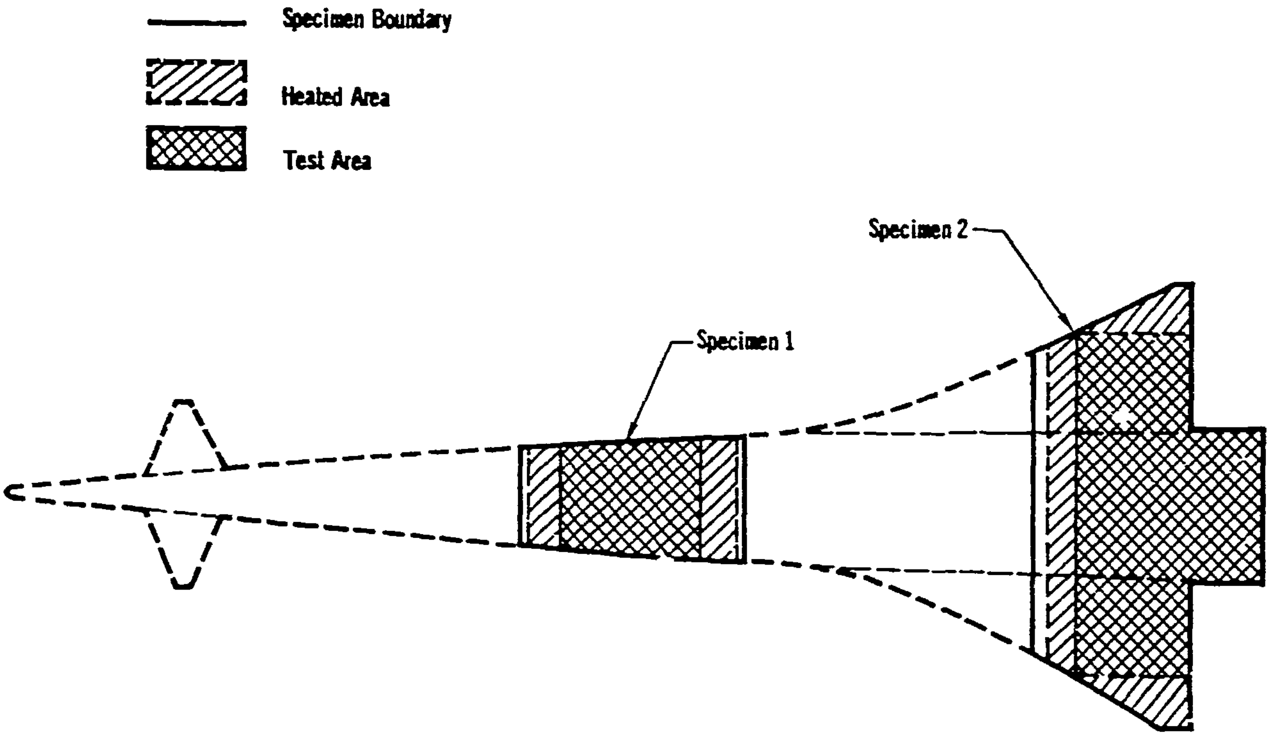
FIGURE 6–94
SELECTED TEST SPECIMENS MACH 3- 4 VEHICLE



Note: Figure Shows Possible Specimen Sizes

FIGURE 6-95
SELECTED TEST SPECIMENS MACH 12 VEHICLE



full-scale vehicle and test equipment to test a major section. A large building would permit full-scale testing, if desired, or the simultaneous testing of three major sections.

6.4.2.2 Altitude Simulation Requirements - Several Research Objectives require that the structure be subjected to the altitude - pressure environment similar to that experienced by the actual vehicle during its flight trajectory. In order to simulate the altitude-pressure environment of a typical vehicle, both the absolute pressure and the rate of climb must be considered. Figure 6-97 shows the pressure-time profiles of four typical vehicles considered in this study. It was found that the pressure-time profiles could be approximated by the following equation:

$$P = P_O e^{-mt}$$

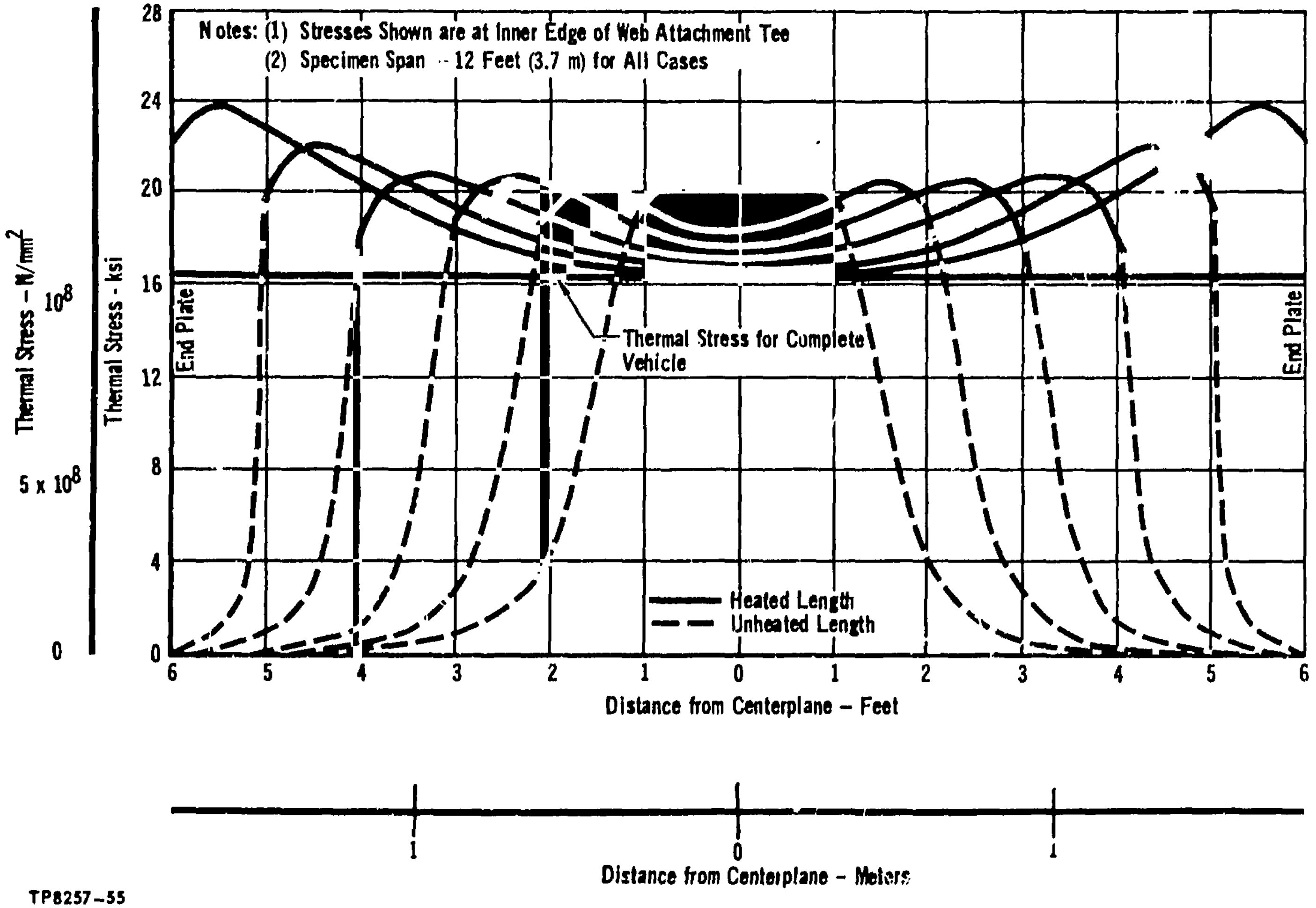
where: P = Pressure at time t

P_O = Pressure at start of pump-down

m = Constant

t = Time

FIGURE 6-96
MAXIMUM THERMAL STRESS AT NODE I FOR VARIOUS HEATED LENGTHS MACH 3-4 VEHICLE



Notes: (1) Stresses Shown are at Inner Edge of Web Attachment Tee
(2) Specimen Span - 12 Feet (3.7 m) for All Cases

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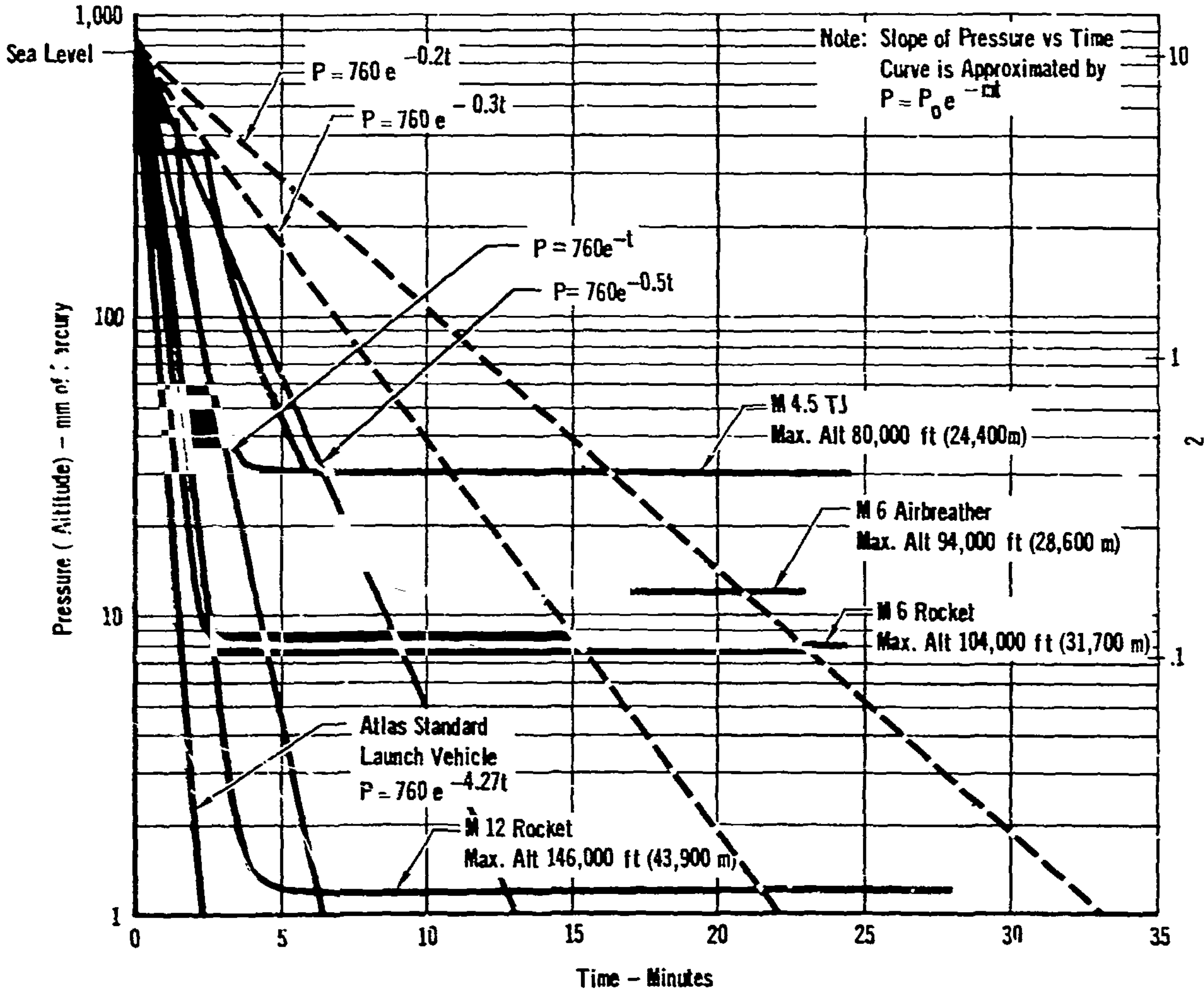
FIGURE 6-97
PRESSURE vs TIME



Another expression was developed to show the relation of the maximum altitude and rate of climb to the vacuum pumping capacity required for both full-scale and major section facilities. This equation was found to be of the form:

$$V_{PR} = m\ V_c$$

where: V_{PR} = Required pumping rate - scfm

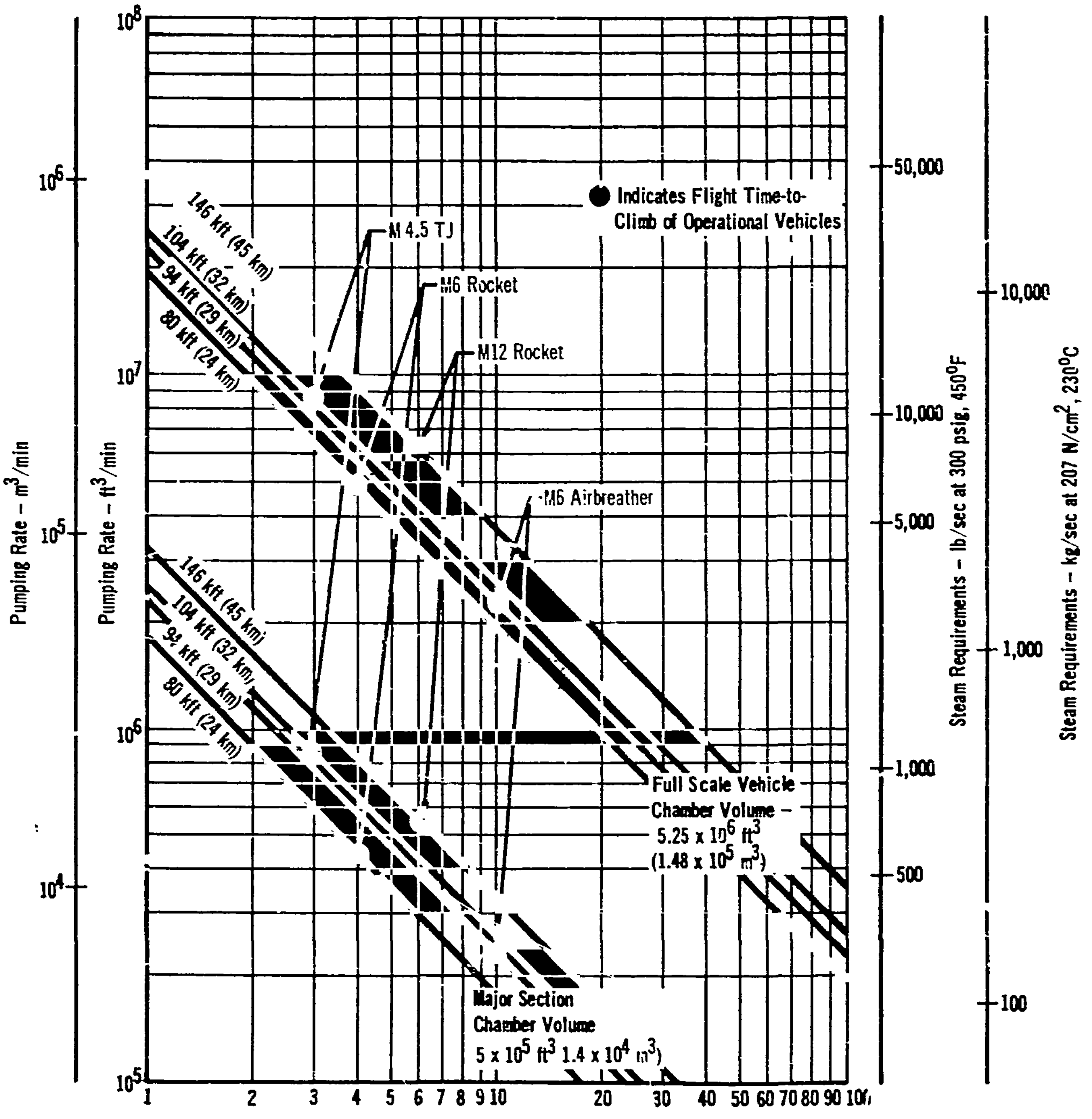
m = Constant derived from the previous equation - 1/min

V_c = Volume of chamber - ft^3

From these equations, a series of curves that shows pumping requirements versus time was developed for 4 pressure-time profiles and is presented in Figure 6-98.

An analysis of the curves in Figure 6-98 shows that extremely severe pumping demands are required if a large chamber must be rapidly evacuated. If the flight

FIGURE 6–98
REQUIRED PUMPING RATE vs TIME TO MAXIMUM ALTITUDE



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profile of the M-12 RKT operational vehicle is required to be simulated on the full scale vehicle, where the time-to-maximum-altitude is approximately 4 minutes and the maximum altitude is 146,000 ft. (1 mm H_g), a pumping rate of approximately 8.6×10^6 SCFM (2.4×10^5 m^3/min) must be provided. The pumping rate is dependent on chamber volume, pump down time, and maximum altitude. By relaxing the time to maximum altitude, or the size of the chamber, substantial cost savings can be realized.

In determining the optimum altitude chamber facility, particular attention must be given to lessening the environmental conditions to reduce the facility cost while still attaining the test objectives. Concern has been indicated that internally trapped air at sea level pressures may not be able to escape with sufficient rapidity from the thermal insulation and internal structure so that a pressure differential could develop, which could cause a failure of the insulation's thermal properties or catastrophic failure of structural components. Thus, a vital test requirement is to simulate the climb rate of the vehicle.

The pressure-time profile of the M-12 vehicle shows that approximately 50 percent of the time-to-maximum altitude is required to increase the altitude from 69 kft (21 km) to 146 kft (43 km), but the absolute pressure is only reduced from 35 mm to 1 mm of mercury, or 4.6 percent of sea level pressure. If the maximum altitude were reduced from 146 to 68 kft (43.9 to 21 km) and the time to attain maximum altitude remained the same (4 minutes), it would be possible to achieve 95 percent of the total pressure differential in the same time as is required for full pressure environment simulation. But note that the initial pressure does not decrease as rapidly which affects the discharge coefficients of trapped air spaces.

If it is determined in Phase III that the climb rate is not an essential environmental simulation parameter, the maximum altitude requirement could be retained but the pumping capacity of the facility could substantially be reduced such that the acquisition cost of the facility is appropriately reduced. Figure 6-98 represents pumping requirements as a function of altitude, pump down time, and chamber volume. Once all test objectives are determined for a particular vehicle, the facility can be satisfactorily specified to verify the design of the vehicle operating in a realistic pressure environment.

A study was conducted to determine the most desirable method of evacuating the altitude chamber. It was concluded that for large chamber volumes, high mass flow requirements, large anticipated chamber leak rates, substantial specimen leakage and outgassing rates, and for absolute pressures not less than 1 mm Hg (.013 N/cm^2), three-stage steam ejectors were the most practical method for evacuating the chamber. Mechanical pumping methods are more expensive and cannot handle the large mass flow rates required for a reasonable climb rate.

Chemical steam generators and boilers are two possible methods for generating sufficient steam for the steam ejectors. Boilers require a very large investment to provide the quantities of steam required for large ejectors. The boilers will have to be fired up for each run requiring long start-up times. Chemical steam generators, such as a LO_2 - alcohol system, provide instantaneous steam in large quantities with substantially less acquisition cost. Due to the large quantities of alcohol and LO_2 consumed in the chemical steam generator, very high operating costs are incurred (see section 6.1.13 for LO_2 - Alcohol operation costs). Thus, if large chambers must be evacuated in a short time and maintained at altitude for a long time, the near optimum system would be a chemical steam generator to provide high mass flow rates while the chamber is being rapidly evacuated, and then switched to boiler-generated steam to maintain the steady state altitude conditions. The smaller boilers could also be used for other utility services within the test complex.

From the pumping rates shown in Figure 6-98, the steam generation requirements were determined. The acquisition cost of the altitude simulation facility using LO_2-alcohol steam ejectors was then determined as a function of steam mass-flow requirements as presented in Section 6.1.4. The acquisition cost includes the LO_2 - alcohol steam generator plant, 3-staged non-condensing steam ejectors, instrumentation, control station, and isolation gate valve systems. Cost relations showing how the altitude simulation facility cost varies with specimen size, climb to altitude, and maximum altitude are shown in Figure 6-99. The costs determined in this study did not include any steam boiler cost.

From the analysis of test article size (Section 6.5.2.1), it was concluded that no requirements exist for altitude simulation testing of full scale size test specimens. Unless extremely large major sections are required for test specimens, existing altitude chambers could be modified to achieve the time-to-climb requirements of the flight trajectory. For Phase III, currently existing facilities will be examined to determine which can be modified to be of use for hypersonic research.

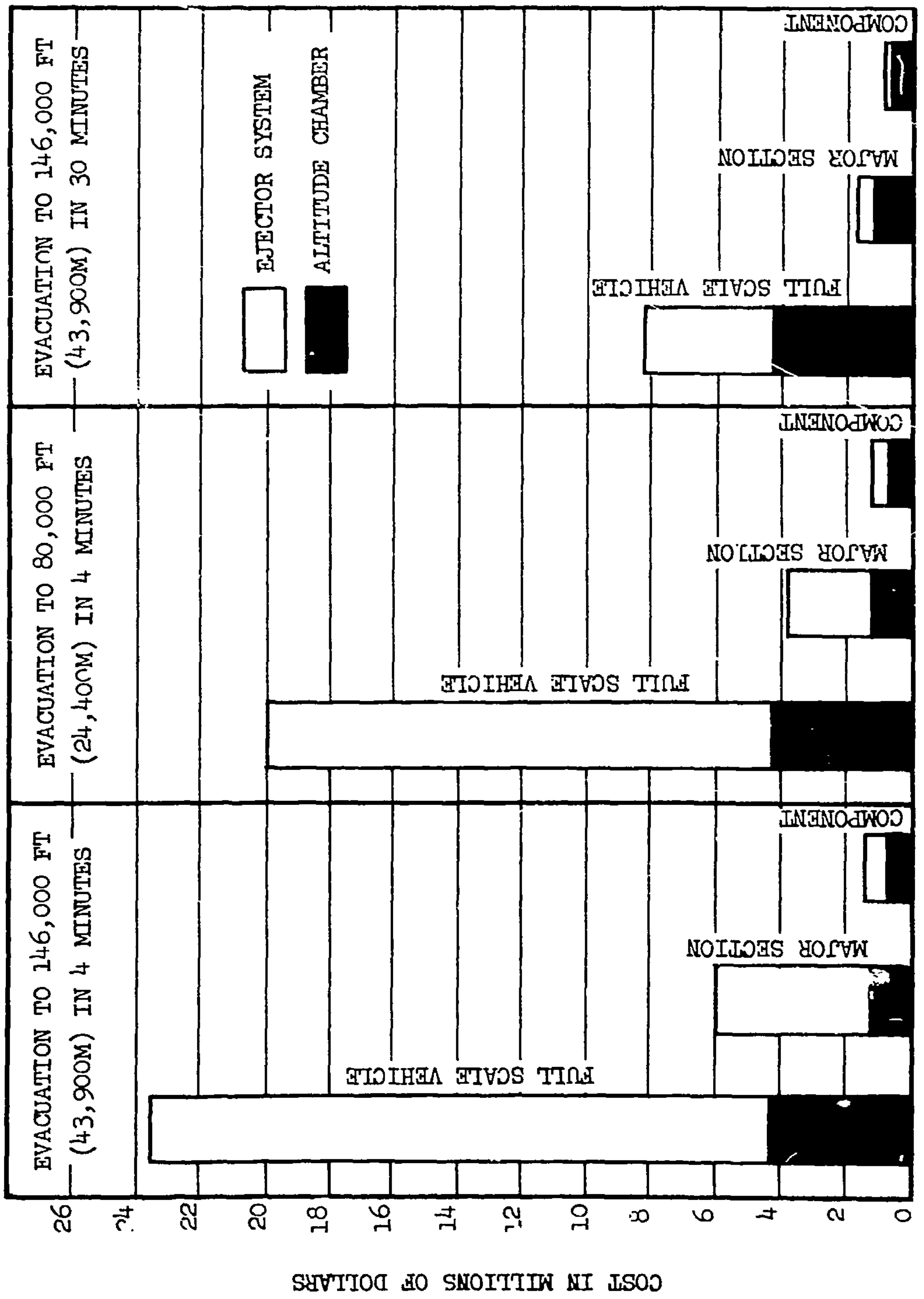
6.4.2.3 Thermal Environment Simulation Systems - The important factors to be considered when selecting a thermal environment simulation system include: rate of heating, maximum temperature, specimen size, and required heat flux.

Aerothermodynamic heating is usually simulated by heating the vehicle with infrared heaters. Other methods have been used and, under limited test conditions, may be preferred, but the response, controlability, flexibility, and high temperature capability of infrared heaters make them more desirable than any other heating method. For most test conditions, quartz infrared heat lamps with tungsten filaments are used as heating elements. The maximum reliable heat flux obtainable from quartz lamps is 150 B/ft^2 -sec (170 $watts/cm^2$). For heat fluxes that range from 150 to 480 B/ft^2 -sec (170 to 540 $watts/cm^2$), graphite heating elements must be used, and if flux levels above 480 B/ft^2 -sec are required, plasma or torch heaters must be used. Since no anticipated flux levels for the hypersonic vehicles exceed 480 B/ft^2 -sec (540 $watts/cm^2$), plasma and torch heaters were not included in this study.

The power required to simulate a representative, flight heating profile is dependent on the maximum temperature and the heating rate. A study was conducted to show the influence of specimen test temperature and heating rate on the power requirements (power is directly related to cost).

The total heat input required to heat the test specimen is the sum of the change of internal energy of the specimen, plus the losses due to convection and radiation as represented in the following equation:

FIGURE 6-99
ALTITUDE SIMULATION SYSTEM INVESTMENT COST



$$Q = C_p K \, (T/t) \, (W/A) + h_c F \, (Ts-Ta) + h_r F \, (Ts-Ta)$$

Internal Energy + Convection Loss + Radiation Loss

Where:
A = Area of specimen, in^2
C_p = Specific heat - Btu/lb°F
h_c = Convection heat transfer coefficient
h_r = Radiation heat transfer coefficient
Q = Total heat flux at specimen - kW/in^2
T_a = Temperature of surrounding medium, °R
T_s = Temperature of heated specimen, °R
t = Time, seconds
W = Weight of specimen, lb
E = Specimen emissivity of specimen surface

which reduces to:

$$Q = C_p K \; T/t \; W/A + 3.53 \times 10^{-7} \left\{ 2.2 \, (T_s - T_a)^{1.25} + E \left(\left(\frac{T_s}{100}\right)^4 - \left(\frac{T_a}{100}\right)^4 \right) \right\}$$

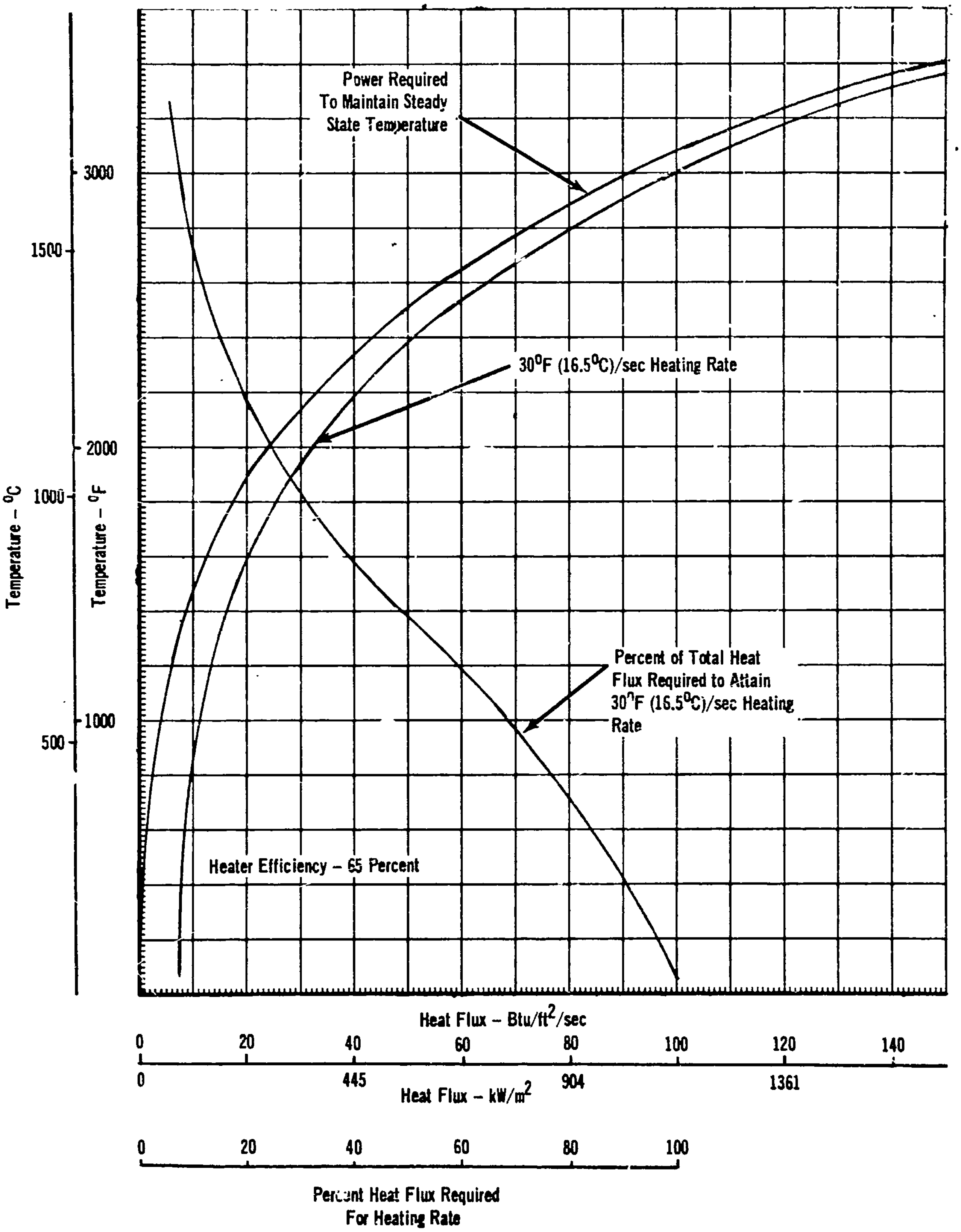
This equation has been verified by empirical test results at MCAIR Structures and Dynamics Laboratory where it has been shown to yield conservative theoretical heat flux levels when compared to measured heat flux levels.

Figure 6-100 presents a series of curves that were derived from this equation showing specimen temperature versus the heat flux required to maintain the test article at a steady state temperature, and specimen temperature versus the heat flux required to heat the specimen at 30°F/sec (16.7°C/sec). These curves, derived for a columbium radiation shingle 0.060 in. (1.5 mm) thick, would differ for other materials.

An analysis of Figure 6-100 shows that the heat flux required to increase the internal energy of the specimen at a given heating rate is constant with respect to temperature. The heat flux required to overcome the convection and radiation heat losses increases at an exponential rate as the temperature increases. Thus, if the specimen temperature is 1500°F (820°C), it requires 50 percent more power to heat the specimen at 30°F/sec (16.7°C/sec) than it does to maintain a steady state temperature of 1500°F (820°C). However, when the specimen temperature is 3000°F (1670°C), only 8 percent more power is required to heat the specimen at 30°F/sec (16.7°C/sec) than it does to maintain a steady state temperature of 3000°F (1670°C).

Thus, in selecting the optimum size heating system, where large areas of relatively low temperature structure must be heated, the maximum heating rate must be determined before the size of the heating system can be selected. On the other hand, if the test temperature is high, the maximum heating rate is not a critical parameter in selecting the heating system.

FIGURE 6-100
SPECIMEN TEMPERATURE vs HEAT FLUX



The cost of the heating system was determined by estimating the amount of power required to heat the full scale operational vehicle. The surface area of the vehicle was divided into 4 zones; Nose cap, leading edge, lower body surface, and upper body surface. Maximum temperatures were determined for each zone and the heating rate was assumed to be 30°F (16.7°C)/sec. The total power was then calculated and the number of control channels was determined. The results of this study are summarized in Figure 6-101. The costs of infrared heaters versus required heat flux levels are presented in Section 6.1.9. These heater costs were developed from known heater costs at MCAIR.

The immense power requirements, facility costs, and difficulty of testing dictate that full-scale testing of the entire vehicle is not feasible.

6.4.2.4 Dynamic Vibration Excitation Method - In order to accomplish the Structures and Materials Research Objectives, the dynamic vibration environment of the operational vehicle must be simulated. During flight, structural dynamic vibration is primarily induced by two methods: propulsion system and aerodynamic flow noise. The primary source of propulsion-induced noise is unsteady burning in the combustion chamber. The noise generated by the propulsion system is generally of low frequency and high intensity, and the primary excitation path is through the structure. Flow induced noise can result from boundary layer fluctuations in transitional or supersonic flight, or from pressure fluctuations due to wakes or shock waves on the exterior vehicle structure. Flow-induced noise is generally low intensity, but with a broad spectrum of pressure fluctuation frequencies.

Dynamic testing of vehicles and their components is performed to determine the dynamic response and structural adequacy of the structure, and to verify component reliability when subjected to a dynamic vibration environment. Dynamic vibration testing is performed either by using electromechanical shakers that physically apply mechanical loads to the structure, or by fluctuating pressure levels induced by acoustic noise. In the past, most vibration testing was performed with electromechanical shakers and acoustic testing was used as a complementary testing method for small components. As the performance of new vehicles increased, the importance of acoustic testing increased until it is now considered that on hypersonic vehicles, major sections should be tested in an acoustic environment. The acoustic noise generation requirement may be for any dynamic testing situation, but it is specifically required to determine the effects of near field noise on minimum gauge structures, composite structures, and non-metallic structures. For applications requiring high overall dynamic loading at lower frequencies, electromechanical shakers are most likely to be the primary excitation method, but for higher frequencies and lower dynamic loading levels, acoustic excitation would be preferred.

A study was conducted to evaluate electromechanical and acoustic excitation methods. In order to induce vibration modes by electromechanical shakers, the shaker must be mechanically attached to the vehicle's structure. On large structures and at high "g" levels, large mechanical loads must be applied to the structure. Exciting a structure using a large number of shakers does not satisfactorily simulate the actual excitation method and the shakers are difficult to synchronize. Thus, fewer large shakers are preferred over a greater number of smaller shakers, but higher loads must be transmitted to the structure by the larger shakers. Herein lies the problem, with large vehicles where the vehicle mass approaches or exceeds 100,000 pounds (45,360 Kg) and the "g" level is 3, excitation loads of over

FIGURE 6-101
HEATER REQUIREMENTS FOR FULL SCALE VEHICLE

TYPE OF STRUCTURL	ASSUMED PERCENT OF SURFACE AREA	AREA		TEMPERATURE		FLUX *		TOTAL POWER	CONTROL ZONE SIZE		NUMBER OF CONTROL ZONES**
UNITS	%	ft^2	(m^2)	°F	(°C)	Btu/ft^2-sec	(kW/m^2)	kW	ft^2	(m^2)	-
Nose Cap	3	1,200	(111)	3500	(1950)	170	(1930)	2.2×10^5	2.5	(.23)	460
Leading Edge	17	7,000	(650)	3000	(1780)	97	(1100)	7.2×10^5	4.5	(.42)	1500
Lower Body and Control Surfaces	40	16,400	(1520)	2000	(1110)	31	(352)	5.1×10^5	18	(1.67)	1060
Upper Body	40	16,500	(1630)	1600	(880)	20	(227)	3.8×10^5	35	(3.24)	790
TOTAL		41,000	(3801)					1.8×10^6			3810

* Flux based on 65% heater efficiency and 30°F (16.7°C)/sec heating rate

** 430 kVA/channel

300,000 pounds (1,340,000 N) must be applied to the structure. If 3 shakers are used to excite the structure, individual shaker loads of 100,000 pounds (444,000 N) must be applied to structural hardpoints that were not designed to accommodate such loads. In addition, no large (100,000 pound) (444,000 N) electromechanical shakers are currently being made, and the size of the inertia block to which the shaker is mounted becomes prohibitively large.

Acoustic noise may be generated for acoustic testing by electropneumatic transducers, sirens, electromagnetic poppet valves, air jets, and electromagnetic load speakers. These acoustic generators may be incorporated in the test setup to best achieve the desired acoustic environment. Three principal methods are used in acoustic testing: reverberating room, progressive wave shroud, and direct impingement. The reverberating room technique entails positioning the vehicle in a room and subjecting it to a diffused sound field that provides multiband excitation over a broad bandwidth. In progressive wave testing, the test article is surrounded with a shroud that contains a series of plane wave tubes that run parallel to the vehicle axis. A separate acoustic generator powers each plane wave tube. The direct impingement method utilizes an array of acoustic generators in proximity to the specimen, to simulate increased sound pressure levels (SPL) and varied spectral content.

The plane wave tube method is particularly desirable where the specimen is cylindrical or conical. The uneven shape of a blended body or all body shape presents difficult problems to adapt a satisfactory tube to that shape. The reverbrating room method requires a large room to accommodate the irregular shape of the vehicle, creating a large wasted space in which the sound intensity must nevertheless be generated. The direct impingement method cannot accurately simulate sound pressure levels over the entire vehicle. Thus, all three methods have inherent drawbacks that prohibit full-scale vehicle testing, but component testing is quite feasible.

This study indicates that both the electromechanical and acoustic excitation methods are desirable. The choice depends on specimen size, excitation frequency spectrum, load levels, and test objectives.

The cost of the acoustic simulation system is dependent on the acoustic intensity required to simulate the desired SPL and cross-sectional area in which that intensity must be generated. The total cost of the acoustic simulation facility was based on a large acoustic plane wave tube and an average SPL of 170 db. The costs of the acoustic facility for other test article sizes are related to the surface area of the specimens.

6.4.2.5 Thermal-Acoustic - The flight profiles of the hypersonic vehicles indicate that the structure will be simultaneously subjected to aerothermodynamic heating (either transient or steady state) and flow induced acoustic noise. Typical tests performed in this environment might include sonic fatigue and verification of the integrity of thermal protection systems. The simulation of the thermal environment cannot be provided for by increasing the sonic loading on an unheated test specimen because changes in physical properties can affect the dynamic response characteristics of the structure in a way that cannot be predicted or accounted for.

A review of past acoustic-thermal tests concluded that the best method of applying the thermal environment was with infrared heaters, and the best method of applying the acoustic environment was with a plane wave shroud. The acoustic shroud will act both as a reflector for the heaters and as a plane wave tube for acoustic purposes. Methods utilizing convection heating are not considered feasible because the airflow is determinative of heating rates and acoustic levels such that it would be impossible to control both.

Increasing the specimen temperature adversely affects the acoustic power required to simulate a desired sound pressure level (SPL). This requires increasing the number of acoustic generators. The elevated specimen temperature tends to increase the air temperature which decreases the density of the air. The SPL is defined by the equation

$$SPL = 20 \log_{10} \frac{P}{Pref}$$

where $Pref = 2.9 \times 10^{-9}$ psi $(2.0 \times 10^{-5}\ N/m^2)$

and SPL is expressed as decibels (dB). The acoustic power intensity required to induce a desired SPL is given by the following expression:

$$Intensity = \frac{P^2}{\rho C}$$

where P = Pressure N/m^2

ρ = gas density at specimen surface kg/m^3

C = speed of sound in medium - m/sec

From these two relationships, an expression was developed that compares the acoustic intensity required to produce various SPL's and the air temperature at the specimen surface.

$$Intensity = \frac{P^2 \quad T^{1/2}}{7 \times 10^3}$$

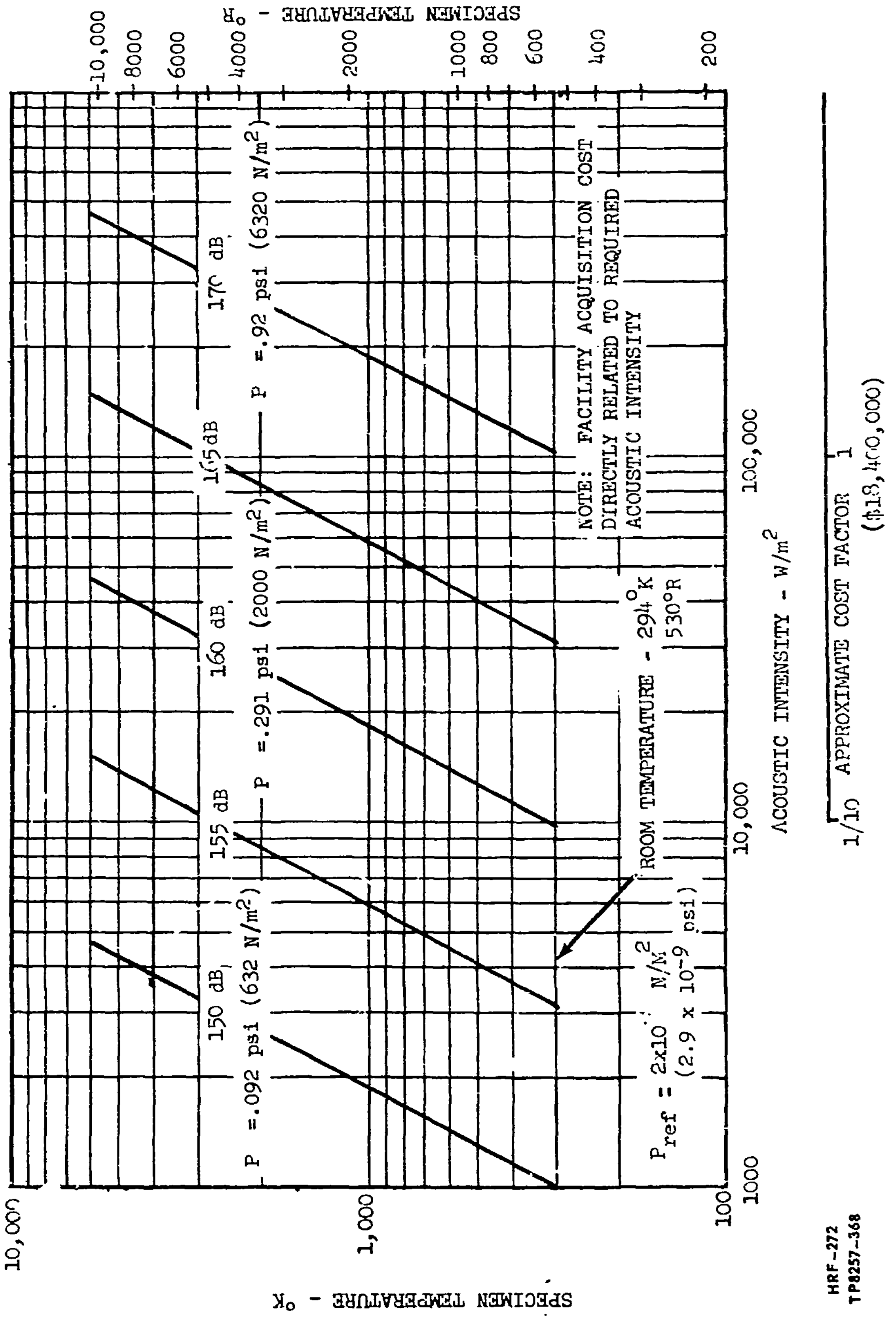
where P = pressure in mm H_g

T = temperature °K

It was assumed that the gas constant and the ratio of specific heats remained constant. A set of curves was developed that compares the acoustic intensity required to produce various SPL and the air temperature at the specimen surface and is presented in Figure 6-102. A conservative assumption was made that the air temperature at the specimen would equal the specimen temperature. An analysis of Figure 6-102 shows that more than twice the acoustic power is required to induce a desired SPL on a specimen at 2000°F (1350°K) than is required to reproduce the same SPL at room temperature.

Certain problems exist in the ability to test large test articles in a thermal acoustic environment that may affect the feasibility of such testing. It may be found that the heaters will be inoperable in the acoustic environment due

FIGURE 6-102
SPECIMEN TEMPERATURE VS ACOUSTIC INTENSITY



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to failures caused by sonic fatigue. Instrumentation has not been developed to measure and monitor the various test parameters. In addition, a development program must be conducted to construct a high temperature acoustic shroud that also functions as a radiation reflector. In general, the state of the art is not now developed to the point to permit thermal-acoustic testing on large test specimens at high temperatures.

The cost requirements for thermal-acoustic testing were estimated by determining the total acoustic power required to simulate the desired thermal-acoustic environment. The acoustic power was supplied by whatever number of 30,000 acoustic watt generators was required to reproduce the desired SPL, and the cost of the acoustic shroud was estimated to be $400,000. The total cost of the thermal acoustic facility for a full scale test article that simulates a 170 db SPL at room temperature was estimated to be $18,400,000 which includes the acoustic generators, acoustic shroud, and a 1,000,000 scfm (28,300 m^3/min) compressed air supply. The thermal requirements are similar to that described in Section 6.4.2.2 and are not included separately in the cost of the thermal acoustic facility.

6.4.2.6 Mechanical Loading Systems - Loads acting on a typical vehicle may result from aerodynamic pressure loading, inertia loads, pressure differentials, and thrust reaction loads among other possible factors. The Structural Research Facility must have the capability to simulate these loading methods. Typical laboratory loading techniques that simulate the desired vehicle loads may include internal or external pressurization, loading systems that have mechanical attachments to the structure and the loads applied by hydraulic loading cylinders, and pressure bags. The hydraulic loading cylinder method has the widest application.

The major equipment in the hydraulic loading systems includes loading cylinders, hydraulic pumps, computer operated load programmer, servo control system, and load monitoring and recording instruments. The structural test facility must include load reaction fixtures and a load bearing floor to rigidly mount the specimen and the loading apparatus. Three techniques of hydraulic load application were compared in this tradeoff study. The loading concepts studied were: load-carrying building to which loads may be reacted, a special test frame surrounding the test article to which loads may be attached, and individual tension-compression load cylinders attached to a structural load bearing floor.

The most important factors in determining the cost of these loading techniques is the cost of the reaction structure, which is dependent on the weight of the structure and the number of loading channels required. The load-carrying building and test frame loading techniques are essentially the same except for the type of the reaction fixture. The load-carrying building gives the utmost in facility flexibility because the test can be performed at any location in the building, making the best use of available floor space with the minimum effort expended in the design and fabrication of special loading fixtures. The test frame approach requires that specialized test fixtures be designed to conduct particular tests. Because the test frame is designed to do a specific task, a minimum size test frame can be constructed using the smallest amount of material. The load-carrying building must be designed to support the most severe loading condition over its entire area with a substantial safety factor. Hence, the extra structure required for the load-carrying building may never be used in actual test operations. The weights of the structural elements of the load-carrying building and test frame were calculated using recognized estimating techniques. Costs were developed based on the weight of the structure so as to include material, fabrication, and erection costs. In all cases, a basic building shell was assumed and all facilities include a load-bearing floor. For the load-carrying building and the test frame, the same number of load channels were used.

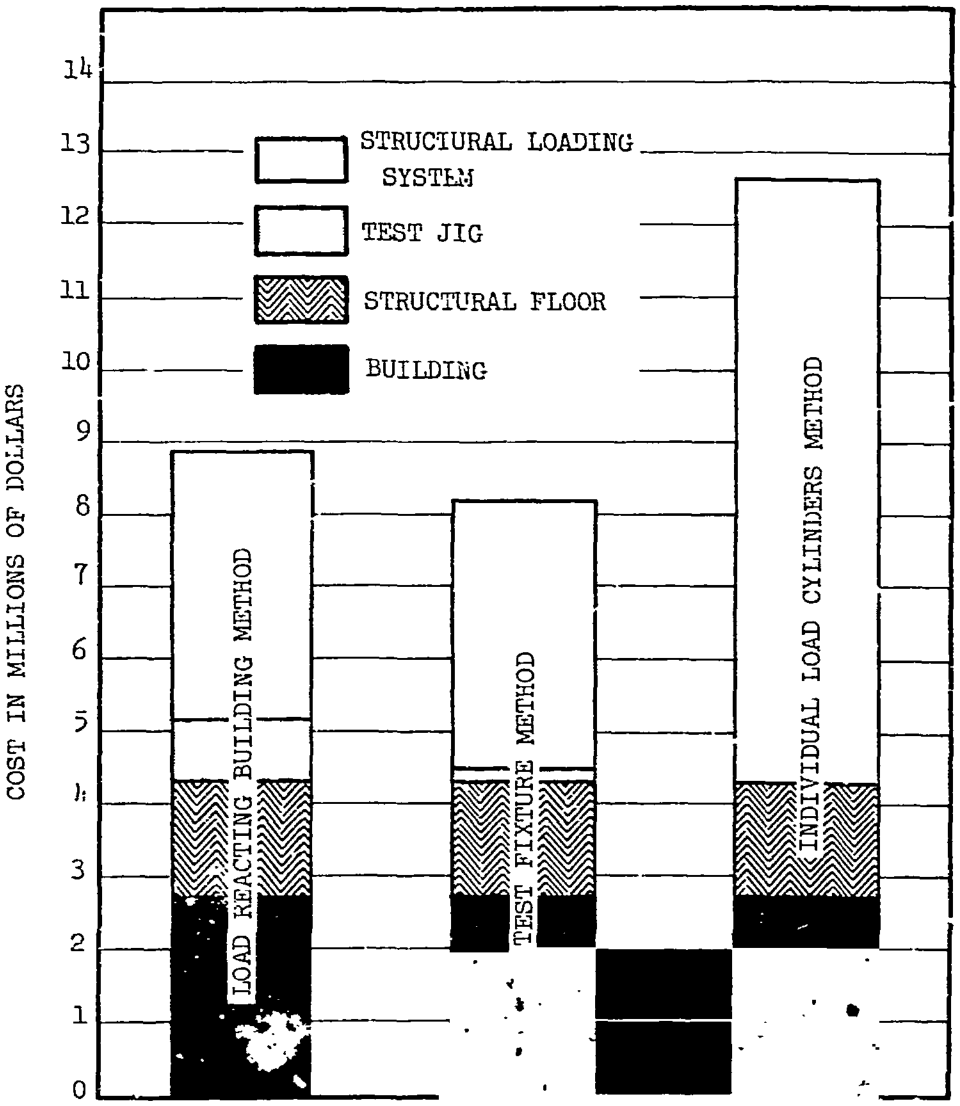
Recent tests of large commercial transports have revealed that the individual load cylinder technique more accurately simulates aerodynamic lift. In the past, lift was simulated by bonding tension pads to the top surface of the wing and pulling an upward acting load. This method was not satisfactory on larger aircraft because the load was not transferred to the structure in a manner similar to actual lift. The individual loading cylinder technique involves attaching loading points to the underside of the wing at structural hardpoints and applying upward acting individual loads to each point. The application of individually applied loads that are capable of being applied either in tension or compression eliminates the need for a large overhead test frame or a load-carrying building. If lateral loads or certain vertical loads cannot be applied by attaching the load cylinders to the floor, smaller test jigs will be necessary.

The individual load cylinder technique will increase the number of load channels that will be required. It was assumed that one individual cylinder will be required for each 9 ft^2 (.835 m^2) of plan area, where for the test frame or load-carrying building technique, one cylinder is required for each 32 ft^2 (2.98 m^2). Fewer load cylinders can be used for the test frame technique because many individual loading points can be combined into one load by utilizing mechanical whiffle trees. For the full-scale operational vehicle test article size, 500 channels are required for the load-carrying building and test frame methods compared to 1700 channels for the individual load cylinder techniques.

The costs for the load-carrying building, test frame, and individual loading cylinder are compared in Figure 1-103. In order to simulate flight loading conditions, loads will be required that simulate static loading levels, transient loading and unloading rates, and quasi-static load cycles. It was determined that all mechanical loads should be applied by fully automatic digital load programmers that control servo hydraulic load cylinders. The rate at which the specimen can be loaded is dependent on the deflection rate of the structure being tested, hydraulic pumping capacity, and the magnitude of the loads applied by each hydraulic loading cylinder. The precise rate at which the test article can be loaded cannot be determined until the structural characteristics are known, but based on past experience at MCAIR, loading rates up to 400,000 pounds (1,778,000 N)/second and load cycling of up to 5 Hz can be achieved, if the load magnitude is less than 20,000 pounds (90,000 N). Since these capabilities are included in the basic system chosen to apply only static load levels, there is no additional cost for the added capabilities of transient loading and load cycling.

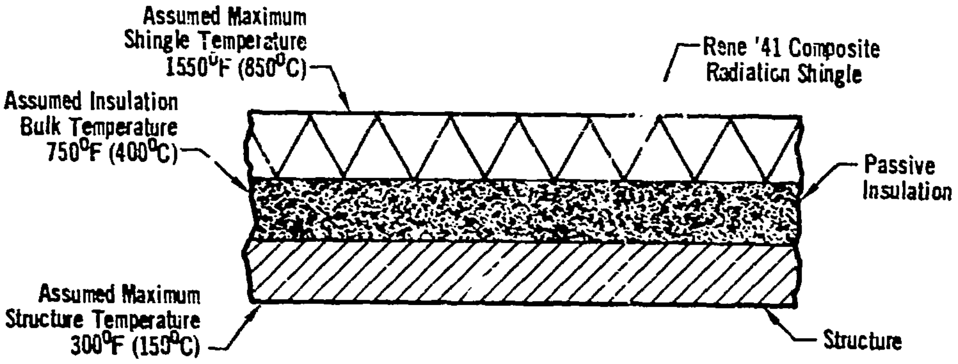
6.4.2.7 Refrigeration Requirements - In order to simulate the temperature-time profiles of the various hypersonic vehicles included in [illegible] study, it may be necessary to cool the structure at a rate in excess of the natural cooldown rate experienced in the test setup. The type and amount of cooling that will be required to simulate [illegible] profile of the airframe is dependent on the type of thermal pro[illegible] chosen for the vehicle. The thermal protection systems presently [illegible] may be either of the passive or active type. Generally,

FIGURE 6-103
DYNAMIC STRUCTURAL EVALUATION FACILITY LOADING METHOD COSTS FOR FULL SCALE VEHICLES



the passive system will consist of a high temperature radiation shingle separated from the major structural members by passive insulation, while the active system utilizes a similar radiation shingle which is separated from the main structural by an active water-wick thermal barrier. In both the active and passive systems, the high temperature radiation shingles were assumed to cool very rapidly to moderate temperatures (300 to 500°F or 145 to 260°C) and had a relatively low heat capacity due to their small mass. The major portion of the heat that must be removed is contained in the structure.

FIGURE 6-104
TYPICAL STRUCTURE IN NONFUEL AREA OF MACH 4.5 VEHICLE



Type of Structure	Heat Capacity Btu/Ft^2-°F	J/m^2-°C
Shingle	0.052	10,600
Insulation	0.176	35,900
Structure	0.529	108,000

If the active thermal protection system is used, the temperature of the structure will not exceed the boiling point of the fluid used in the active thermal barrier. Hence, it was assumed no refrigeration will be required for structures that incorporate an active thermal protection system and for test requirements that do not require reduced temperature environments. Because heat is transferred through the passive insulation, it may be possible to subject the primary structure to over-temperatures if the length of time which the passive system is subjected to elevated temperatures is sufficient. Due to the thermal lag characteristics of the passive system, the structure may not be subjected to over-temperatures until some time after the high speed portion of the flight has been completed. A study was conducted to determine the best technique of cooling the structure, the quantity of cooling fluid that must be supplied, and the feasibility of completing the cooling of the aircraft structure by external methods after landing. A typical structure for a Mach 4.5 vehicle with a passive thermal protection system was assumed. The structure and the assumed heat capacities of the structure are shown in Figure 6-104. The amount of heat that must be removed by the cooling system was determined by assuming that all the heat contained in the structure and 1/2 the heat in the insulation is removed by the cooling air. It was assumed that the total surface area of the full scale vehicle was 41,000 ft^2 (3810 m^2) and only the non-fuel areas of the structure, which were assumed to account for 70 percent of the surface area, or 28,700 ft^2 (2660 m^2), must be cooled. It was also assumed that the maximum permissible temperature of the primary structure was 300°F (150°C) and the bulk temperature of the insulation 750°F (400°C). Thus, the total heat that must be removed was found to be 5.2 x 10^6 Btu (5.49 x 10^9 J).

Assuming no heat is removed from the interior of the airframe by convection, it is estimated that from 8 to 10 hours will be required for the structure to cool to 70°F (22°C), as it is installed in the test setup with no forced cooling. To overcome the insulating characteristics of the passive insulation that prevents a more rapid cooldown, a large temperature difference between the structure and the cooling air is required. The lowest practical temperature to which large quantities of cooling air can be chilled by refrigeration is approximately -65°F (-54°C), thus limiting the maximum temperature difference to 365°F (187°C). Because a large temperature difference cannot be obtained, only a low heat transfer rate through the passive insulation is possible. Thus, it is not feasible to cool the structure by passing cooling air over the exterior surface of the vehicle.

An alternative cooling technique is to build a special manifold system on the interior of the structure and blow cooling air directly on the heated structure. Assuming that all the cooling was achieved by convection, the cooling rate is dependent on the film heat transfer coefficient and the temperature difference. The heat transfer coefficient is proportional to the velocity of the cooling air passing over the structure, and it was assumed that the maximum obtainable heat transfer coefficient was 10 Btu/hr ft^2 °F (20.3 x 10^5 J/hr m^2 °C) due to cooling air velocity limitations. If 70°F (22°C) air is used as the cooling fluid and the heat transfer coefficient is 10 Btu/hr ft^2 °F (20.3 x 10^5 J/hr m^2 °C), the total heat transfer rate (q) is 3.8 x 10^7 Btu/hr (4.0 x 10^{10} J/hr). This shows that if cooling air can be directly impinged on the structure, the primary structure can be cooled from 300°F (150°C) to 70°F (22°C) in less than 10 minutes. If access is not available to the backside of the structure, ground cooling is of little benefit regardless of the type and amount of the cooling system.

The cooling requirements cost estimates were based on the preceding analysis and the assumption that no reduced temperature tests are required. The only cooling that is required is to duct ambient temperature air over the inside surface of the structure through a special manifold. It is estimated that 1,000,000 scfm (283,168 m^3/min) of compressed air are required to cool a full scale operational vehicle. This air capacity is included in facility's utilities for acoustic testing and is estimated to cost $13,500,000.

It may be found that a ground cooling unit will be necessary to enable an operational vehicle to have a rapid turnaround time. If such a unit is available, it could be used in the Structural Research Facility to cool the test articles.

6.4.3 STRUCTURAL RESEARCH FACILITY (S2) - In Phase I of this study, nine structural research facilities were examined to determine their value in performing research leading to the development of an operational hypersonic vehicle. For Phase II, only the S2 Structural Research Facility was retained for further study. The S2 Facility includes the capability to perform all types of structural testing conditions and environments on any of the proposed operational vehicles.

6.4.3.1 Facility Specifications - The building in which the facility is contained is a minimum cost building, which will incorporate three primary sections: offices, low bay, and high bay areas. The low bay areas will provide space for equipment storage, test control rooms, fabrication shops, instrumentation, and small article testing. The high bay areas will incorporate a load reacting structural floor such that bearing loads of 70,000 psf (348,000 kg/m^2) and shear and tension loads of 100 kips (45,360 kg) on 4 foot (1.2 m) centers may be reacted. Overhead crane services over all structural test and fabrication areas of at least 10 ton (9072 kg) capacity should be provided. The size of the structural test building is directly influenced by the size of the test articles. A generalized schematic of the S2 facility is shown in Figure 6-105. The parametric studies in Section 6.4.2 indicated that test articles representing major structural sections of full scale hypersonic aircraft were, in general, large enough to obtain test data uncompromised by unknown end effects or interactions and yet small enough to achieve considerable acquisition and cost savings compared to a facility sized for a complete vehicle. Accordingly, the baseline definition for S2 has been chosen as a facility with the capability to test a major section of an operational hypersonic aircraft.

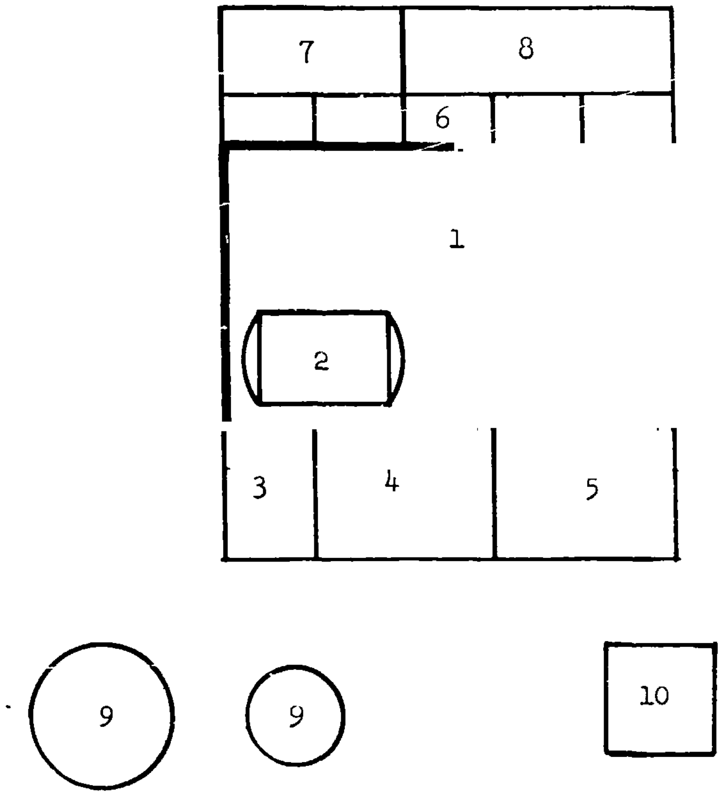
In order that the capabilities and costs of such a facility may be compared on the basis of test article size, two alternate facility definitions have been made. Alternate 1 is a facility sized for a complete full scale vehicle and Alternate 2 is sized for aircraft component testing. Figure 6-106 characterizes the test specimens used in the three facility definitions and Figure 6-107 summarizes the sizes and capacities of the various systems provided in the three facilities.

6.4.3.2 Facility Component and Cost Summary - Figure 6-108a shows a cost breakdown of the baseline and alternate facilities. Cost estimates of individual components or systems were made according to the guidelines given in Section 6.1. A visual display of the relative proportion of the cost of each facility element is shown in Figure 6-108b. The area of the "pie" charts is proportional to the total facility acquisition cost. Thermal simulation accounts for a major share of each facility cost, so that any possible reduction of the heating requirements would have a major impact on total facility costs. A breakdown of the facility operating costs per total available occupancy hour is shown in Figure 6-108c. These costs were estimated according to the operating model given in Section 6.1.13. It should be remembered that the cost of a given test must be determined according to the specific equipment and utilities used, whereas the figures given represent the annual cost of operating all the facility systems, divided by 2000 available occupancy hours.

6.4.3.3 Facility Development Assessment - The S2 facility is primarily composed of existing, off-the-shelf equipment. Except for thermal-acoustic testing at high temperatures, the technology required to structurally test a hypersonic vehicle is now in existence. The feasibility and operation of such large test setups creates doubts as to the practicality of such tests. Past structural tests have shown that as the complexity and size of the test increase, operational problems tend to drastically increase. Tests of this magnitude will require a major engineering and management effort to assure success. In general, the facility has a confidence level of 4 because of the large size and capability of the test equipment and the need for combined environmental simulations.

6.4.4 FACILITY EVALUATION AND CONCLUSIONS - Existing structural test facilities were evaluated to determine their ability to accomplish the research indicated in the applicable research objectives. It was found that the existing structural test facilities could accomplish 38 percent of the required research. The S2 facility was then evaluated in conjunction with the existing facilities, and the total research value was found to be 42, 51, and 55 percent when the S2 facility was sized for component, major section, and full-scale sized test articles, respectively.

FIGURE 6-105
S2 STRUCTURAL RESEARCH FACILITY SCHEMATIC LAYOUT



1 STRUCTURAL TEST AREA
2 ALTITUDE CHAMBER
3 LO_2 - ALCOHOL STEAM GENERATOR AND EJECTOR
4 EQUIPMENT ROOM
5 THERMAL POWER CONTROLS
6 CONTROL ROOMS
7 OFFICES
8 DATA ACQUISITION AND REDUCTION
9 LO_2 AND ALCOHOL STORAGE
10 ELECTRICAL SUBSTATION

FIGURE 6-106
TEST ARTICLE DESCRIPTIONS - STRUCTURAL TEST FACILITY

Parameter	Units		Coupon		Component		Major Section		Full-Scale Vehicle	
Length	ft	m	2	.6	20	6.1	100	30.5	325	98.5
Width	ft	m	2	.6	20	6.1	70	21.3	125	38
Height	ft	m	2	.5	20	6.1	30	9.1	90	27.5
Volume	ft^3	m^3	8	.16	6000	198	45,000	2830	150,000	4950
Plan Area	ft^2	m^2	2	.2	400	36	7000	465	16,000	1487
Surface Area	ft^2	m^2	8	.8	2500	332	15,000	1392	41,000	3810
Weight	lb	kg	100	45	40,000	18,100	566,000	22,600	1,025,000	465,000
Max. Avg. Test Surface Load	lb/ft^2	N/m^2	2500	1,193,000	2500	1,193,000	2500	1,193,000	2500	1,193,000
Max. Altitude	ft	m	150,000	45,800	150,000	45,800	150,000	45,800	150,000	45,800
Max Nose Cap Temp.	°F	°C	3500	1930	3500	1930	3500	1930	3500	1930
Max. Leading Edge Temp.	°F	°C	3000	1670	3000	1670	3000	1670	3000	1670
Avg. Lower Body Temp.	°F	°C	2600	1440	2600	1440	2600	1440	2600	1440
Avg. Upper Body Temp.	°F	°C	1600	880	1600	880	1600	880	1600	880
					Chosen to Define The Alternate 2 Facility		Chosen to Define The baseline Facility		Chosen to Define The Alternate 1 Facility	

FIGURE 6-107
DESCRIPTION OF EQUIPMENT AND CAPABILITY

SIMULATION	UNITS	COMPONENT	MAJOR STRUCTURAL COMPONENT	FULL SCALE OPERATIONS VEHICLE
THERMAL SYSTEM				
Max. Heat Flux 50 ft^2 (4.65 m^2)	B/ft^2-sec (KW/m^2)	500 (5680)	500 (5680)	500 (5680)
Avg. Heat Flux	B/ft^2-sec (KW/m^2)	40 (372)	40 (372)	40 (372)
Total Available Power	MW	100	430	1700
Number of Control Channels		200	1000	3810
Heating Rates Obtainable	°F/sec (°C/sec)	0 to 30 (0 to 16.7)	0 to 30 (0 to 16.7)	0 to 30 (0 to 16.7)
ALTITUDE				
Altitude Chamber Volume	ft^3 (m^3)	1×10^5 (2.83×10^3)	5×10^5 (14.15×10^3)	5.25×10^6 (14.85×10^4)
ACOUSTIC				
Acoustic Sound Pressure Level	db	170	170	170
Total Acoustic Power	acoustic watts	2.5×10^6	4.8×10^6	1.75×10^7
Acoustic Frequency	Hz	15-10,000	15-10,000	15-10,000
Number of Acoustic Generators		90	160	600
MECHANICAL LOADS				
Number of Mechanical Load Channels		40	200	1000
Max. Load/Channel	lb (n)	50,000 (222,000)	50,000 (222,000)	50,000 (222,000)
Max. Loading Rate	lb/sec (n/sec)	400,000 (1,778,000)	400,000 (1,778,000)	400,000 (1,778,000)
Cycling Rate	Hz	0 to 5	0 to 5	0 to 5
MECHANICAL VIBRATION				
Number of Mechanical Shakers - 30,000 lb (133,100 N)		5	20	40
Frequency Range	Hz	30-3000	30-3000	30-3000
FUEL FLOW				
Cryogenic Fuel Tankage & Control System	ft^3 (m^3)	10,000 (283)	50,000 (1410)	100,000 (2830)
Cryogenic Pumping	gpm (m^3/min)	60,000 (264)	60,000 (264)	60,000 (264)
		Alt. 2 Facility Capability	Baseline Facility Capability	Alt. 1 Facility Capability

FIGURE 6 -108a
S2 FACILITY COMPONENT AND COST SUMMARY

Facility Component		Cost Estimate ($Thousands)		
Acquisition Costs		Baseline Major Section	Alt 1 Full Scale	Alt 2 Component
1. BUILDING COMPLEX (Lab/Office/Control Room/Fabrication Shops)	Total	5,347	5,347	5,347
2. TEST EQUIPMENT	Total	98,587	206,896	29,784
2.1 Altitude Simulation System	Sub Total	7,030	23,602	1,520
Chamber (Incorporates Structural Floor)		1,280	4,302	820
Steam Ejector System		6.601	19,300	700
2.2 Thermal Simulation System	Sub Total	48,280	103,254	12,456
Heaters (Infrared - Quartz and Graphite)		22,650	49,724	5,690
Controllers and Ignitrons		8,830	19,050	2,320
Electrical Substation		16,800	34,480	4,446
2.3 Electromechanical Vibration Exciters	Sub Total	9,180	21,000	2,620
2.4 Mechanical Loading System	Sub Total	2,187	4,595	560
Hydraulic Pumps, 6000 psi (4140N/cm^2)		356	750	91
Load Programmers		715	1,500	183
Load Cylinders		211	444	53
Load Transducers		476	1,000	122
Test Fixtures		429	901	111
2.5 Acoustic Simulation System	Sub Total	9,100	18,400	2,295
Acoustic Generators		2,020	4,500	562
Acoustic Shroud (Plane Wave Tube)		180	400	43
Air Supply - 1,000,000 scfm (28,300m^3/min) (for Alt. 1)		6,900	13,500	1,690

FIGURE 6-108a (Continued)
S2 FACILITY COMPONENT AND COST SUMMARY

2.6 Instrumentation (Data Acquisition System, Transducers, Data Reduction)	Sub Total	11,995	21,150	2,626
2.7 General Purpose Lab Equipment	Sub Total	1,610	1,610	1,610
2.8 Fabrication Equipment	Sub Total	1,605	1,605	1,605
2.9 Cryogenic Fuel Flow (Storage and Pumping)	Sub Total	7,600	11,680	4,492
3. SERVICES AND UTILITIES (Includes Water, Air, Power)	Sub Total	800	800	800
	Sum Total	104,734	213,043	35,931
	10% Contingency	10,473	21,304	3,593
	Facility Cost	115,207	234,347	39,439
	6% A&E Fee	6,900	14,010	2,360
	4% Management Fee	4,600	9,280	1,570
	Grand Total	126,707	257,637	43,369

It was recognized that the research value of the S2 facility could be enhanced if elements of other facilities that were not retained for further study in Phase II could be added to the S2 facility. A new facility (S20) was evaluated that contained the capabilities of the baseline S2 facility plus two test cells for thermal fatigue and acoustic fatigue testing and an acceleration track for conducting fuel tank slosh tests. The S20 facility was found to be capable of accomplishing 54 percent of the required research.

It was noted that the E9 Scramjet Test Facility had the capability of testing component sized structural test specimens under full-flight flow conditions. Thus, the structure could be subjected to actual aerothermodynamic heating and aerodynamic loading. In order to perform structural testing in the E9 facility, a special aerodynamic nozzle must be used that was estimated to cost an additional $1.1 million. The research value for the combined capabilities of existing facilities, S2, S20 and E9 were determined and are shown in Figure 6-109. Facility acquisition costs are also shown in Figure 6-109.

The research values for all the facilities were analyzed and a plot of research value versus test article size was obtained that shows the effect of increasing test article size on research value. This curve is presented in Figure 6-110. Research values were then plotted against facility acquisition cost to show the cost effectiveness of the various facilities. These curves are shown in Figure 6-111.

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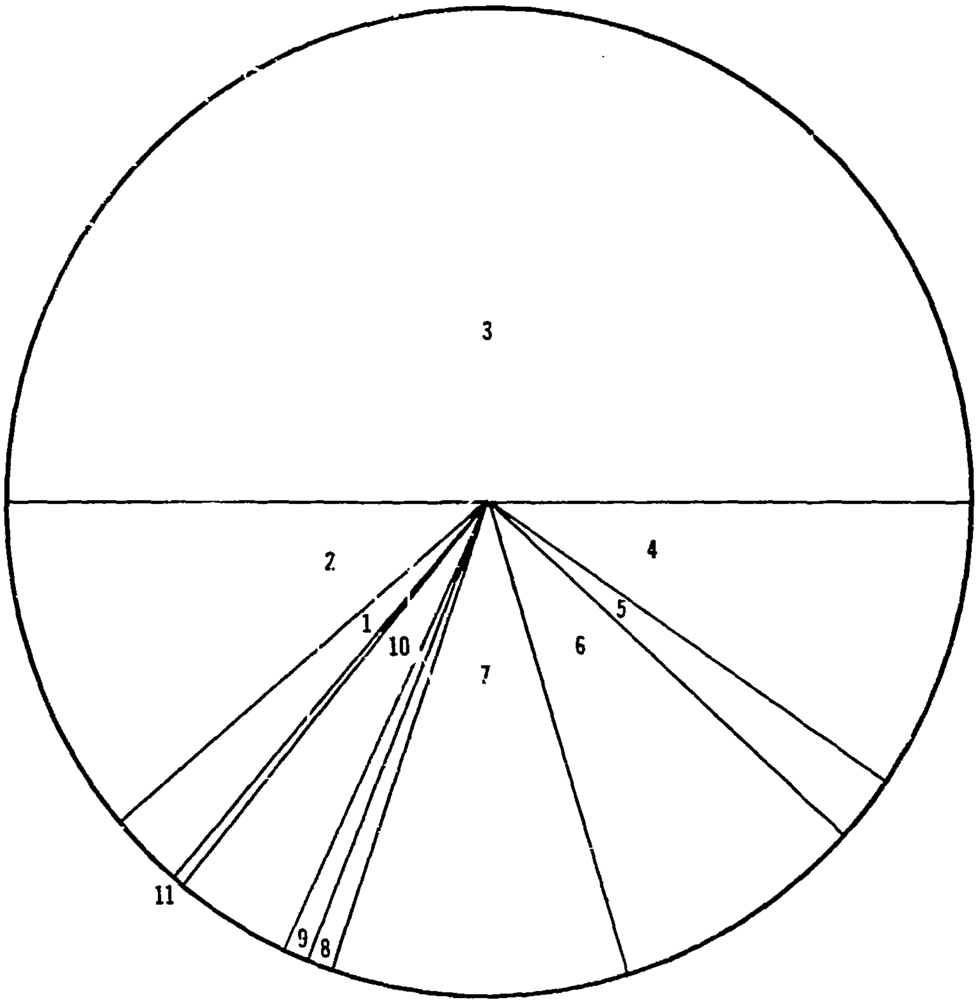
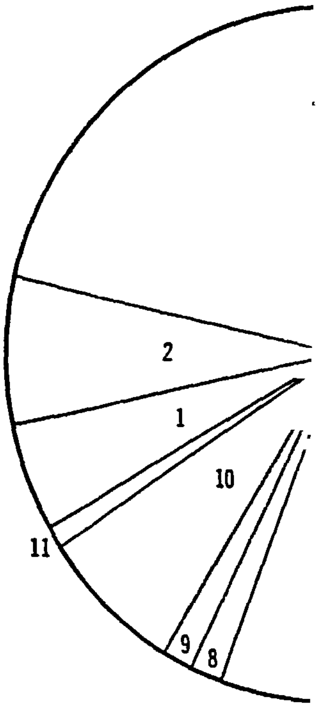
FIGURE 6-108b
DISTRIBUTION OF FACILITY COMPONENT COSTS - S2



Alternate 1



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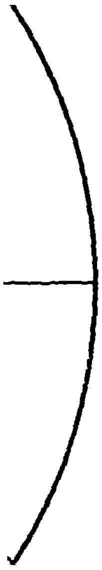
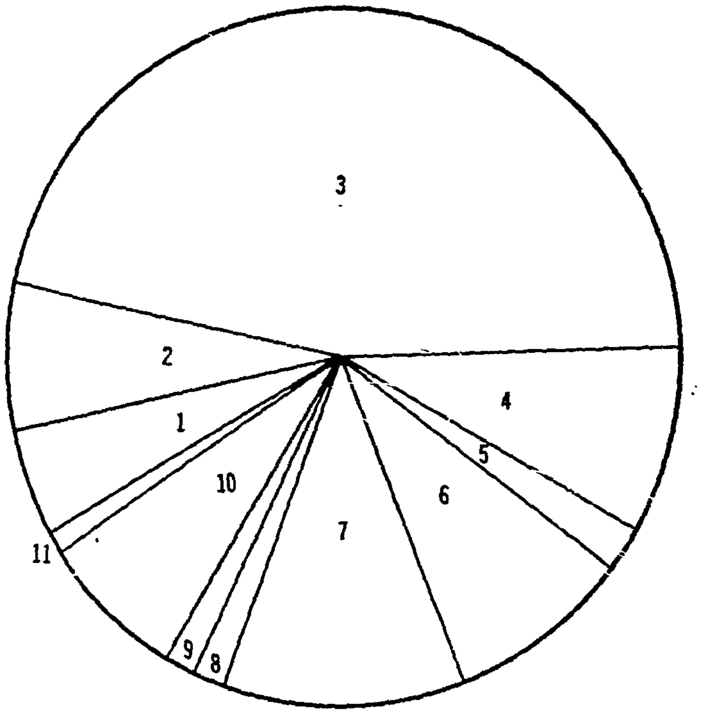
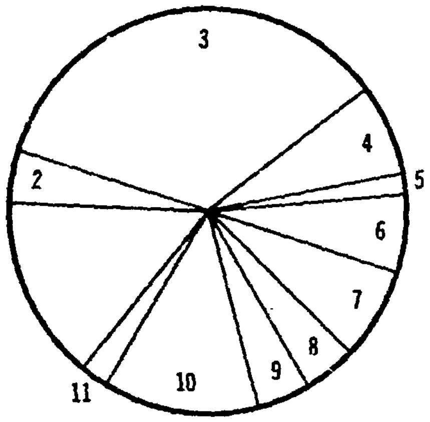
FOLDOUT FRAME 2





Baseline



Alternate 2

Key

1 Building Complex

2 Altitude Simulation System

3 Thermal Simulation System

4 Electromechanical Vibration Exciters

5 Mechanical Loading System

6 Acoustic Simulation System

7 Instrumentation

8 General Purpose Laboratory Equipment

9 Fabrication Equipment

10 Cryogenic Storage and Pumping

11 Services and Utilities

FIGURE 6-108c
S2 FACILITY OPERATING COST SUMMARY

Operating Costs - Dollars Per Occupancy Hour	Baseline Major Section	Alt 1 Full Scale	Alt 2 Component
Building Maintenance	117	117	117
Test Equipment Maintenance and Operation	4,687	10,224	1,254
Service and Utilities Operation	2,718	4,069	640
Power and Steam	4,456	20,880	1,330
Total	11,978	35,290	3,341

A combined structural research facility, consisting of the S20 facility supplemented by the E9 engine test facility with the structural test nozzle, was shown to yield the highest research value at the lowest cost for a facility of sufficient capability to adequately verify the structure of a hypersonic operational vehicle. It is estimated that a major portion of the applicable Structures Research Objectives can be accomplished in these facilities for an acquisition cost of 130.3 million dollars.

6.4.5 COMBINED STRUCTURAL RESEARCH FACILITY (S20) - The S20 facility (Figure 6-112) consists of a main building that has the same equipment and capability contained in the baseline S2 facility for major section test articles. Component test article sized test areas have been added so thermal fatigue and acoustic fatigue research can also be performed. A fuel tank slosh acceleration track has also been provided.

6.4.5.1 Facility Specifications - The specifications of the S20 facility are presented in Figure 6-113.

6.4.5.2 Facility Component and Cost Summary - A breakdown of the component costs of S20 and their totals are shown in Figure 6-114a. A breakdown of the facility operating costs is shown in Figure 6-114b, and, as for S2, represents the total cost of operating all the equipment per available occupancy hour. The costs, both acquisition and operating, of the supplemental testing capability represented by the E9 engine test facility, are listed in Section 6.3.9.2.

FIGURE 6-109
FACILITY EVALUATION
(Structural)

FACILITY	AVERAGE RESEARCH VALUE (Percent)		ACQUISITION COSTS (MILLIONS OF DOLLARS)
		See Note 1.	
S2 Alternate 2 Component of full scale aircraft	42	(66)	43.4
S2 Baseline Major section of full scale aircraft	51	(73)	120.7
S2 Alternate 1 Complete full scale aircraft	55	(77)	257.6
S20 Major section of full scale aircraft, plus component fatigue, acoustic capability fuel tank acceleration track	54	(76)	129.2

Structural/Material
Research Objectives

NOTES:

1. Indicates research value with structural test nozzle added to E9 so component-sized structural test articles may be tested under full-flight temperature and airloads.

2. Additional cost of E9 nozzle for structural testing is $1,100,000.

FIGURE 6-110
FACILITY RESEARCH VALUE vs FACILITY SIZE FOR THE STRUCTURAL RESEARCH FACILITY

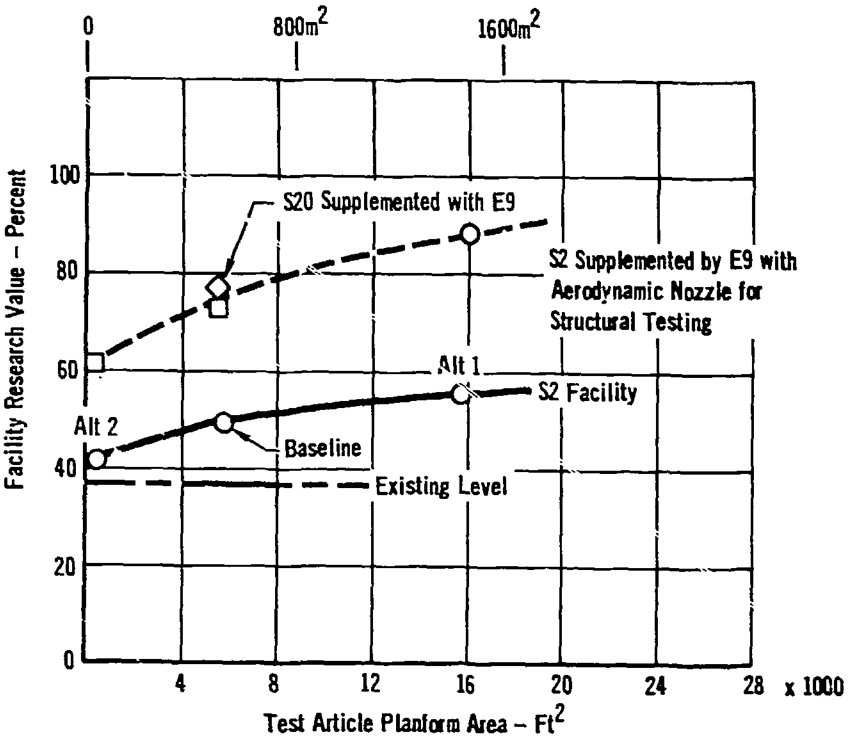


FIGURE 6-111
EVALUATION OF THE RESEARCH CAPABILITY OF THE STRUCTURAL RESEARCH FACILITY AS A FUNCTION OF TEST ARTICLE SIZE AND ACQUISITION COST

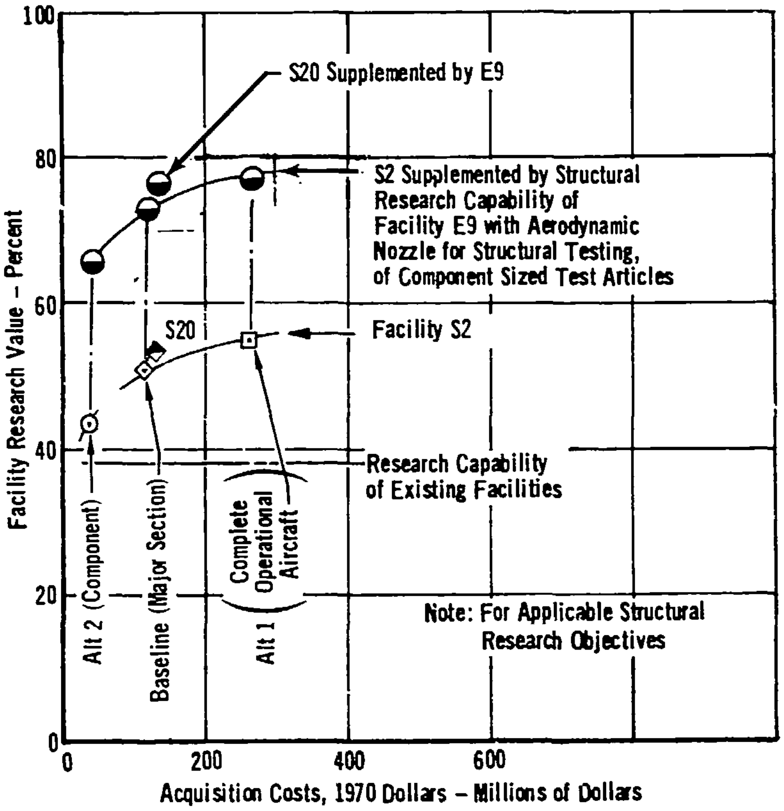
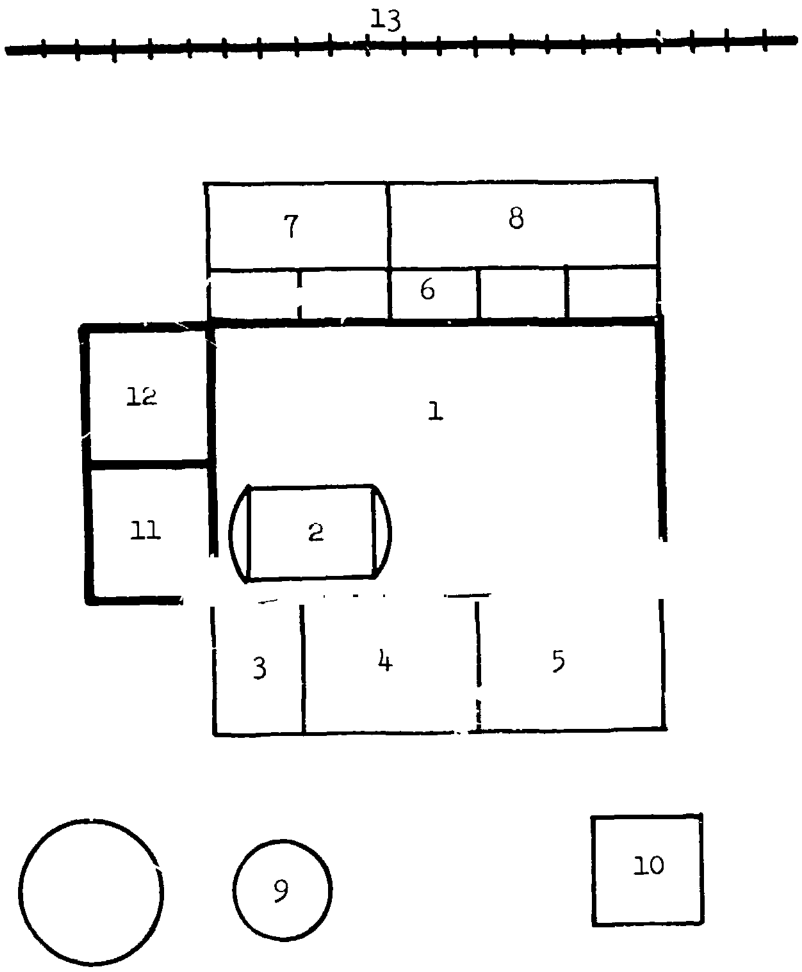


FIGURE 6-112
S20 STRUCTURAL RESEARCH FACILITY SCHEMATIC LAYOUT



1 STRUCTURAL TEST AREA
2 ALTITUDE CHAMBER
3 LO_2 - ALCOHOL STEAM GENERATOR AND EJECTOR
4 EQUIPMENT ROOM
5 THERMAL CONTROL
6 CONTROL ROOMS
7 OFFICES
8 DATA ACQUISITION AND REDUCTION
9 LO_2 AND ALCOHOL STORAGE
10 ELECTRICAL SUBSTATION
11 THERMAL FATIGUE TEST CELL
12 ACOUSTIC FATIGUE TEST CELL
13 FUEL TANK SLOSH ACCELERATION TRACK

FIGURE 6-113
SPECIFICATIONS OF THE COMBINED STRUCTURAL RESEARCH FACILITY - S20

	UNITS	PARAMETER CAPABILITY
THERMAL SYSTEM		
Max. Heat Flux 50 ft^2 (4.65 m^2)	B/ft^2-sec (kW/m^2)	500 (5680)
Avg. Heat Flux	B/ft^2-sec (kW/m^2)	40 (372)
Total Available Power	MW	430
Number of Control Channels	--	1000
Heating Rates Obtainable	°F/sec (°C/sec)	0 to 30 (0 to 16.7)
ALTITUDE		
Altitude Chamber Volume	ft^3 (m^3)	5 x 10^5 (14.15 x 10^3)
ACOUSTIC		
Acoustic Sound Pressure Level	dB	170
Total Acoustic Power	acoustic watts	4.8 x 10^6
Acoustic Frequency	Hz	15-10,000
Number of Acoustic Generators	--	160
MECHANICAL LOADS		
Number of Mechanical Load Channels		200
Max. Load/Channel	lb (N)	50,000 (222,000)
Max. Loading Rate	lb/sec (N/sec)	400,000 (1,778,000)
Cycling Rate	Hz	0 to 5
MECHANICAL VIBRATION		
Number of Mechanical Shakers - 30,000 lb (133,100 n)	--	20
Frequency Range	Hz	30-3000
FUEL FLOW		
Cryogenic Fuel Tankage & Control System	ft^3 (m^3)	50,000 (1410)
Cryogenic Pumping	gpm (m^3/min)	60,000 (264)
FUEL SLOSH ACCELERATION TRACK		
Length	ft (m)	1500 (457)
Maximum Acceleration	g	4
Test Time	sec	4

FIGURE 6-114a
S20 FACILITY COMPONENT AND COST SUMMARY

Facility Component		Cost Estimate ($1,000's)
1. BUILDING COMPLEX (Lab/Office/Control/Fabrication)	Total	2,566
2. TEST EQUIPMENT	Total	103,446
2.1 Altitude Simulation System	Sub Total	7,030
Chamber		1,280
Steam Ejector System		5,750
2.2 Thermal Simulation System	Sub Total	47,280
Thermal Control		8,830
Heaters		22,375
Electrical Substation		16,800
2.3 Electromechanical Vibration Exciters	Sub Total	9,180
2.4 Mechanical Loading System	Sub Total	2,127
Pumps, Load Programmers, Load Cylinders Transducers		1,828
Test Fixtures		299
2.5 Acoustic Simulation System	Sub Total	13,315
Acoustic Generators		2,170
Acoustic Test Cell		5,245
Air Supply		5,900
2.6 Fuel Tank Slosh Acceleration Track	Sub Total	1,040
2.7 Instrumentation	Sub Total	10,599
2.8 Test Control Complex	Sub Total	3,000
2.9 General Purpose Lab Equipment	Sub Total	1,610
2.10 Fabrication Equipment	Sub Total	1,605
2.11 Cryogenic Fuel Flow and Storage	Sub Total	6,660

FIGURE 6-114a (Continued)
S20 FACILITY COMPONENT AND COST SUMMARY

3. SERVICES & UTILITIES	Total	800
	Sum Total	106,812
	Contingency 10%	10,681
	Facility Cost	117,493
	A&E Fee 6%	7,000
	Management Fee 4%	4,700
	Grand Total	129,193

FIGURE 6-114b
S20 FACILITY OPERATING COST SUMMARY

Operating Costs - Dollars Per Occupancy Hour	
Building Maintenance	177
Test Equipment Maintenance and Operation	6623
Services and Utilities Operation	3000
Power and Steam	4700
Total	14,500

6.5 MATERIALS RESEARCH FACILITY

6.5.1 DESIGN CRITERIA - One of the primary areas in hypersonic research is that of developing usable materials that will withstand the loads and environments expected of a typical hypersonic trajectory. The Materials Research Facility was designed to provide a facility that is capable of solving the technology gaps indicated in the various materials-related Research objectives. In Phase I, a group of five material research facilities was investigated, their capability was determined, and their performance was rated. The capabilities of all the materials facilities were consolidated into one facility for further refinement in Phase II.

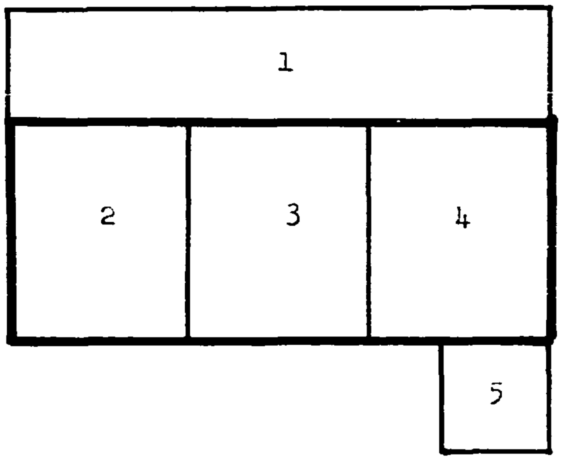
In Phase I, it was apparent that the materials research area differed from the other technology areas because much of the research that could be applicable to the hypersonic vehicles is currently being conducted at installations all over the country. In Phase II, the research objectives pertaining to hypersonic technology were reviewed with cognizant materials specialists at MCAIR and it was generally felt that the laboratory equipment presently available was sufficient to develop the required technology. The M20 Materials Research Facility represents a consolidation of technological resources at a central location, rather than a facility of unique size or innovative design principles. As a centralized testing laboratory, the M20 facility really represents a new test management concept, where program related materials problems are investigated on a coupon-sized basis, integrated into subassemblies and components, and proof tested in component-sized test articles. All this work can be supervised and coordinated with other elements of the vehicle design program, to ensure proper transmittal of data and coordination of design changes which may be caused by test results.

6.5.2 M20 MATERIALS RESEARCH FACILITY DESCRIPTION - The basic tasks of the M20 facility are to conduct basic materials research, to determine the physical and thermal properties of candidate materials to develop manufacturing techniques, and to develop non-destructive testing methods. The facility was organized into three general laboratories which were: material properties, fabrication development, and non-destructive testing laboratories. A schematic of the M20 facility is shown in Figure 6-115.

The basic facility capability depends solely on the type and amount of the test equipment included in the facility. Using the applicable research objectives, a list of major equipment was compiled that was calculated to accomplish these objectives. This equipment is representative of the types of equipment currently incorporated in materials facilities and is known to be necessary for material research. It was beyond the scope of this study to determine the justification for each item of test equipment.

The M20 facility will function by identifying candidate materials that appear to solve the materials problems. These candidate materials will then be investigated to determine their properties and abilities to be transformed into a usable structure. This structure will then be tested in the S2 Structural Research Facility to evaluate the design and selected materials in a realistic test environment. Non-destructive testing and inspection methods will be concurrently developed to permit the development of more efficient designs, manufacturing techniques, and structural repair methods.

FIGURE 6-115
SCHEMATIC LAYOUT OF MATERIALS RESEARCH FACILITY – M20



1 OFFICES
2 MATERIALS PROPERTIES LABORATORY
3 FABRICATION DEVELOPMENT LABORATORY
4 NON-DESTRUCTIVE TESTING LABORATORY
5 EQUIPMENT ROOM

6.5.2.1 Facility Specifications, Components, and Cost Summary - The facility specifications, acquisition costs, and operating costs are presented in Figure 6-116. The research capability of the facility is directly affected by the type and amount of equipment included in the facility. The acquisition cost was determined by estimating the cost of the building complex, major test equipment, and services and utilities. The equipment was organized into three laboratories and the costs for each were determined. The cost of any combination of these laboratories can be determined by adding or subtracting appropriate equipment costs. The cost of the building complex and utilities can be reduced on a pro rata basis if reduced facility capability is desired. Figure 6-116b summarizes the cost of running the entire laboratory, based on 2000 available occupancy hours per year.

6.5.2.2 Facility Development Assessment - Since all the types of test equipment included in this facility are presently being used in materials research centers, there are no anticipated facility development problems. A confidence level of 5 is applicable.

6.5.3 EVALUATION AND CONCLUSION - The M20 facility and existing facilities were collectively evaluated and it was determined that 52% of the applicable research objectives can be accomplished. The added value of the M20 facility cannot be segregated from the value of the existing facilities and the M20 facility because both have similar capabilities. It is intuitively felt that a substantial increase in research can be accomplished in the consolidated facility through minimization of duplicated research efforts; centralized management of project oriented research programs, from coupon testing to component fabrications; coordination with project design levels for flexibility in design and engineering changes; unified data transmittal to government agencies and industry. In view of the importance of materials research to the entire hypersonic effort and the relatively low acquisition cost of the facility, the M20 Materials Research Facility should be further studied in Phase III.

FIGURE 6-116a
M20 MATERIALS RESEARCH FACILITY SPECIFICATIONS, COMPONENT, AND COST SUMMARY

Facility Component	Cost Estimate $1000's
1. BUILDING COMPLEX Total	2,172
2. TEST EQUIPMENT Total	11,515
2.1 Metallurgical Laboratory Sub Total	1,723
Tensile Test Machine 1×10^6 Lbs (4.4×10^6 N)	150
Impact Test Machine 5000 Ft-Lbs (6750 J) -450°F to +4500°F (-271°C to 2500°C)	25
Creep Test Machine 20 kip -450°F to +4500°F (88,000N, -271°C to 2500°C) (50 units)	337
Thermal Properties Determination Apparatus	35
Electron Microscope 200 kV 1.5 Å Resolution	110
Scanning Electron Microscope 150 kV 10 Å Resolution	84
Vacuum X-ray Spectrometer 75 kV	27
Electron Microscope	90
Low Energy Electron Diffraction Camera	50
Hardness Testers (3 units)	9
Microscopes, Optical (5 units)	6
Metalograph	20
Vacuum Chamber 15 ft diam. x 30 ft long (4.5 m diam. x 9.1 m long)	740
Salt Bath Furnace 3 ft x 4 ft x 5 ft +1200°F to +2400°F (.9 x 1.2 x 1.5 m) (680°C to 1330°C)	10
Induction Furnace 30 kV	30
2.2 Fabrication Development Laboratory Sub Total	6,815
Electron Beam Welder	128
Laser Welding Machine 100 Watts	50
Ultrasonic Welder 300 Watts	35
N/C Fusion Welder W/5 Axis Table	260

FIGURE 6-116a (Continued)
M20 MATERIALS RESEARCH FACILITY SPECIFICATIONS, COMPONENT, AND COST SUMMARY

	MIG Welder	500
	TIG Welder	200
	Heliarc Welder	65
	Rolling Mill	60
	Stretch Forming Equipment 500 Ton (4.4×10^6 N)	3,140
	Stretch Forming Equipment 350 Ton (3.1×10^6 N)	750
	Stretch Forming Equipment 100 Ton ($.9 \times 10^6$ N)	627
	Electrical Discharge Machine	50
	Electro-Chemical Milling Machine	80
	Cleaning Equipment	1
	Tube Bender	1
	Induction Welding Machine	58
	Pressure Forming Machine	400
	Glass Shot Peening Apparatus	1
	Autoclave 80 x 40 x 20 ft (24.2 x 12.2 x 6.1 m) 500 psi (345N/cm^2) 1200°F (680°C)	168
	Vacuum Furnace 10 x 10 x 10 ft (3 x 3 x 3 m) 3000°F (1660°C)	44
	Hydroclave 10 ft Diam. x 20 ft (3 x 6 m) 10,000 psi (6900N/cm^2) 2000°F (1100°C)	200
2.3	Non-Destructive Test and Inspection Laboratory Sub Total	1,551
	X-ray Radiographic Machine	70
	Neutron Radiographic Machine	225
	Ultrasonic Inspection Equipment	57
	Thermal NDT Apparatus (IR Scanner)	35
	Microwave NDT Apparatus	30
	Holographic Interferometer .5 ft x 8 ft x 50 ft (.1 x 2.4 x 15.3 m)	75
	Acoustic Emission NDT Apparatus	30
	Fatigue Machine 1,000,000 lbs (4.4×10^6 N)	350

FIGURE 6-116a (Continued)
M20 MATERIALS RESEARCH FACILITY SPECIFICATIONS, COMPONENT, AND COST SUMMARY

Thermal Control System (Heaters) 150 Btu/sec ft^2 (5.1 x 10^3 kW/m^2)	72
Data Acquisition and Reduction System 500 Channels	500
Astro Furnace 5000°F (2800°C)	12
Microwave Oven	4
Ball Mill	1
Gleeble	90
2.4 Miscellaneous Laboratory Equipment Sub Total	1,426
3. SERVICES AND UTILITIES Total	854
Air Supply	206
Water	20
Refrigeration	65
Electrical	20
Cryogenic (LH_2, LO_2, LN_2)(Fuel Storage and Dist. System)	468
JP Fuel Storage and Distribution System	75
Facility Total	14,541
Contingency 10%	1,454
Facility Total Cost	15,995
A&E Fee - 6%	960
Management Fee - 4%	640
Grand Total	17,595

FIGURE 6-116b
M20 FACILITY OPERATING COST SUMMARY

Operating Costs - Dollars Per Occupancy Hour	
Building Maintenance	108
Test and Laboratory Equipment - Maintenance and Operation	875
Services and Utilities	10
Total	993

7. GROUND RESEARCH FACILITY SCREENING AND SELECTION

Each of the eleven ground research facilities retained from Phase 1 was evaluated to determine the most favorable size. The characteristics of these facilities and the rationale for selecting the combinations of specific ground facilities to accomplish a significant portion of the total required research is given in Sections 6.3.8, 6.4.9, 6.5.4, and 6.6.3 for each class of ground research facility.

The selection of the most attractive facilities for continued refinement in Phase III, and recommendations, are given in Section 7.2.

7.1 FACILITY RESEARCH VALUES

The definition of the research value is given in Section 3.5.3 of Volume III, Part 1, and the process of arriving at a total facility research value is explained therein. The facility research values (FRV) as applicable to four of the potential operational systems are given in Figure 7-1. These numbers were arrived at by summation of the individual research value for each Research Objective as presented in Figures 3-27 to 3-30 in Section 3.5.3. Unlike a flight research facility which is capable of some portion of the Research Objective in each technical area, simply because it is a complete system which flies, each ground research facility represents a particular facet of the overall research program. The fundamental difference between flight research facilities and ground test facilities is illustrated in the sketch below. The flight research vehicle has the capability of doing research in all applicable technical areas and on all systems incorporated in the vehicle, throughout its entire test regime. Only those systems and configurations

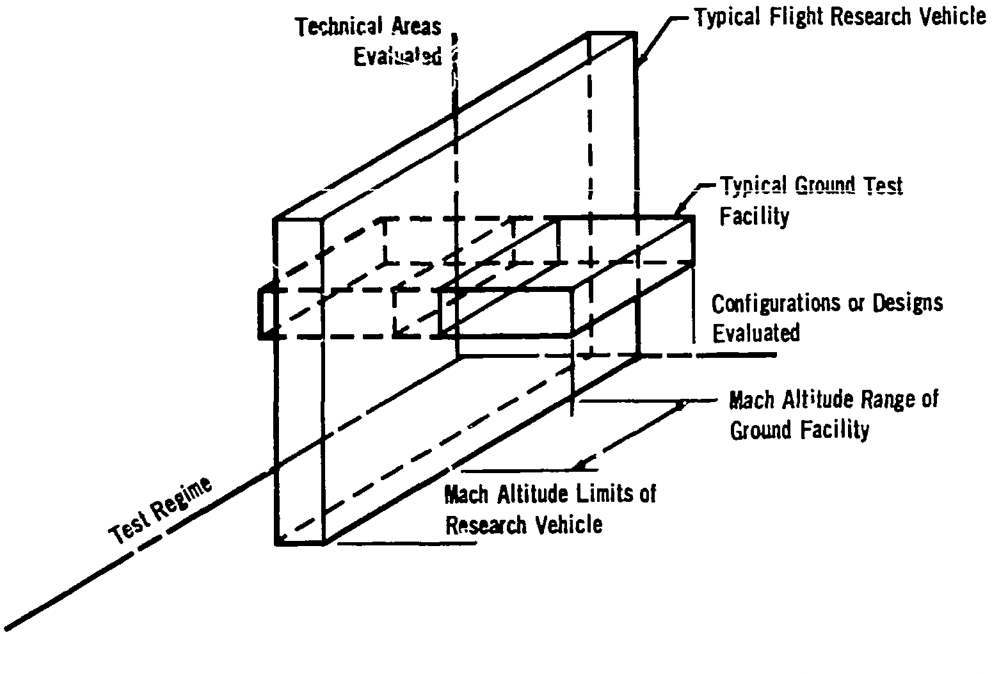


FIGURE 7-1
FACILITIES RESEARCH VALUES - BASELINE FACILITIES
(Capability of Existing Plus New Facilities)

	OPERATIONAL SYSTEM			
	L2	C1	M1	M2
TOTAL	8905	8897	7947	9004
EXISTING	3295	4425	4646	3203
GD3	3949	4955	5201	3957
GD20	4306	5019	5254	4230
GD7	3844	4569	4786	3781
E6	3539	4941	5091	3456
E20	3898	5372	5547	3940
E8	4142	4971	5163	4122
E9	4035	5024	5203	3974
S2	4098	5153	5211	3997
M20	3653	4773	4936	3563
* C/1	4689	5422	5661	4652
C/2	4941	6133	6304	4931
C/3	5457	6434	6545	5463
C/4	6218	7108	6994	6227
C/5	6593	7438	7155	6614

* Research values of various combinations of facilities were calculated. The key to the combination code is:

C/1 = GD20 + GD7
C/2 = C/1 + E20
C/3 = C/2 + E9
C/4 = C/3 + S2
C/5 = C/4 + M20

incorporated in the vehicle can be evaluated. A ground facility, on the other hand, can perform testing only in a limited amount of technical areas, and only throughout its design test regime. This testing can be performed on any number of designs or configurations, including partial and therefore unflyable configurations. Whereas the flight research vehicle is its own test article, a ground facility is a means of providing the proper environmental conditions, and once constructed, is available for testing many diverse programs over the lifetime of the facility. These basic differences must be considered when comparing relative research values of flight and ground test facilities. In fact, because of these differences, flight and ground test facilities cannot be considered as competitive alternates, but as complimentary test methods, both of which are necessary for the ultimate technical and economic success of an operational hypersonic system.

FIGURE 7-1 (Continued)
FACILITIES RESEARCH VALUES - BASELINE FACILITIES -
(Capability of Existing Plus New Facilities)

PERCENT ACHIEVED OF TOTAL RESEARCH INVOLVED

	OPERATIONAL SYSTEM			
	L2	C1	M1	M2
TOTAL	100	100	100	100
EXISTING	37	49	58	35
GD3	40	46	48	42
GD20	48	56	66	47
GD7	43	51	60	42
E6	39	55	64	38
E20	43	60	69	43
E8	46	55	65	45
E9	45	56	65	44
S2	46	57	65	44
M20	41	53	62	39
C/1	52	60	71	51
C/2	55	68	79	54
C/3	61	72	82	60
C/4	69	79	88	69
C/5	74	83	90	73

The sketch also illustrates the fact that the various ground test facilities are non-competitive with each other. For instance, all the gasdynamic facilities included in the study are Reynolds number-Mach number simulators which cover the same technical test areas, represented by the vertical height of the block typifying the ground facilities. Each of the three test legs of these facilities cover a different test regime, however, with an overlap of one-half of a Mach number. Therefore, all three test legs are necessary to completely span the full Mach range required by the operational systems. A similar observation is true for the engine test facilities, the turbo-machinery facilities covering the test range up to Mach 6, and the scramjet test facilities going from Mach 3 to 12. The only competitive facilities in the study are the E8 and E9 scramjet facilities which cover essentially the same test regime, but differ greatly in the method of heating the test gas and in the composition of the test gas. The structural and materials test facilities cover a wide range of technical test areas which don't duplicate each other or those of the gasdynamic or engine test facilities. These facilities, unlike the gasdynamic and engine test facilities, each cover the entire applicable test regime range, so only one facility of each type is necessary.

7.2 FACILITY EVALUATIONS

The facility evaluation will summarize the results presented in the sections discussing each category of facilities (Gasdynamic, Engine, Structures, Materials), and indicate why the facilities recommended for Phase III were selected.

7.2.1 GASDYNAMIC FACILITIES - The baseline gasdynamic facilities were based on a significant increment above existing capability levels, which could provide a majority of the necessary research. The increment chosen was Reynolds number capability at least double the existing capability, throughout the entire range of Mach .5 to 13.

Provided this minimum increment, a series of facilities were specified covering the Mach number range of the potential operational aircraft. These facilities in their baseline specifications were sized to be the smallest possible based or model strength, balance capability, and inlet duct detail. When facilities larger than this minimum size, or of greater Reynolds number capability were evaluated, the costs incurred in increasing the capability greatly exceeded the increase in Research Value, as shown in Figure 7-2. For example, a group of facilities with 2.5 times the baseline Reynolds number capability (Alternate 2) have a 30% improvement in Research Value at a cost increase of 600% more than the baseline facilities. Since the three test legs incorporated in the C/I combination cover different parts of the Mach number range from .5 to 13, all three must be provided unless a gap in Mach number capability can be tolerated. This is not recommended since there is a considerable gap in the Reynolds number capability of existing facilities (referenced to the desired goal of at least 1/5 maximum flight Reynolds number) throughout the entire Mach number range. For this reason, the facilities recommended for further study in Phase III are GD20 and GD7 in their baseline sizes. The cost savings possible by integrating these facilities into existing wind tunnel complexes will be studied, and their specifications will be refined in order to minimize total costs without reductions in test capabilities.

7.2.2 ENGINE FACILITIES - The two basic categories of engine facilities, the turbomachinery facilities and the scramjet facilities, are of such differing capabilities in total pressure and temperature and mass flow, by virtue of the flight Mach number and altitude conditions being duplicated, that they will be considered separately in this evaluation.

The two turbomachinery engine facilities can accommodate full scale turbojet, turbofans, turboramjets, and ramjets of the size projected for the 1975 to 1985 time period. The choice between the two facilities centers around the need for research associated with inlet/engine compatibility. Facility E6 can operate a subsonic combustion engine in a direct connect mode under flight duplicated conditions to Mach number 5.5. Facility E20 provides this capability supplemented with a free jet facility capable of duplicating the free stream conditions for an inlet/engine combination over the range of flight angles of attack up to Mach 5. The cost of attaining this free jet capability with flight duplicated conditions is very high, as Figure 7-3 testifies. However, the primary purpose of the free jet facility is engine/inlet compatibility research at supersonic Mach numbers. If the assumption is made that direct connect mode testing is sufficient for engine research at subsonic and transonic conditions, and that the free jet facility is required primarily for flight duplication in the supersonic flight regime, then the large compressor capac-

FIGURE 7-2a
FACILITY EVALUATIONS (GAS DYNAMIC)

Facility	Average Facility Research Value (Percent)	Acquisition Cost (Millions of Dollars)	Mach Number Range
GD3	44	97.2	0.3 to 5
GD20	54	124.8	0.3 to 8
GD7	49	11.7	8 to 13
GD20 + GD7 (C/1)	60	136.5	0.3 to 13

FIGURE 7-2b
COMPARISON OF RESEARCH VALUE AND COST FOR THE C/1 FACILITY COMBINATION (GD20 AND GD7) BETWEEN THE BASELINE AND ALTERNATE FACILITY SPECIFICATIONS

Facility GD20 + GD7 (C/1)	Average Facility Research Value (Percent)	Acquisition Cost (Millions of Dollars)	Mach Number Range	Description
Baseline	60	136.5	0.3 to 13	Minimum Sized 1/5 Flight Reynolds Number Facility
Alternate 1	63	524.7	0.3 to 13	Larger 1/5 Flight Reynolds Number Facility
Alternate 2	78	1,053.5	0.3 to 13	Minimum Sized 1/2 Flight Reynolds Number Facility

For Research Objectives Applicable to Aerodynamic/Thermodynamic Research.

ity required for transonic, low level operation and the refrigeration capacity for high altitude, transonic operation can be deleted. The result is a 43% reduction in cost and only a minimal reduction in the facility research value. Although still costly, the critical nature of maintaining engine operation over a wide range of Mach numbers, altitudes, and angles of attack requires considerable research in this area. For this reason, the turbomachinery facility recommended for Phase III is the

FIGURE 7-3
FACILITY EVALUATION
(Engine, Turbomachinery)

Facility	Average Research Value (Percent)	Acquisition Cost (Millions of Dollars)	Remarks
E6	68	114.519	Direct Connect Only
E20	74	712.012	Free Jet and Direct Connect
E20 Alt 1	73	432.824	
E20 Alt 2	73	423.729	Deletes regions best accomplished by E6 leg, and retains capability most necessary for inlet/engine research

For Research Objectives Applicable to Turbomachinery Research

integrated direct connect-free jet facility E20. This facility provides the size and performance necessary to do research on engine systems proposed for the potential operational vehicles. Integration of a facility of this type into a major ground test facility complex which already has major air compressor and cooling capability, such as AEDC, could result in major savings. For example, the direct connect leg of E20 would probably be an adjunct test leg for engine test cell T-1 with supplementary air compressors and air heater. That could reduce the cost of this leg (which is equivalent to E6) by 50%. Again, using similar techniques for the free jet leg of E20 could reduce the compressor costs by a significant level. Thus, the cost of the facility, estimated independently of any capability existing at the construction site, represents a maximum, and what is yet to be established is what total installation compromises could be made to significantly reduce this cost.

The scramjet facilities posed a difficult problem in terms of evaluation. The baseline facility sized for a 15 ft^2 (1.39 m^2) capture area engine module appeared feasible. Beyond this point, the mass flow/enthalpy combination became of such magnitude that it challenged most existing concepts. Figure 7-4 shows the increasing costs when engine module size is increased. The confidence level decreases rapidly as the module size increases, requiring considerable increase in the development required to achieve that level of performance. Based on the size of the hardware components involved in the construction of E9, it appears that up to a 50 per cent increase in capture area test capability could be provided without much more risk than the 15 ft^2 (1.39 m^2) module capability. The 45 ft^2 (4.19 m^2) module test capability would involve a greater degree of risk owing to the complexity of pneumatically connecting and valving a large number of hot gas components. The

90 ft^2 (8.38 m^2) test capability would not only have this risk, but an additional risk that all components would be at least twice the size of the largest being conceived for AEDC's TTT facility.

A similar curve of facility research value versus cost for different capture areas was not generated for E8 because the task of providing the shaft power for even the 15 ft^2 (1.39 m^2) size facility is an extreme challenge to current technology.

The facilities recommended to be carried into Phase III are:

E9, in baseline size, with the provision that as the hardware definitions are further defined it could be increased 30 to 50 percent in size to accommodate a larger engine module with only minimum cost increase.

E8, in the baseline size, with the provision that only the specification for the equipment be further refined. This facility could provide additional flight duplication capability in the Mach number 10 to 12 flight regime compared to E9, but because of the low confidence level of the multirecompression heater concept, must be considered a far term facility. In practice, if E9 existed, the E8 capability could be easily integrated into the complex with little alteration to the basic facility, and perhaps this is a reasonable method of estimating the eventual cost increment. This approach also appears reasonable from the performance of the individual hardware items. The carbon-monoxide combustor of E9 is limited to flight duplicated conditions at Mach 9 to 9.5. The high enthalpy range multirecompression heater (Figure 6-68) begins operation at about Mach 8.5 to 9 and therefore appears to supplement the basic performance capability of E9, and removes the major drawback of E8 alone, that is, the requirement of two multirecompression heaters to cover the entire Mach number range for convertible scramjets and scramjets. E9 would then be the potential near term facility, supplemented by a multirecompression heater as a far term performance increment (Figure 7-4).

7.2.3 STRUCTURAL FACILITIES - The synthesis of the structural facility involved a large number of parametric evaluations involving degree of simulation and test article size. The procedure employed to assess the structural trade-off was to consider the parameters involving degree of simulation separately from those involving test article size. The task for Phase II was to determine which was the test article size most amenable to accomplishing a significant amount of research at a reasonable cost. The costs given in Figure 7-5 are for providing complete simulation time histories of altitude, thermal and mechanical loads. Altitude simulation for the rapidly climbing vehicles represents a major cost factor in the total cost of S2. If in Phase III it can be shown that a majority of the tests associated with this facility do not require this degree of simulation, then a significant cost reduction is possible (see Figure 6-108b).

The facility capable of testing component-sized test articles provide only a 2% Research Value increase over the capability of existing facilities and represents the size capability currently available.

The test article size which provides a meaningful increment in size and research capability compared to existing capabilities is the major section of a full scale aircraft. Again the cost of the facility includes full duplication of trajectory time-dependent parameters, and could be reduced, depending on the Phase III

FIGURE 7-4
FACILITY EVALUATION
(Engine, Scramjet)

Facility	A_c Ft^2 (m^2)	Average Research Value (Percent)	Acquisition Cost (Millions of Dollars)	Remarks
E9	15(1.39) 45(4.17) 90(8.34)	45 59 75	71.2 228.7 586.9	Near Term, Based on Current Technology
E9 Alternate	15	40	62.4	Limited Temperature, very High Operating Costs
E8	15	48	172.3	Requires Considerable Development, Far Term
E8 Alternate	15	48	251.9	Beyond Technology in Electrical/Mechanical Drives

For Research Objectives Applicable to Scramjet Research

analysis. This recommendation is consistent with that put into practice for the Concorde supersonic transport in a five year research and development program to qualify the Concord structure based on altitude/mechanical/thermal tests on a major section of the full scale aircraft.

It appeared from the Phase I work that certain research requirements which did not require a major section sized test article were important to the total research program, but could not justify a separate facility. These conditions could be included in the basic S2 facility at small additional cost (about 1.8%) but increasing the research value about 6%. These requirements were mechanical/acoustic fatigue research, and thermal/acoustic fatigue research on component sized test articles and an acceleration track to accommodate liquid hydrogen tanks which could be accelerated and rotated to simulate aircraft motion. This combined facility is called the Combined Structural Research Facility and is referred to as S20. It is this facility complex which is recommended to be carried into Phase III for further refinement.

As discussed in Section 6.3.4, the engine facilities E8 and E9 can be supplemented with an aerodynamic nozzle system which can be used for thermodynamic research and structural research on full scale components. The additional cost to the engine facilities is about 1.2 million dollars, which results in a significant increase in total research value. Thus, S20 supplemented with the research capability of the engine facilities to do structural research provides a significant research capability.

FIGURE 7-5
FACILITY EVALUATION
(Structural)

FACILITY	AVERAGE RESEARCH VALUE* (Percent)	ACQUISITION COST (MILLIONS OF DOLLARS)
S2		
Component of full scale aircraft	42	43.4
Major section of full scale aircraft	51	126.7
Complete full scale aircraft	55	257.6
S20	54	129.2
Major section of full scale aircraft, plus component fatigue, acoustic capability fuel tank acceleration track		(Add $1.2 Million for E9 Facility Aerothermal Nozzle Capability)

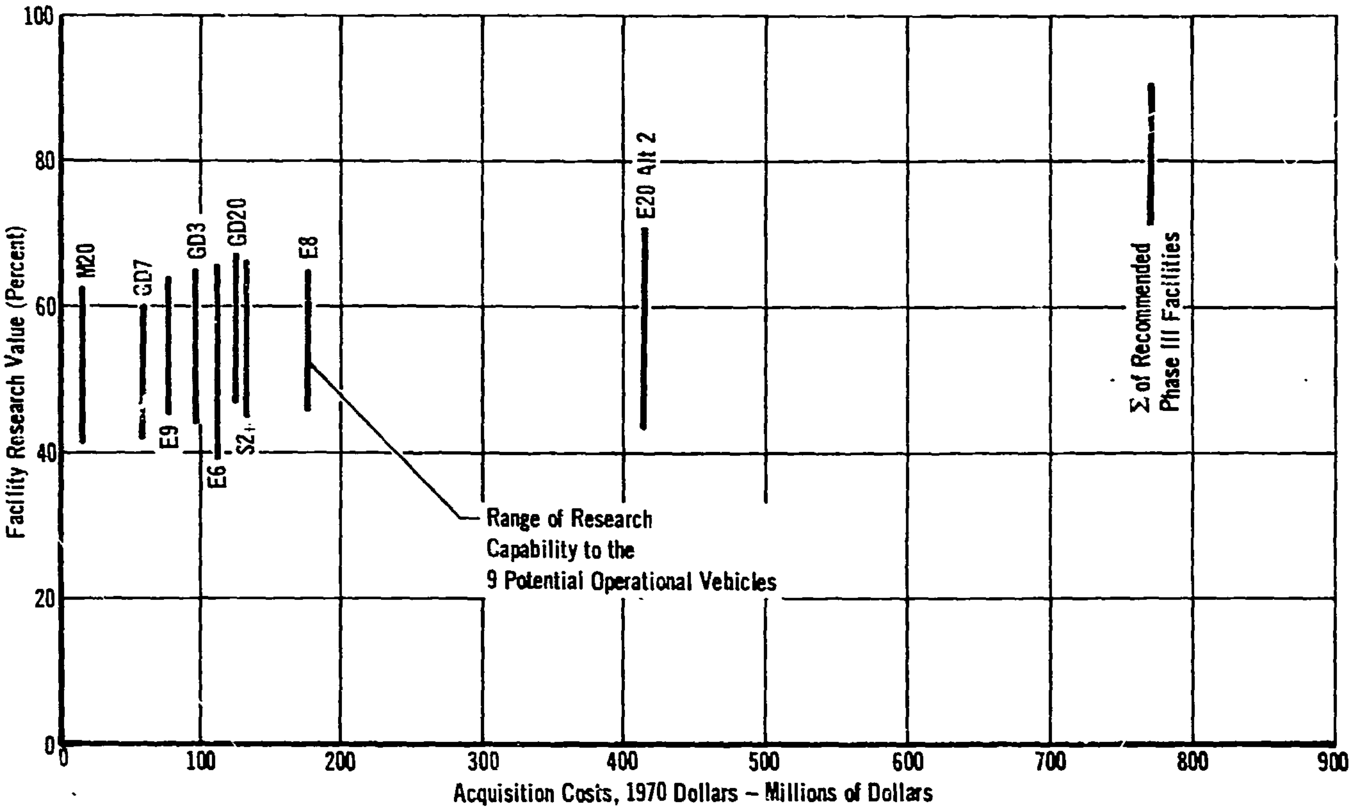
FIGURE 7-6
FACILITY EVALUATION
(Materials)

FACILITY	AVERAGE RESEARCH VALUE* (Percent)	ACQUISITION COSTS (MILLIONS OF DOLLARS)
M20	52	16.3

* For Applicable Research Objectives

7.2.4 MATERIALS FACILITY - The materials technology facility rates very high in the area of research accomplished compared to acquisition costs (Figure 7-6). This particular facility requires no additional increment in hardware performance, and represents a collection of equipment available in many different research laboratories. Its concept however is a centralized laboratory where data obtained on coupon sized specimens can be translated into viable structural concepts that can be verified in an S2 class structural facility and used as a basis for determining the feasibility of the potential operational vehicle's structural weight fraction and performance. As presented in Phase II, its description is essentially complete.

FIGURE 7-7
RESEARCH CAPABILITY OF INDIVIDUAL GROUND RESEARCH FACILITIES, AS A FUNCTION OF ACQUISITION COST



GD3,	Trisonic Blowdown Wind Tunnel
GD20,	GD3 Supplemented With An Additional Hypersonic Test Leg Similar to GD15 in Phase I
GD7,	Hypersonic Gas Piston Driver Impulse Wind Tunnel
E6,	Direct Connect Turbomachinery Facility
E20,	Integrated Direct Connect/Free Jet Turbomachinery Facility, E6 Supplemental With E7 From Phase I
E8,	Multirecompression Heater Scramjet Facility
E9,	Hybrid Heater Scramjet Facility
S20,	Structural Research Facility
M20,	Materials Technology Facility

7.2.5 FACILITY COMBINATIONS - The facility research values for the individual ground facilities are given in Figure 7-7. As stated in Section 7.1, each of these facilities achieves a given facet of the total research necessary.

The recommended Phase III facilities indicate a dominance of the engine facilities in the total cost picture. This is not really any different than the situation which currently exists. Figure 7-8 attempts to illustrate this point. The existing facilities most closely related in terms of operating concept and size

FIGURE 7-8
EXISTING FACILITIES WITH ACQUISITION COSTS
Expressed in Terms of 1970 Dollars

EXISTING FACILITY	ACQUISITION COST 1970 DOLLARS (1000'S $)	MOST CLOSELY RELATED STUDY FACILITY
(1) North American Rockwell Trisonic Blowdown	26,000	GD3
(2) North American Rockwell Trisonic Blowdown AEDC Tunnel B	26,000 28,300 54,300	GD20
(3) AEDC Tunnel C AEDC Tunnel F	26,400 7,150 33,550	GD7
(4) AEDC Engine Test Cell T-1	45,600	E6
(5) AEDC Engine Test Cell T-1 AEDC 16S AEDC 16T	45,600 141,000 104,000 290,600	E20
(6) FDL, 50 Megawatt Facility	15,000	E9
(7) NASA Langley Structures Laboratory Fatigue Research Laboratory High Intensity Noise Lab Low Freq. Noise Facility Landing Impact Facility Structural Research Lab.	 1,378 433 700 1,620 5,700 9,831	S20

Summation of existing ground research facilities corresponding most closely to the recommended Phase III facilities, GD20, GD7, E20, E9, S20, M20

$403,281,000 with acquisition costs represented in 1970 dollars.

FIGURE 7-9
COMPARISON OF COST FRACTION FOR EXISTING AND STUDY FACILITIES

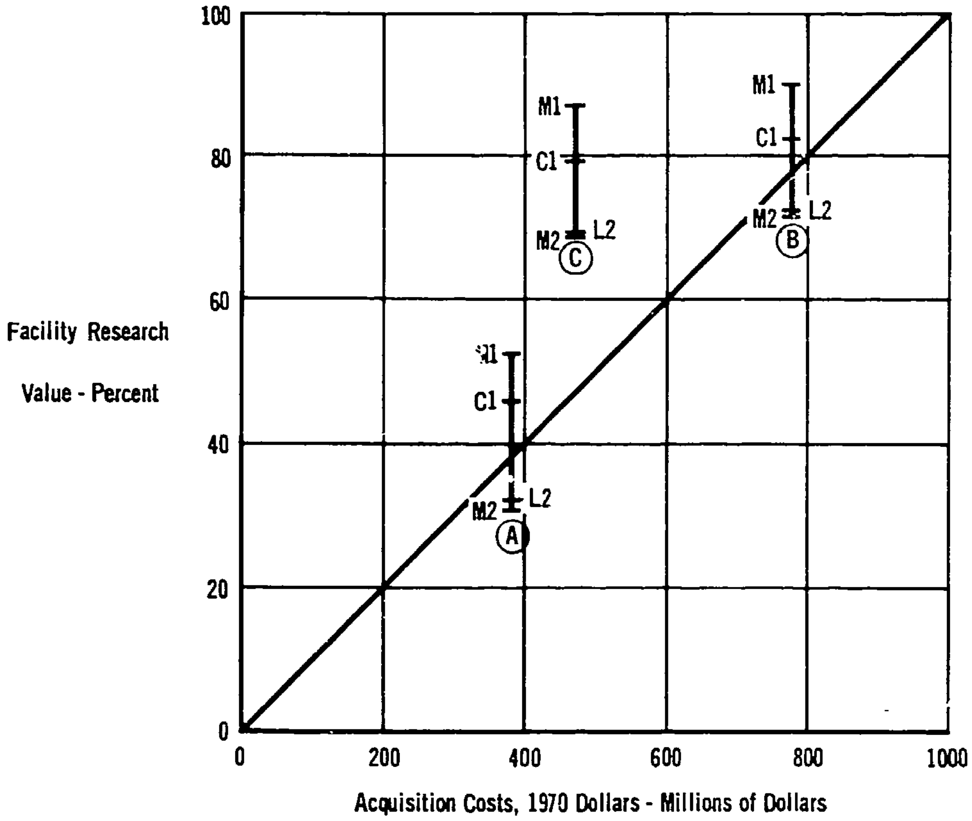
FACILITY TYPE	MOST CLOSELY CORRESPONDING EXISTING FACILITIES (SEE FIGURE 7-8)	STUDY FACILITIES
Gas Dynamic GD20, GD7	21.8%	17.6%
Engine E20, E9	75.7%	63.6%
Structural	2.3%	16.7%
Materials	< 1%	2.1%

to the recommended Phase III facilities were selected, and the acquisition costs expressed in terms of 1970 dollars using the historical cost data presented in Figure 6-5..

The relative contributions of the costs of the existing facilities most directly comparable to the recommended Phase III facilities to the total cost of the group of existing facilities were calculated and grouped by facility category. A similar calculation was done for the Phase III recommended facilities. The comparison is shown in Figure 7-9, and shows a striking similarity. This indicates, for instance, that engine research facilities have in the past and will, in the future, require the largest share of facility funding. The proposed structural facility will require a higher relative investment than would be indicated by historical data. This is so because of the current emphasis placed on the need to provide combined testing environments on large test articles, whereas this type of testing in the past has been restricted to very small test articles.

An interesting comparison can also be made between the Research Values and costs of the recommended facilities and existing facilities. Figure 7-10 shows this comparison, where the costs for both new and existing facilities are shown, for consistency, in 1970 dollars. It may be argued that the Research Value represented by the existing facilities should be shown at zero cost, since they represent research capability which requires no additional funding to obtain. The intent of Figure 7-10 is, however, to show a correlation between the Research Value of a group of facilities with their cost, if they were all to be built today. It is seen that the total recommended facilities provide a combined capability about

FIGURE 7-10
COMPARISON OF THE RESEARCH VALUE OF EXISTING FACILITIES WITH THE RECOMMENDED PHASE III STUDY FACILITIES AS A FUNCTION OF TOTAL COST



Research Value Based on the 4 Operational Vehicles M1, C1, L2, and M2

Ⓐ = Existing facilities defined in Figure 7-8.
Ⓑ = Total group of Phase III recommended facilities.
Ⓒ = Total Phase III recommended facilities without the free jet capability of E20.

twice that of the existing facilities at about twice the acquisition cost. Also shown is the RV and cost of the recommended facilities minus the free jet capability of E20. This line on Figure 7-10 suggests that very little research value is lost by eliminating free jet turbomachinery test capability and retaining only direct connect capability, while about $310 million is saved in acquisition costs.

7.3 RECOMMENDED PHASE III FACILITIES

Each of the facilities recommended is listed and its attributes and favorable factors affecting its selection for Phase III are summarized. Also, some overall observations resulting from the Phase II work are presented.

7.3.1 SUMMARY OF FACILITY CHARACTERISTICS, COSTS, AND RESEARCH VALUES - Figures 7-11 thru 7-13 present "pie" charts representing the magnitude of the cost of the recommended Phase III facilities. For the gasdynamic facilities, which are intermittent operating, the air compressor system and storage tanks represent a major portion of the total facility costs, with the exception of GD7, which as an impulse wind tunnel has its primary cost in the test leg. For the engine facilities, which are continuous operating, the compressor plants and prime movers represent about 75% of the total facility costs. The actual test legs are "near optimum" in design and little further refinements can be done unless detail design studies are undertaken. However, the current definitions of the compressor plants are very elemental, and further refinement, using the compressor manufacturer's plant concepts and methods to integrate into existing capability can provide substantial changes in overall facility costs. The major refinement necessary is not on the test leg itself but the system complex which provides the overall capability for the test leg to function.

7.3.2 SELECTED FACILITIES, RATIONALE - Each facility recommended for Phase III [illegible] be listed, and the rationale for its selection will be summarized.

7.3.2.1 GD20 Baseline, Trisonic/Hypersonic Blowdown Facility

- Represents a very low risk facility. Care must be exercised in the design so that lesser components do not adversely affect its reliability by attempting to extrapolate component hardware to too large an individual size.

- The one-fifth of maximum full scale Reynolds number capability provides the most significant increase in capability over existing levels considering facility acquisition costs.

- Provides needed research in the Mach 0.3 to 5 range with the trisonic leg, and from 4.5 to 8.5 with the hypersonic leg. Its large Research Value increment is based on the fact that it provides up to five times the Reynolds number capability of best existing facilities.

7.3.2.2 GD7 Baseline, Hypersonic Gas Piston Impulse Wind Tunnel

- A low risk facility based on the higher Mach number, and smaller wind tunnels operating at the Naval Ordnance Laboratory and New York University. Again, care must be exercised in the design, and attention to detail is important, but it is certainly capable of being a near term facility.

- The one-fifth of maximum full scale Reynolds number capability provides a significant increase in capability over existing levels considering the facility acquisition costs required.

7.3.2.3 E20 Alternate 2, Integrated Direct Connect-Free Jet Turbomachinery Facility

- o Very costly, but provides a research capability not available at any facility in terms of size and flight duplication.
- o Probably could be substantially reduced in cost by integrating into an existing large facility complex.
- o Provides an essential testing capability and research capability to match inlet performance and engine requirements for advanced engines.

7.3.2.4 E8 Baseline Multirecompression Heater Scramjet Facility

- o Can provide for far term increases in performance for scramjet engines.
- o Very high risk in terms of prime mover concept which can provide power density necessary.
- o Multirecompression heater could be incorporated into E9 at some later date as an improvement at minimal cost, and after subscale development.
- o Retained only for refinement of specifications.
- o Concept feasible only in baseline size, regardless of research value.

7.3.2.5 E9 Baseline Hybrid Scramjet Facility

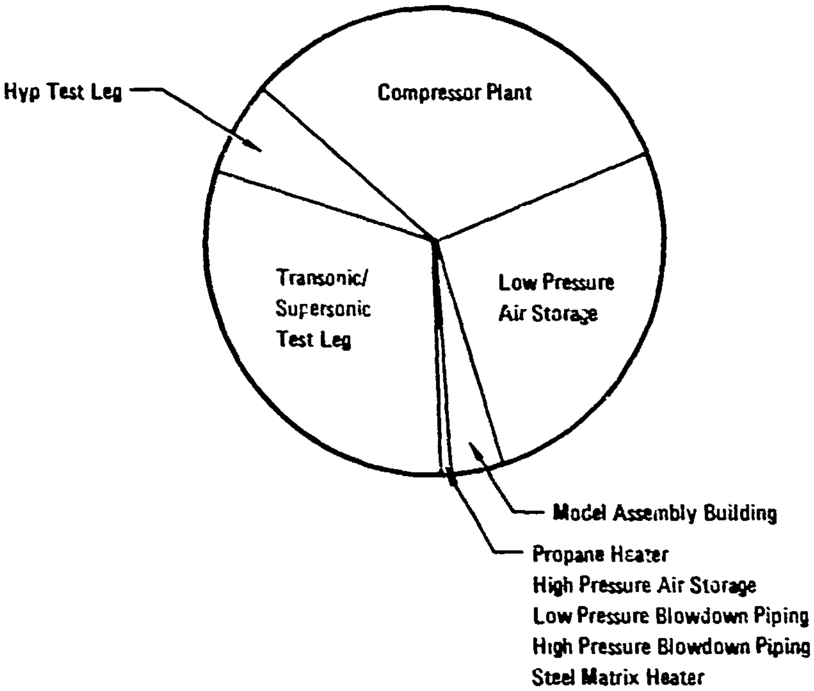
- o Based on concepts operating in present industrial plants and research laboratories. Development of existing technology. Moderate risk in particular items for pneumatically connecting hot gas sections of facility components, and in developing design details and material applications for scramjet test section.
- o High research value and moderate cost. Best of scramjet facilities.
- o Possible to increase engine size capability by 30 to 50% without incurring prohibitive cost increases. Larger increases rapidly increase technical risk and increase costs.

7.3.2.6 S20 Combined Structural Research Facility

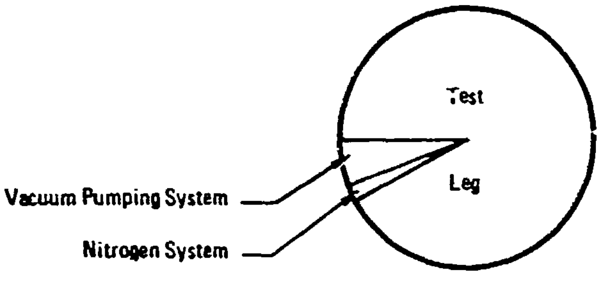
- o Provides meaningful increment over existing capability.
- o Moderate cost, considering sophisticated degree of simulation.
- o Cost reductions possible by analyzing test program requirements and correlating with degree of simulation, in Phase III.
- o Provides fatigue research capability, and evaluation of horizontal liquid hydrogen fuel tank for only 1% increase in cost

FIGURE 7-11
GAS DYNAMIC FACILITY COST COMPARISONS

GD-20 Baseline
Total Facility Cost $124,807,000

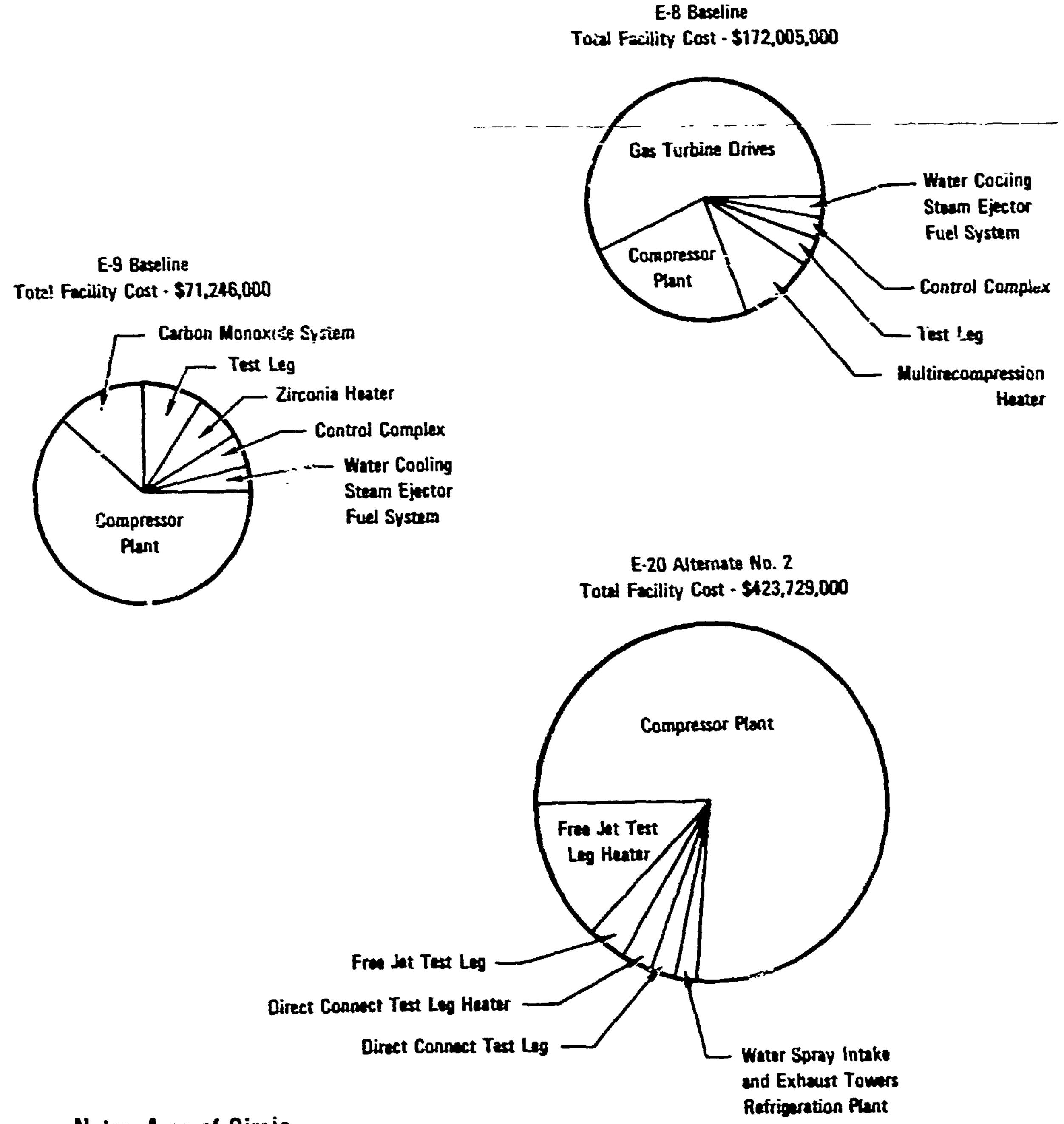


GD-7 Baseline
Total Facility Cost - $11,723,000



Note: Area of Circle Proportional to Total Cost

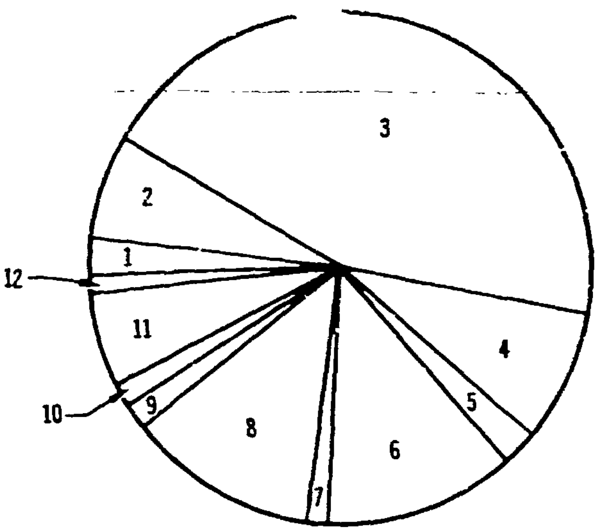
FIGURE 7-12
ENGINE TEST FACILITY COST COMPARISONS



Note: Area of Circle
Proportional
to Total Cost

FIGURE 7-13
STRUCTURES AND MATERIAL FACILITY COST COMPARISON

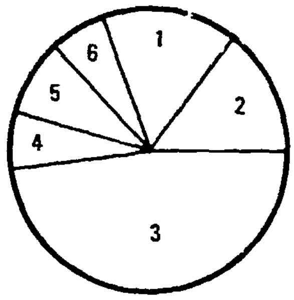
S-20 Combined Structural Research
Total Facility Cost $129,193,000



Key

1 Building Complex
2 Altitude Simulation System
3 Thermal Simulation System
4 Electromechanical Vibration Exciters
5 Mechanical Loading System
6 Acoustic Simulation System
7 Fuel Tank Slush Acceleration Track
8 Instrumentation and Test Control Complex
9 General Purpose Lab Equipment
10 Fabrication Equipment
11 Cryogenic Storage and Control
12 Services and Utilities

M-20 Materials Technology
Total Facility Cost $17,595,000



Key:
1 - Building Complex
2 - Metallurgical Laboratory
3 - Fabrication Development Laboratory
4 - Nondestructive Test and Inspection Laboratory
5 - Misc. Laboratory Equipment
6 - Services and Utilities

Note: Area of Circle Proportional to Total Cost

- When supplemented by E9 capability with aerodynamic nozzles for structural research, research value increases significantly for a 2% additional cost to E9.
- Low risk facility, based on existing hardware components.

7.3.2.7 M20 Materials Technology Facility

- Very high research value for very low cost.
- Equipment defined in Phase II sufficient for Phase III.
- Retained for incorporation into existing laboratory facilities.
- Provides essential research to translate coupon thermophysical data into viable structural concepts.

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