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AERO-SPACE DIVISION LAUNCH SYSTEMS BRANCH

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INVESTIGATION OF THE FEASIBILITY OF FLOX FOR PERFORMANCE IMPROVEMENT ON THE S-IC

M. E. Schlapbach

Dec 64

THE BOEING COMPANY
AERO-SPACE DIVISION
LAUNCH SYSTEMS BRANCH

H-R Baumann

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PREFACE

This document contains detailed data pertinent to the S-IC FLOX feasibility study authorized by TAO-22. Propulsion Division, RP&VE-P provided technical supervision. The study period was May through September 1964 and averaged approximately 9 men. A reproduction of the technical work statement is contained in the appendix.

D5-11464-2, released in November 1964, is a general summary of the program and also shows the potential impact of FLOX on Saturn V growth.

Following is a list of personnel who have contributed to the support of TAO-22.

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ABSTRACT

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The payload of the Saturn V vehicle can be increased up to 65 percent by using 70 percent Liquid Flourine and 30 percent Liquid Oxygen (FLOX) as the oxidizer on the S-IC. This would require moderate changes to the engine and stage. By using essentially the existing engines and stage, the payload can be increased approximately 38 percent. Implementation of FLOX on the S-IC will require minor stage material changes and redesign of some items to minimize contaminant traps since flourine reacts with most contaminants. A passivation procedure may be used to minimize contaminant reaction. Toxic exhaust cloud problems exist, however, investigation indicates general feasibility. A fairly sophisticated launch or test area weather sampling network fed into an appropriate computer system for continuous cloud behavior predictions would probably be required before large scale use of FLOX on the S-IC could be implemented. Launch time restrictions can be expected under certain weather conditions. Storing and handling of FLOX would require modifications and additions to the Ground Support Equipment.

author

FLOX
Thrust
Payload
Contamination
Spills
Costs
Specific Impulse
Mixture Ratio
Materials
Passivation
Air Pollution
Physical Properties

SECTION 1

FEASIBILITY STUDY PROGRAM SUMMARY

1.0 FEASIBILITY STUDY PROGRAM SUMMARY

1.1 GENERAL SUMMARY

Payload of the Saturn V vehicle can be increased up to 65 percent, in LOR capability, by using FLOX in the S-IC. The changes to the stage and engine to make them suitable for the maximum case (70% FLOX) are considered moderate; however, significant vehicle structural "beef up" is to be expected when the effects of the large payloads (mass and volumes) are included. Payload increase of 15% to 20% can be achieved at approximately 38% FLOX with essentially the existing engine and S-IC stage.

Implementation of FLOX on the S-IC will require minor stage material changes and redesign of some items to minimize contaminant traps. Results from initial evaluation strongly suggest that an alternate oxidizer-tank pressurization system is desirable

New items, such as fluorine and FLOX storage tanks, a gas recondenser, and handling and passivation equipment will be required at the test and launch site. Production test operational problems at MTF may be eliminated by using LOX as a substitute oxidizer, thereby eliminating the hazard and equipment cost. This approach requires evaluation. Relative to the toxic cloud problem, specific prediction of suitable launch or static test time periods was not required by the contract, however, investigation indicates general feasibility. Launch time restrictions can be expected under certain weather conditions. A fairly sophisticated launch or test area weather sampling network fed into an appropriate computer system for continuous toxic cloud behavior predictions will probably be required before large scale use of FLOX on the S-IC could be implemented.

The following paragraphs summarize the major findings from the study.

1.1.1 Performance Summary

Performance increase with FLOX has been defined by a series of step limitations to the engine and stage. Two definitive engine limits exist. The first F-1 engine step or "stopping point" is a cooling limit defined by the heat rejection capacity of the existing F-1 chamber. This problem, as defined by Rocketdyne, can be eliminated with a revision to the cooling tube network in the chamber (i.e., change in diameter wall thickness, etc.). The second limitation is the power capacity from the existing G.G. (gas generator). Holding G.G. turbine inlet temperature to existing values is a ground rule that determined maximum F-1 performance in the study.

Significantly, the engine used in the performance study then is essentially the existing F-1, inasmuch as no change is required to the G.G., turbopump, or subsystems. Changes, other than the cooling tube revision noted above, are those associated with local increases in operating pressure and some incompatible materials.

The stage stopping points were identified as (1) the existing structure and tank capability, (2) the performance limit within the existing tank volumes and (3) the performance with tank bulkheads moved to match optimum mixture ratio (stage and engine). The total S-IC length was not changed for any of the study configurations.

The engine and stage steps have been used in various combinations and seven basic configurations identified. Performance of the seven configurations (stopping points) are shown on Table 1.1. Details of the vehicles are shown on Table 1.2 and are discussed below:

Configuration 1, on the table, is the existing stage with the F-1 engine rated at 1522K thrust. The stage propellant loading has been reduced to assure that loads on the structure are not in excess of the current full tank vehicle.

The 10,000 pound Δ payload value (referenced to LOR), therefore, is a minimum FLOX improvement point because the propellant off-loading was used without regard for the favorable effects that would be realized from optimization between systems (i.e., pressurization NPSH requirements). System optimization undoubtedly would allow higher propellant loadings and consequently greater payloads. Note that the engine is derated and operates at 92% of the existing F-1 total propellant flow rate and FLOX is approximately 30%

Configuration 2, at 37% FLOX, also uses the existing engine (derated to 1522K) but shows increased performance as a result of loading the S-IC tanks to a point limited only by thrust to weight at launch (set arbitrarily at 1.17). The net payload increase, i.e., corrected Δ payload is shown as 14,000 pounds.

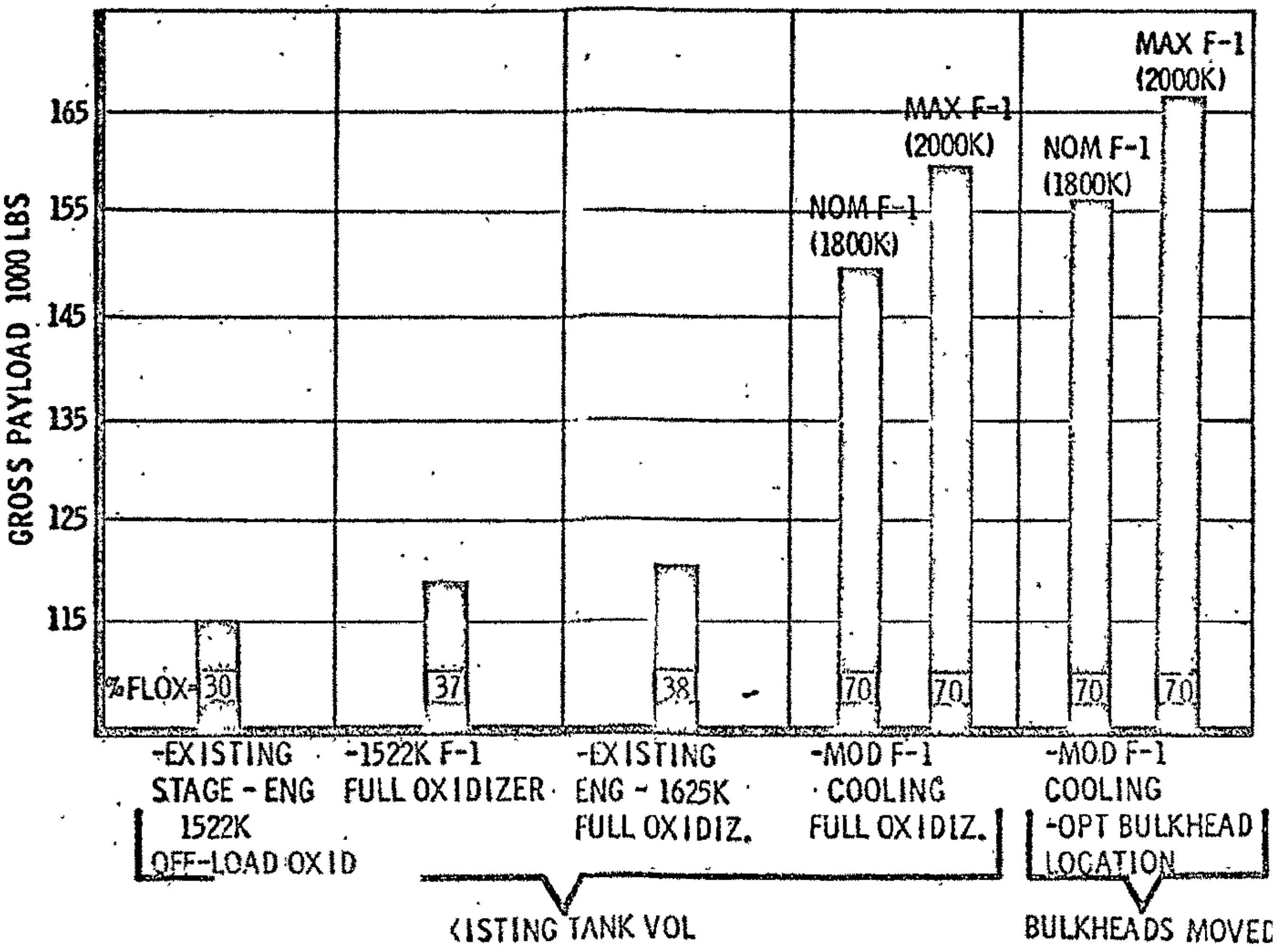
The adjacent column indicates that a theoretical payload increase of 17,000 pounds is available. Theoretical Δ payload is the value which would be achieved without consideration for inert weight effects on the stages. Corrected payload increase is a value that has been determined by a generalized inert weight curve. The correction curve considers payload mass, volume and stage factors (propellant loading and thrust) and assumes a linear relationship with growth.

Configuration 3 uses the capability of the existing F-1 within the chamber cooling limits. The total mass flow rate is 98% of the existing F-1. Thrust to weight at launch is 1.21 and the corrected LOR payload increase is 17,000 pounds. The inert weight penalty used is probably excessive (3300 pounds payload loss) depending, of course, on the payload volume and aerodynamic characteristics.

It should be noted that the engine main chamber cooling limits discussed previously has been predicted by Rocketdyne based on a confident estimate of the carbon build-up rate on the chamber-inner-tube walls. Should the carbon build-up rate actually be higher than estimated, the unchanged engine performance could be extended in terms of mixture ratio or percent FLOX. Should this

TABLE 1-1

FLOX PERFORMANCE SUMMARY



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DS-11464-1

PERFORMANCE SUMMARY

FLOX S-IC

TABLE 1-2

	THRUST	ΔI_{SP}	% FLOX	M. R.	L. WT.	W_P	% FUEL OFF-LOAD	η_W	W-% F-1	THEORETICAL ΔPL	CORRECTED ΔPL
1. EXISTING ENG & STAGE (OXIDIZER OFF-LOAD)	1522K	21	30	2.81	6.23M	4.50M	22.4	1.22	92	——	10,000
2. EXISTING ENG (FULL OXIDIZER)	1522K	24	37	2.81	6.52M	4.75M	16.0	1.17	92	17,000	14,000
3. EXISTING 1625K ENG (FULL OXIDIZER)	1625K	22	38	2.54	6.70M	4.80M	6.5	1.21	93	20,300	17,000
4. MOD. F-1 COOLING (FULL OXID) (EXIST TANKS-NOM. THRUST)	1800K	54	70	3.45	6.80M	4.99M	23.8	1.32	100	54,700	45,000
5. MOD. F-1 COOLING (FULL OXID) (EXIST TANKS-MAX THRUST)	2015K	52	70	3.25	6.83M	5.06M	21.5	1.46	113	65,600	54,000
6. MOD. F-1 COOLING OPT. BULKHEADS (NOM. THRUST)	1800K	54	70	3.35	7.21M	5.40M	0	1.25	100	61,500	51,000
7. MOD. F-1 COOLING OPT. BULKHEADS (MAX THRUST)	1985K	54	70	3.50	7.23M	5.41M	0	1.37	110	74,000	62,000

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Sec I Pg 5

be the case, payload values in excess of those quoted would be possible.

On configurations 4 through 7, it is assumed that a change in engine cooling tube design is accomplished, thereby extending engine performance up to the next major component limit, i.e., the gas generator power limit. This allows operation at favorable mixture ratios and 70% FLOX.

Power availability from the gas generator is restricted by the turbine inlet temperature. At peak performance, 2027K pounds thrust is available and total propellant flow is approximately 113 percent compared to the existing F-1. This performance level can be accomplished within the capability of the current F-1 with the exception of the cooling tube geometry change mentioned previously.

Allowing for error in theory, vehicle performance investigations with modified F-1 cooling tubes have been approached using two engine ratings; one at predicted maximum available, the other derated to a more nominal engine (i.e., existing F-1 total mass flow rate). Configuration 4 with the nominal rating (100% F-1 mass flow rate) has 45,000 pound corrected payload increase. The maximum performance case, configuration 5, shows 54,000 pounds LOR payload increase.

The last two configurations, 6 and 7, identify the benefits from moving tank bulkheads to best match engine mixture ratio. The engine conditions match the previous two configurations except that vehicle performance optimizes at 1985K instead of 2015K pounds F-1 thrust. Mass flow rate is dropped from 113% to 110% of the existing F-1 value.

Summarizing payload can be increased from approximately 10,000 pounds to 62,000 pounds using FLOX. These gains can be accomplished by varying FLOX concentration using "no change" engine and stage at the lower values up to moderate modifications to both engine and stage at the maximum performance range.

1.1.2 Stage Design Summary

Material and process compatibility, sub-systems design, and problem area identification received primary attention. Based on published data and limited Boeing R&D work, the materials used in the material construction of the oxidizer tank and systems apparently are FLOX compatible. Seven minor areas, primarily valves and instrumentation, contain organics or construction techniques that are not FLOX suitable. (See shaded areas on Fig. 1-1.)

Aside from the materials noted above, the current LOX cleaning procedures augmented by fluorine or FLOX gas passivation should make the stage ready for FLOX loading.

Practical evaluation, however, indicates several design areas should receive close attention. Typical are contamination and/or flow stagnation traps such as those in the slosh baffle mounts and convolutions in the GOX and LOX gimbal and flex connectors. Also, as

MATERIALS COMPATIBILITY

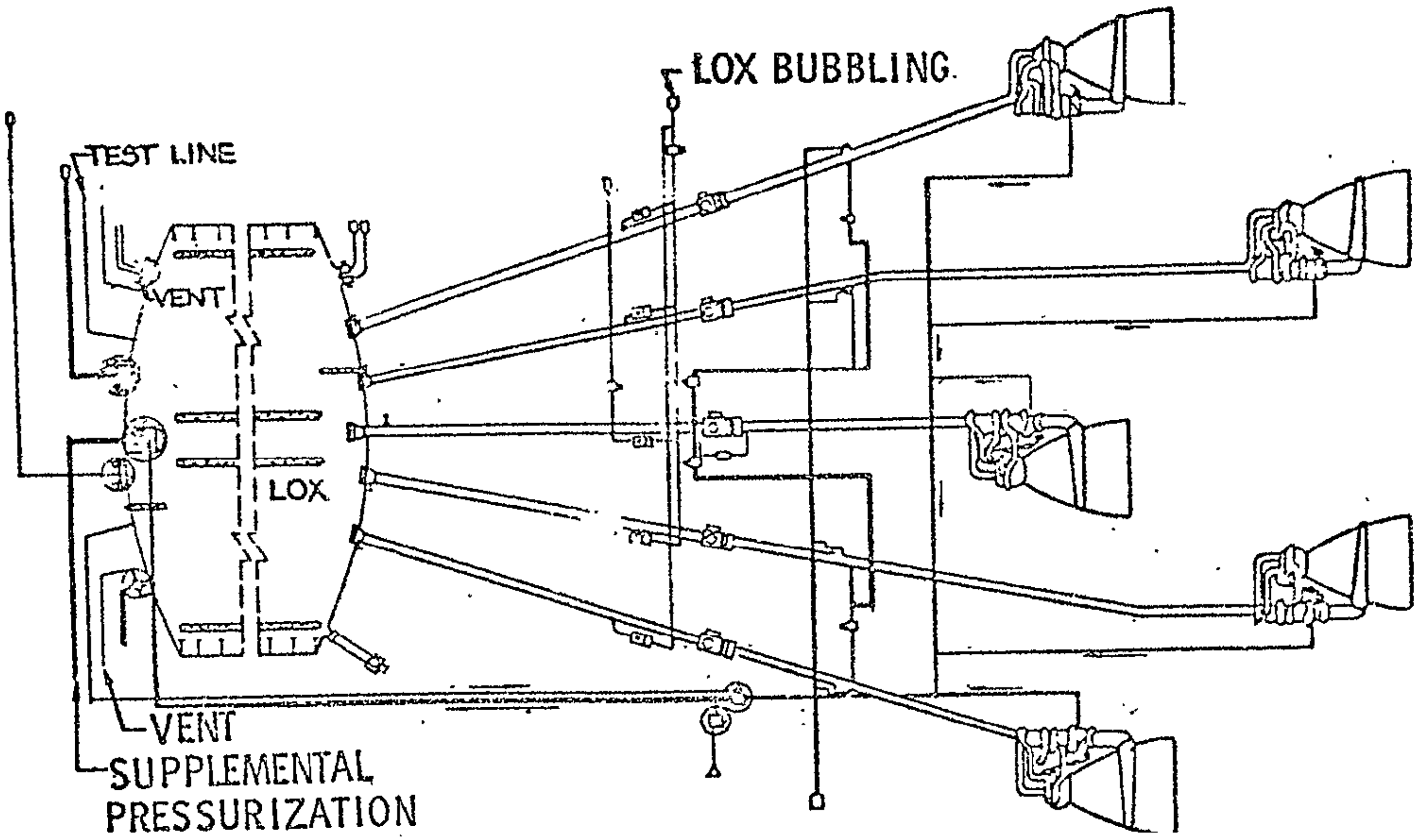

FIG. 1-1

a matter of good practice, fluorine gas at elevated temperatures should be avoided. An alternate oxidizer pressurization system that avoids the hot gas problem is possible and probably would be recommended if detailed design studies were made.

No detailed structural studies were conducted as a part of the TAO. Information developed from previous vehicle uprating studies was generalized to give an approximate estimate of inert weight effects. Follow-on work should include the development of inert weight equations and should include specific design point vehicle studies to properly assess vehicle weights.

1.1.3 Operational Factors Summary

The contract requirements on this subject covered only a problem identification phase and did not specify that magnitude of, or solutions to the problems be defined. However, because this area proved fundamental to feasibility, a general study of the launch area equipment and toxic cloud problem was accomplished.

Figure 1-2 is a schematic of an operational system for FLOX application. All the equipment, except the LOX enrichment storage tank, is new, however, no advancement in the "state of the art" is required for these designs. In fact, it appears that the detail design concept should be determined from overall economic considerations rather than specific design problems.

Toxic cloud effects from "cold spills" do not appear to be governing factors in feasibility. Proper design and operational procedures to alleviate the major portion of the hazard are believed possible.

A normal launch creates large quantities of hydrogen fluoride that are expelled in the lower atmosphere. However, an analysis, based on Army Chemical Corps, ORG Study No. 17, indicates contamination is well within the region of feasible operation, provided weather conditions are not unusually unfavorable. Figures 1-3 and 1-4 show typical study results. The dosage tolerance level used is approximately 50% of the quantity reported by some authorities as acceptable for civilian populations.

Catastrophic (fall back) failure from the analysis technique used, has proved to be the most severe condition. Again using a dosage level well within those predicted as tolerable for a civilian population, the analysis shows that favorable weather conditions are necessary for safe launch. (See Figure 1-5.) Favorable weather conditions are those expected during daytime hours with sunshine and/or favorable winds.

It should be noted that the analysis technique used in the study did not account for elevated temperatures (burning). For analysis simplicity, it was assumed there was an instantaneous gas release. The results shown, therefore, are probably conservative.

GENERAL FLOW DIAGRAM FOR FLOX USAGE

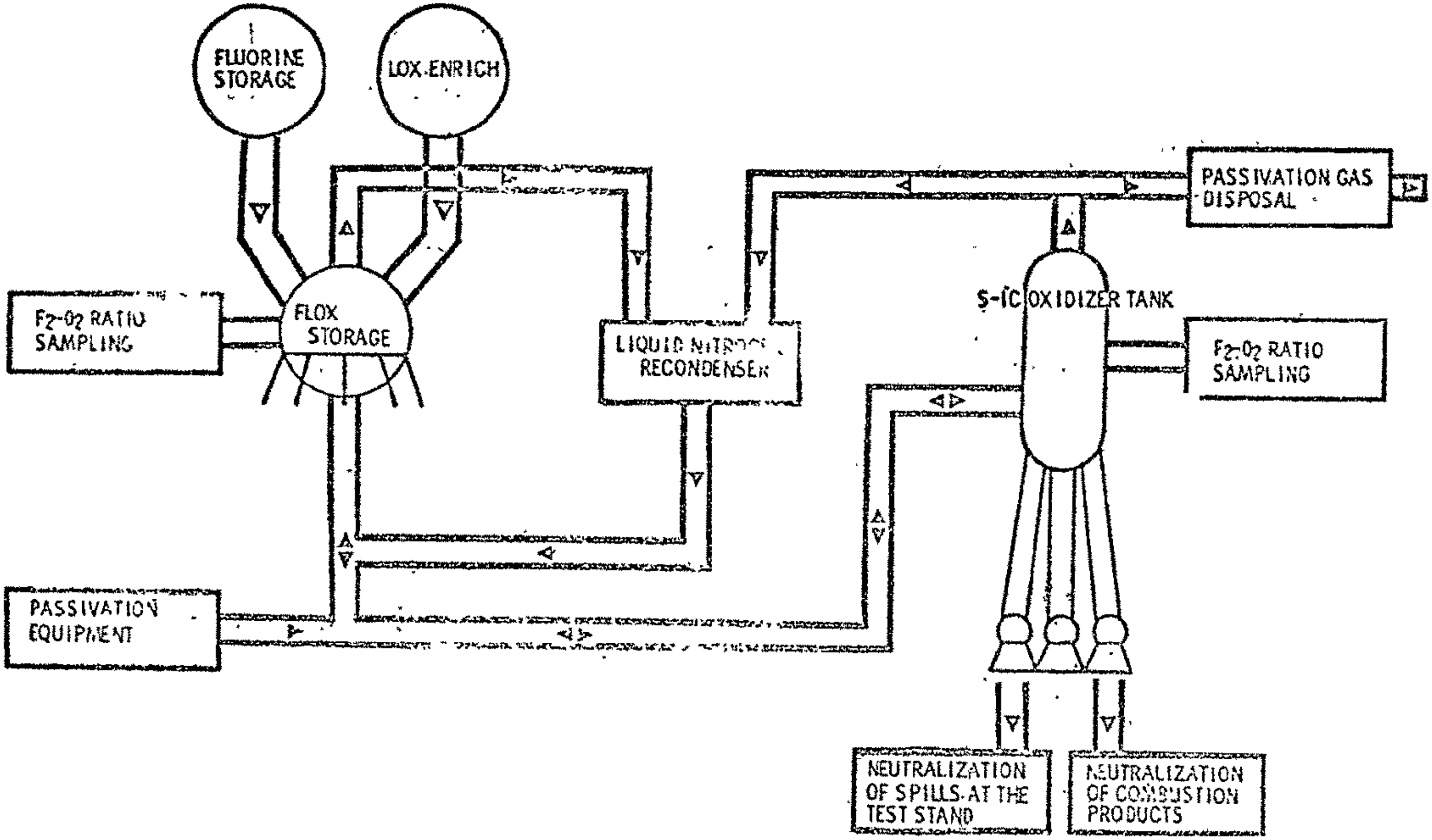

FIG. 1-2

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LAUNCH ANALYSIS

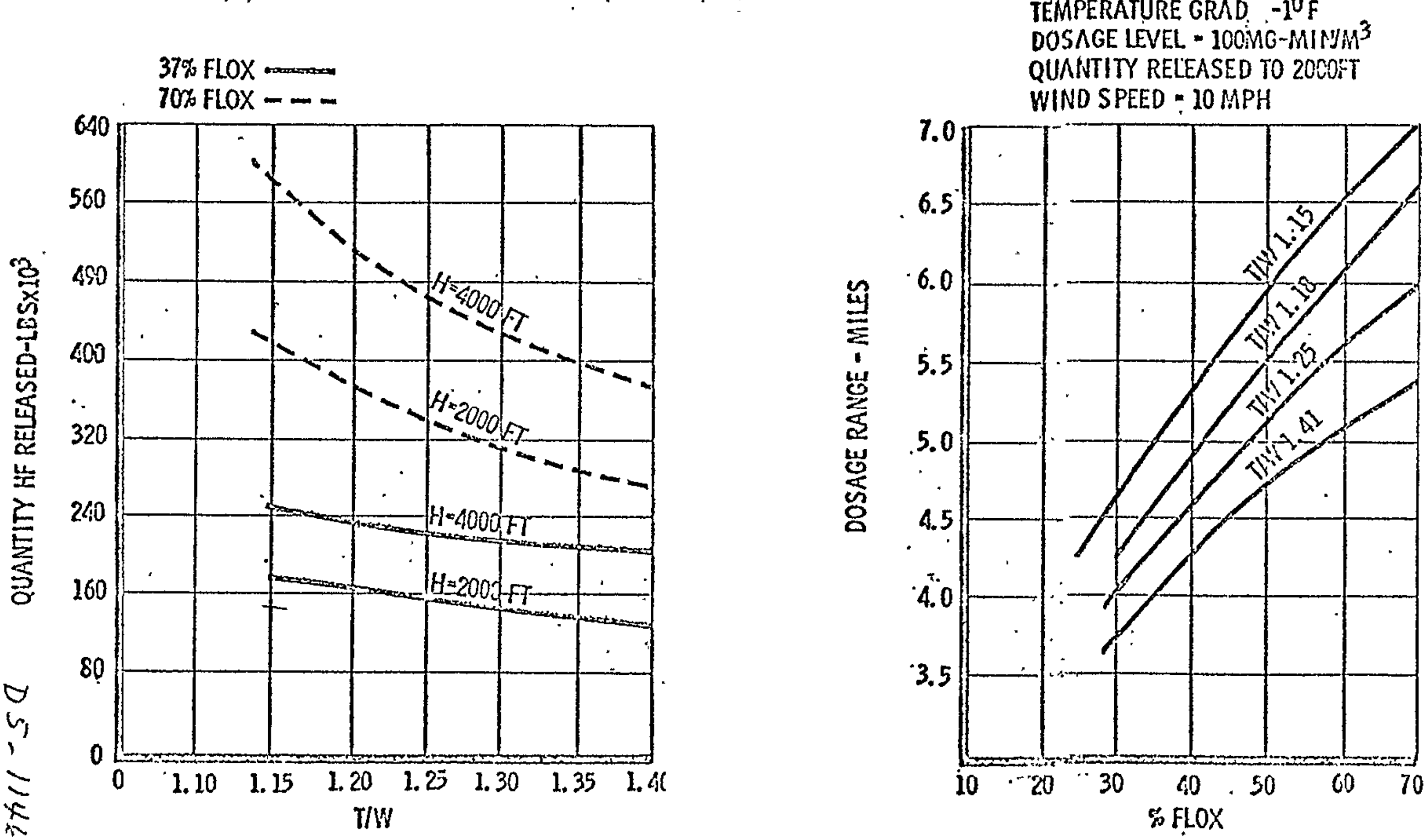

FIG. 1-3

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HYDROGEN FLUORIDE CONCENTRATIONS

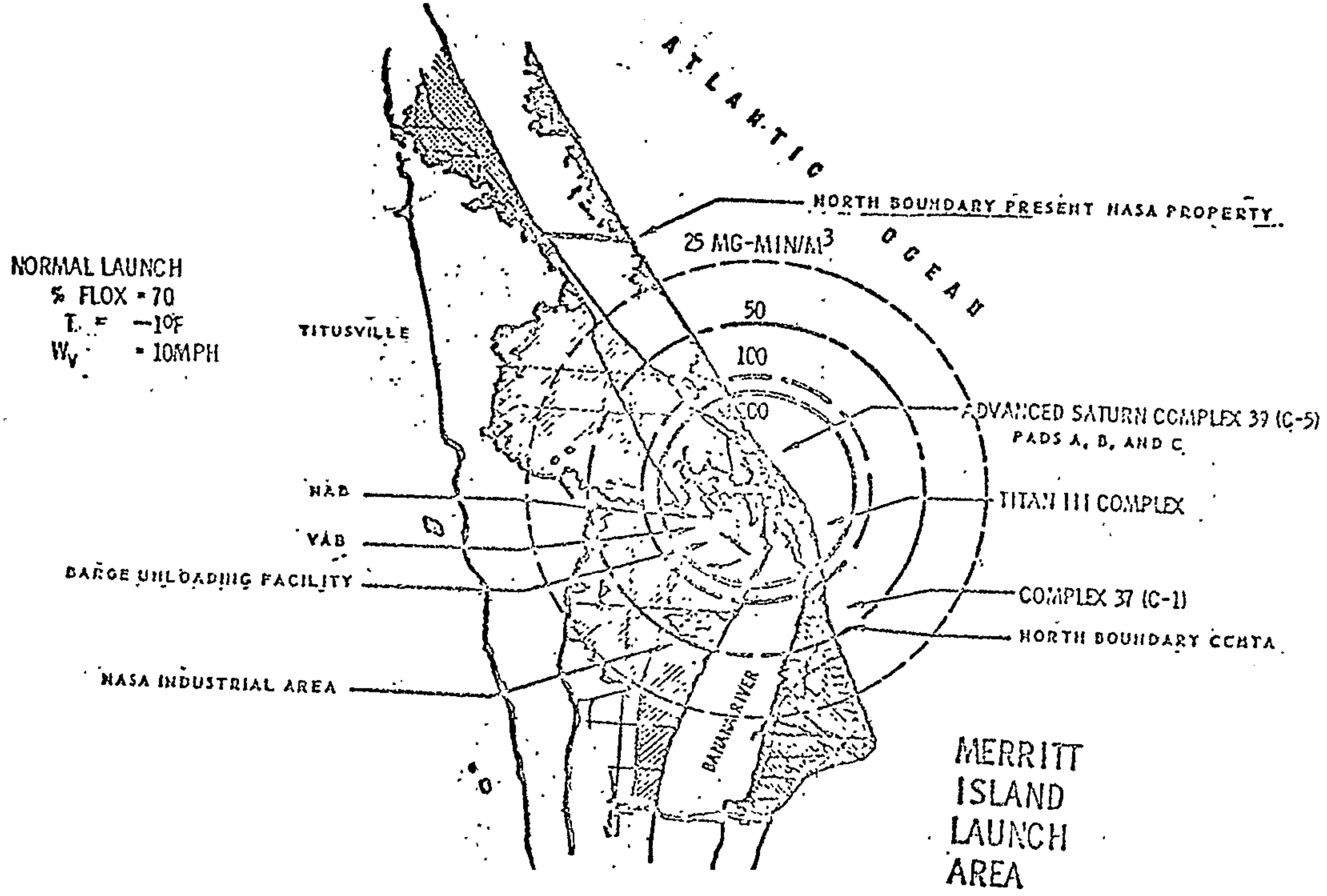

FIG. 1-4

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Sec I Pg II

TOXIC CLOUD STUDIES

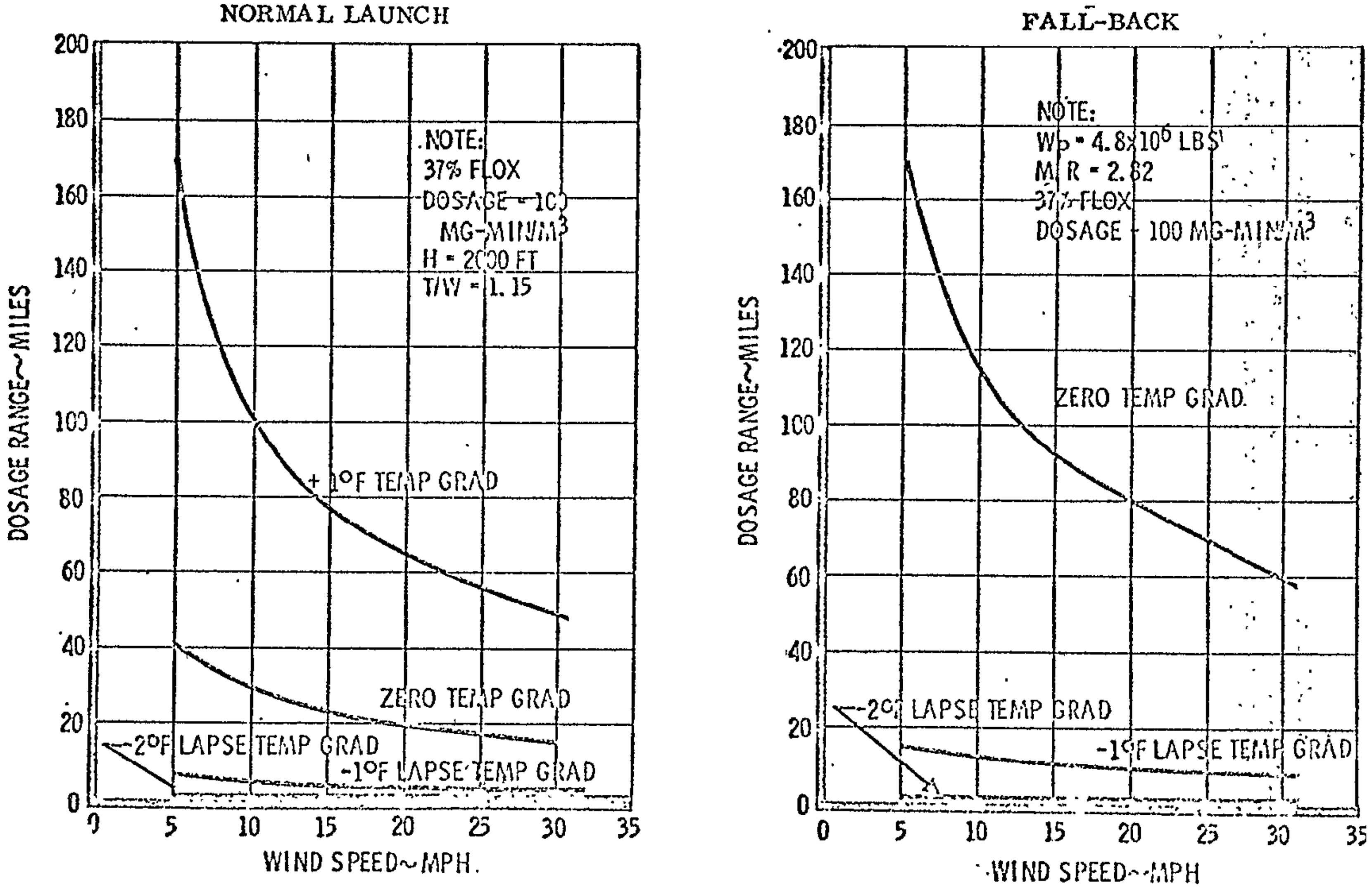

FIG. 1-5

Weather conditions are extremely influential and as a result continuous monitoring of the launch area with suitable computers will probably be necessary for large scale FLOX operation.

In any case, the study shows that if launch time restrictions can be accepted, operation with FLOX is feasible. Further study using more sophisticated analysis methods would be expected to yield even more favorable results.

SECTION 2

PERFORMANCE ANALYSIS

2.0 PERFORMANCE ANALYSIS

2.1 INTRODUCTION AND SUMMARY

This section contains engine performance, vehicle definition and performance, and numerous side study results pertinent to FLOX application. Additional data is contained in the appendix. Both Rocketdyne and Boeing conducted a general analysis of the F-1 engine response with FLOX. Rocketdyne concentrated on limitations of the existing F-1, whereas, Boeing concentrated on conditions of engine operation that could be logically introduced into the stage. Slight discrepancies in Boeing and Rocketdyne performance data exist, however, as a rule, the discrepancies exist at obscure mixture ratios which are of no practical interest.

The status of the performance data is such that the vehicle performance improvement quoted in this report can be used to identify and compare FLOX application, however, confirmation of engine performance by experimental (sub-scale) tests appears necessary.

The following summarize the pertinent performance findings from the study:

1. Payload improvement of 10 percent to 15 percent can be achieved by use of FLOX in the existing engine and stage.
2. Maximum payload using essentially the unchanged F-1 engine is limited to approximately 20 percent.
3. With F-1 chamber cooling tube modification, performance improvement up to 65 percent can be achieved.
4. The existing F-1 chamber cooling limit (based on "coking" carbon build-up) characteristics of RP-1 and (FLOX) is a primary question. Rocketdyne proposed a conservative estimate in the study.
5. Stage system operating performance with FLOX is superior to LOX.

2.2 BACKGROUND

Fluorine is commonly known as a highly reactive element and is, in fact, hypergolic with most organic and several inorganics at room temperatures. Liquid fluorine which has a density of approximately 1.3 times that of LOX, has a basic advantage of loading in a given propellant container.

Mixing fluorine with LOX results in a miscible solution whose density increases as the ratio of fluorine to LOX is increased. FLOX in this study, is defined as the percent fluorine in the total oxidizer quantity, i.e., 50 percent FLOX means 50 percent of the total mixture is fluorine.

Though important, the primary advantage of FLOX in a LOX-RP-1 rocket stage is not the density factor, but the effect on engine performance.

Simplifying, the use of FLOX in the combustion process generally takes advantage of the high reactivity (heat release) of fluorine and because of a change in the gas properties the velocity of the nozzle gases is increased for a given set of chamber operating conditions.

Engine performance can be expressed in the following terms:

$$F = \frac{WVe}{g} + (Pe-Pa)\ Ae$$

where:

F = Thrust

$\dot{W}$ = Chamber weight flow rate

Ve = Exhaust gas velocity

g = Gravitational constant

Pe = Static pressure at nozzle exit

Pa = Ambient pressure

Ae = Exhaust nozzle exit area

Simplifying, the second term "(Pe-Pa) Ae" can be dropped from the equation when gases are expanded ideally within the nozzle. This simplification is valid for general comparison, thus performance maximization can be examined within the basic equation:

$$F = \frac{\dot{W}Ve}{g}$$

Since the W term can be varied arbitrarily with the power availability of the gas generator-turbo-pump system of the engine, it is apparent that the effect of Ve (Velocity) is a primary term. This is further illustrated by substituting specific impulse (Isp) in the equation and simplifying:

$$Isp = \frac{F}{\dot{W}} \text{ or } \frac{Ve}{g}, \text{ for ideal expansion}$$

Maximizing velocity, among other things, is related to the gas properties, consequent acoustic velocity at the nozzle throat and the degree of thermal ionization and recombination. The factors of primary influence on gas properties (performance) are the static temperature and the molecular weight of the combustion products. Based on an energy analysis, if the pressure ratio (chamber to ambient) is fixed at a given value, the velocity term can be expressed as:

$$Ve = C\sqrt{\frac{Tc}{M}}$$

C = Constant

Tc = Combustion temperature

M = Molecular weight

Thus, performance is maximum when combustion temperature is highest and the molecular weight term is minimum.

FLOX in reaction with RP-1 has an effect on both terms and theoretically $\frac{Tc}{M}$ maximizes at approximately 70 percent FLOX.

The table below summarizes the correlation of Ve and $\sqrt{Tc/M}$ of some propellants at arbitrarily selected mixture ratios.

Propellants	Tc(°R	M	$\sqrt{\frac{Tc}{M}}$	Ve-Ft/sec
O_2/RP-1	6610	23.3	16.8	9,660
30%FLOX/RP-1	6500	21.7	17.3	10,700
70%FLOX/RP-1	7800	21.0	19.3	11,700
N_2O_4/N_2H_4	5890	21.5	16.5	9,360
O_2/H_2	5395	10.0	23.2	12,500
H_2/Nuclear	4500	2.0	47.5	25,000

Another factor of major significance is the effect of FLOX on the rest of the engine cycle specifically the turbopump, gas generator and systems.

The benefits of increased density are readily apparent in terms of pump and system performance. The improvement in engine-nozzle performance discussed previously also applies to the gas generator in terms of turbine power availability.

Summarizing, the overall impact of FLOX on vehicle/engine performance is: increased density for increased loading and reduced pressure drop, greater power availability from components and most significant, the substantial improvement in chamber/nozzle performance.

2.3 PERFORMANCE LIMITATIONS

2.3.1 Thrust Considerations

Limitations to uprating the F-1 engine can be defined specifically in terms of major components or subsystems. Rocketdyne has conducted a study on the limitations of the F-1 engine with FLOX addition. The limitations from their study, are of a systems operation nature and do not necessarily include stress limits. Increasing material strength or gage and redesigning minor components are considered straightforward, non-development changes. In the F-1 system, the primary limit is the turbine and a secondary limit is chamber cooling. As FLOX is added, the thrust level is increased and the corresponding power requirement is met either by greater power availability from FLOX or increased turbine weight flowrate. If the turbine inlet pressure requirement increases at a faster rate than the pump discharge pressure, then all orificing capability in the gas generator feed line is lost. This is offset somewhat by the increase in pump speed which accompanies the developed head rise but a flow imbalance results and the engine main line must be orificed to maintain the proper mixture ratio. In the study, the maximum attainable thrust level was established as that thrust delivered with no orifices in the gas generator feed line other than that which would be required to adjust for the nominal turbine inlet temperature. Figure (2-1) shows the maximum thrust as a function of mixture ratio for the three fluorine concentration investigated by Rocketdyne. Figures 2-2 through 2-5 show the corresponding specific impulse improvement. All data are referenced to the F-1 model specification of date.

2.3.2 Turbopump Considerations

Boeing conducted investigations to determine the turbopump power requirements for the FLOXed F-1 engine and any associated thrust limits. The required pump power was calculated from ideal model laws and does not account for any changes in orifices or line configuration, therefore, fuel pump power may not decrease as much as is shown. Figures (2-6) and (2-7) show the results of this study. For the cases of constant volume and weight flowrate, it should be possible to get significant increases in thrust with little or no change.

2.3.3 Engine Heat Transfer - Performance Considerations

2.3.3.1 General

Rocketdyne conducted investigations to determine the heat transfer limits of the present F-1 engine system with FLOX. The assumptions made in generating the results follow:

(1) The 1522K thrust "qualification" F-1 engine configuration is used with only minor change except substitution of FLOX as the oxidizer.

(2) Changes required are straightforward and do not involve appreciable R&D which would be necessary for new components. and are restricted to such "quick fixes" as:

- (a) Routine structural increases to overcome stress redlines.
- (b) Substitution of materials for compatibility with the new propellant.
- (c) Dimensional modification to existing hardware to optimize system performance and/or to extend operational limits (pump impeller trimming, component flow passage refinement to reduce pressure drop, etc.)

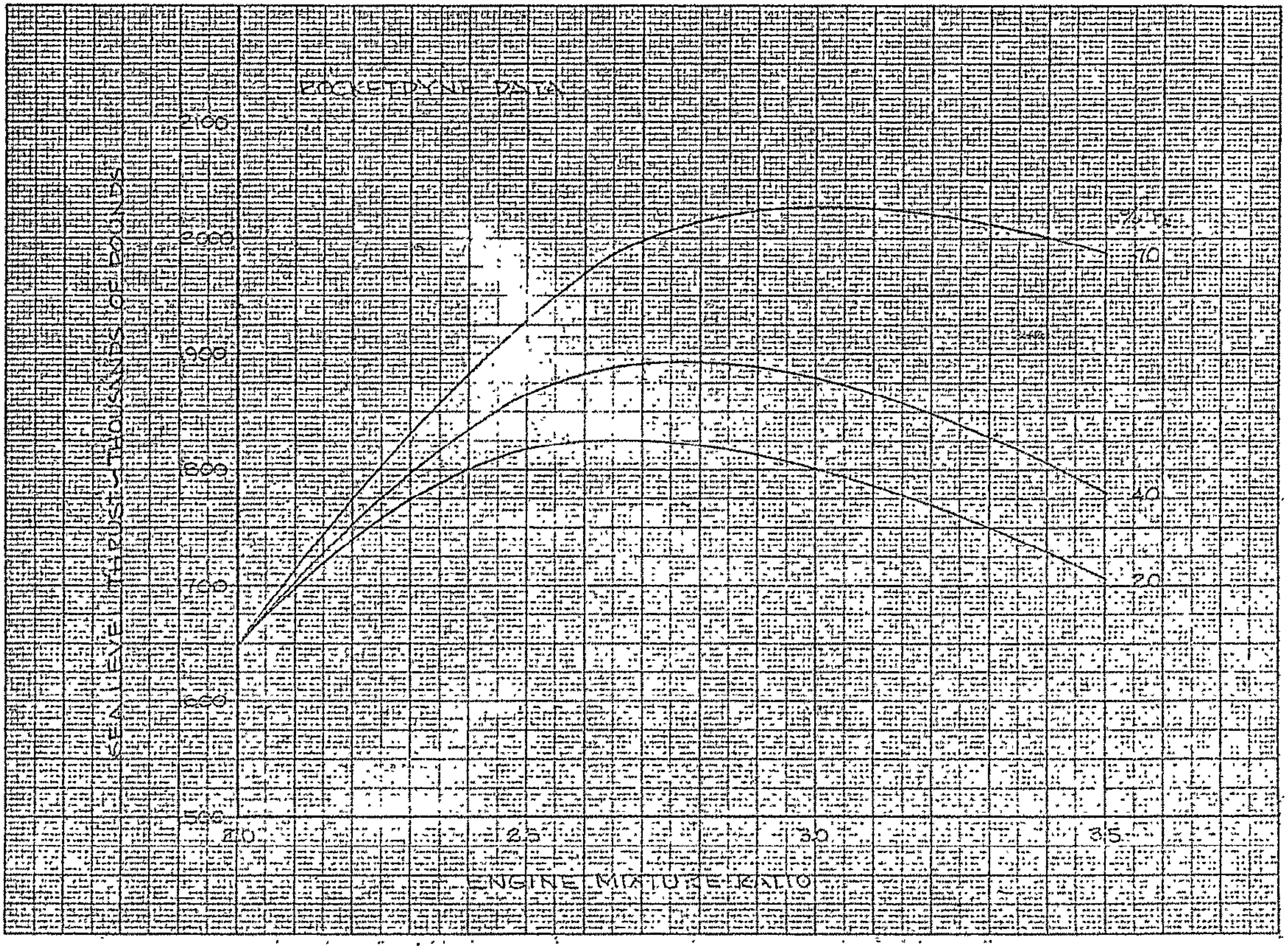

Fig. 2-1 Estimated FLOX/RP-1 Performance

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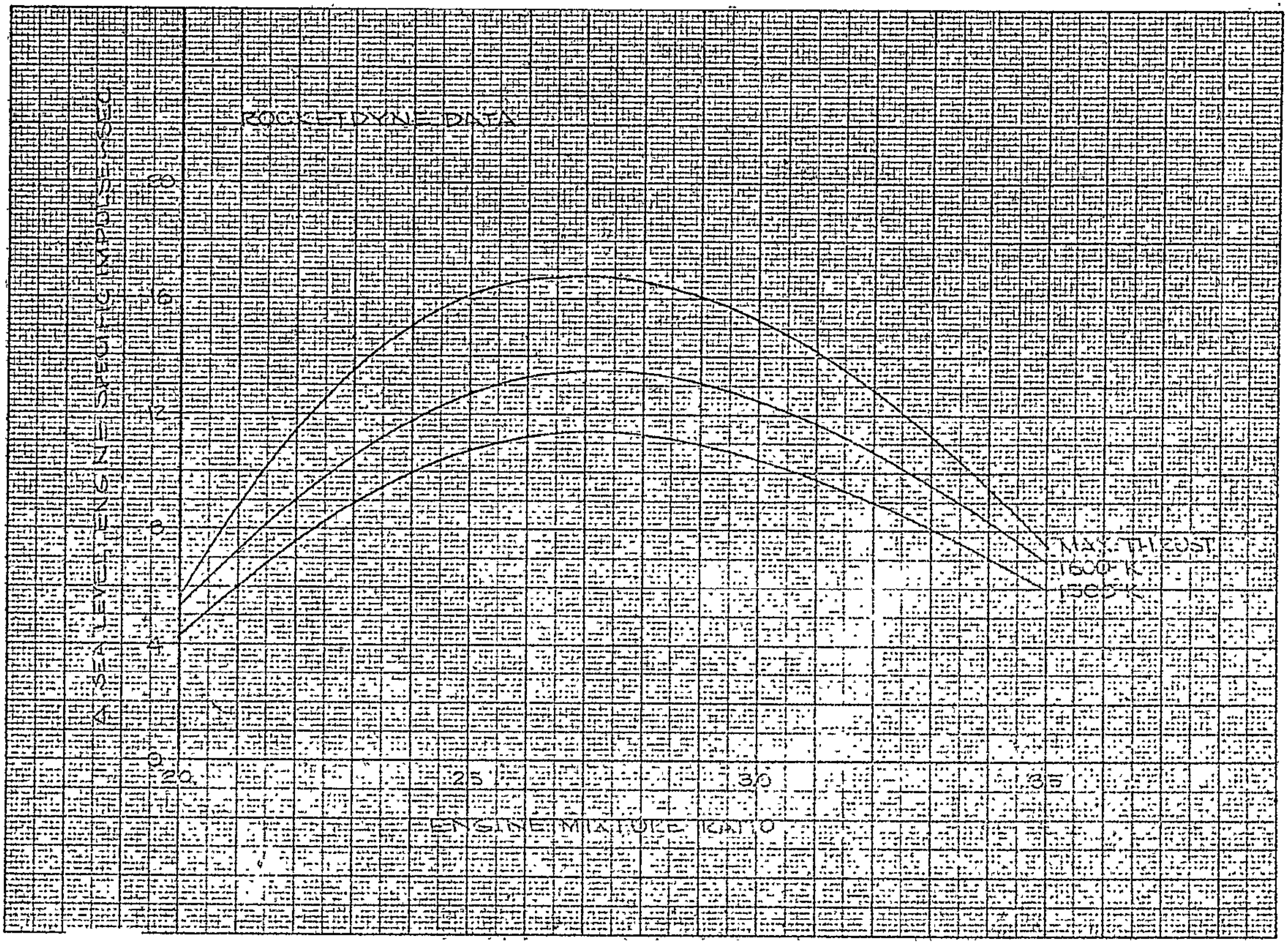

Fig. 2-2 Estimated F-1 20% FLOX/RP-1 Performance

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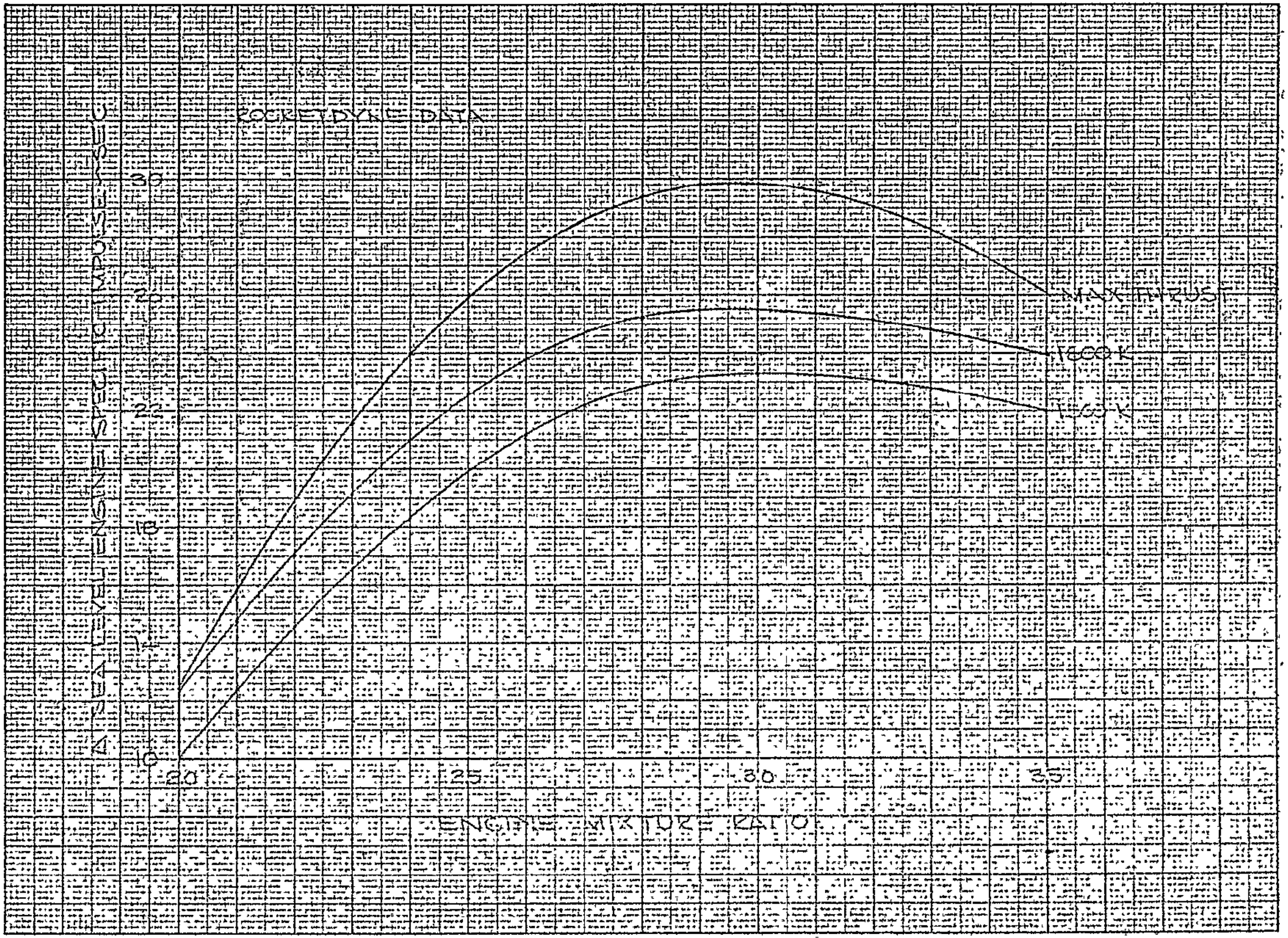

Fig. 2-3. Estimated F-1 40% FLOX/RP-1 Performance

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Pg

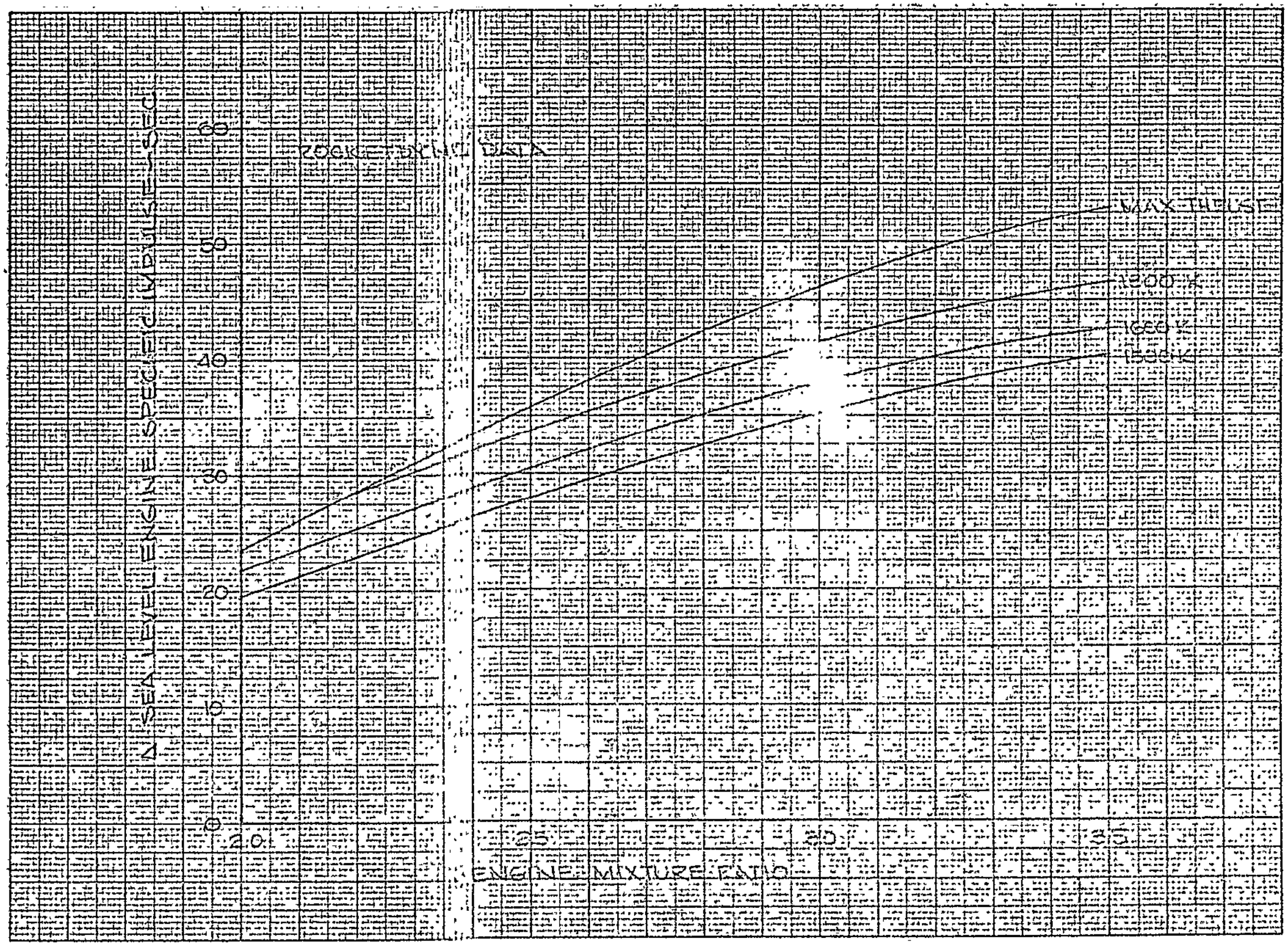

Fig. 2-4 Estimated F-1 70% FLOX/RP-1 Performance

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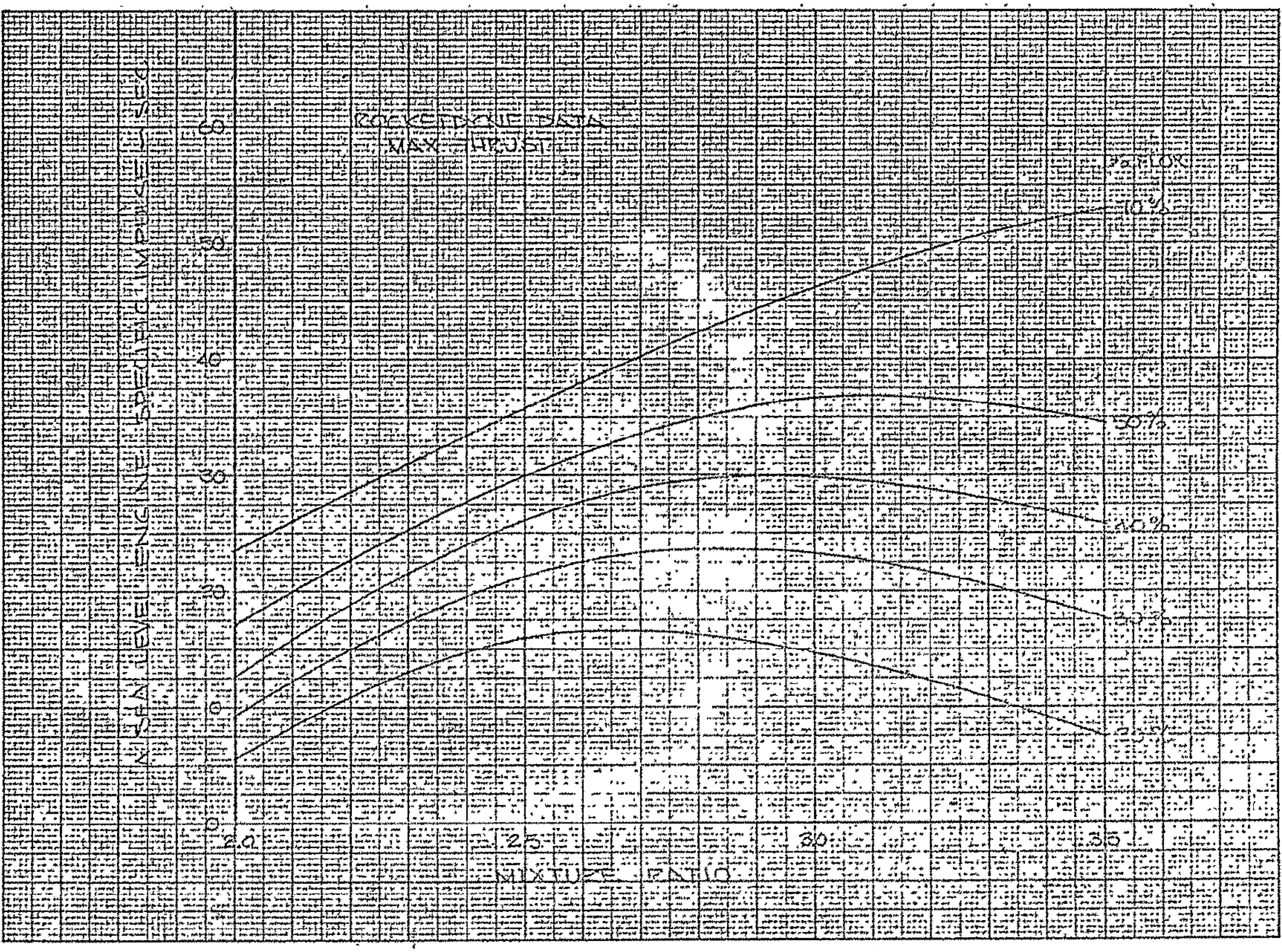

Fig. 2-5 Estimated F-1 Engine Performance at Various FLOX Percentages

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K&E 10 X 10 TO ½ INCH 46 1323
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

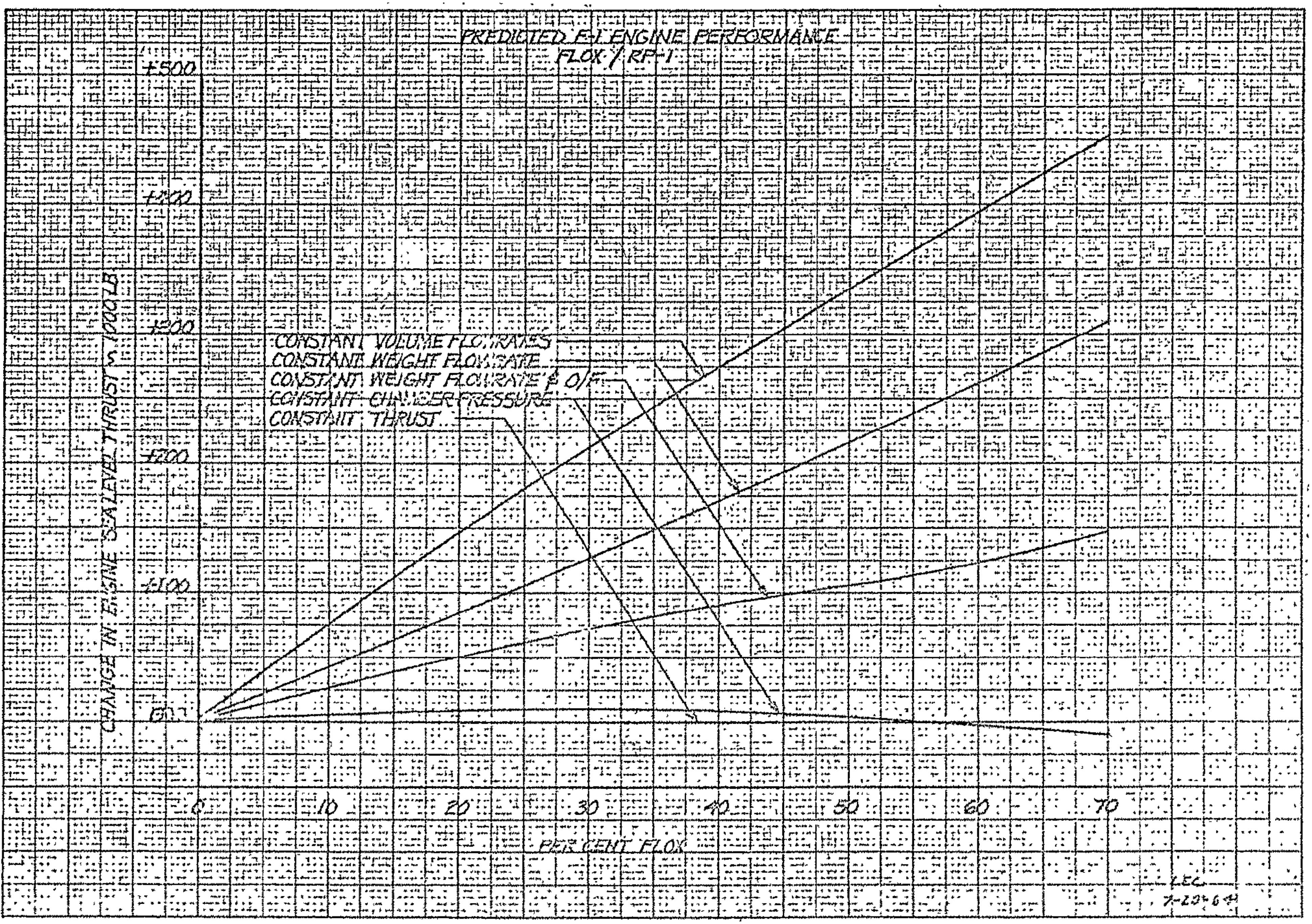

Fig. 2-6

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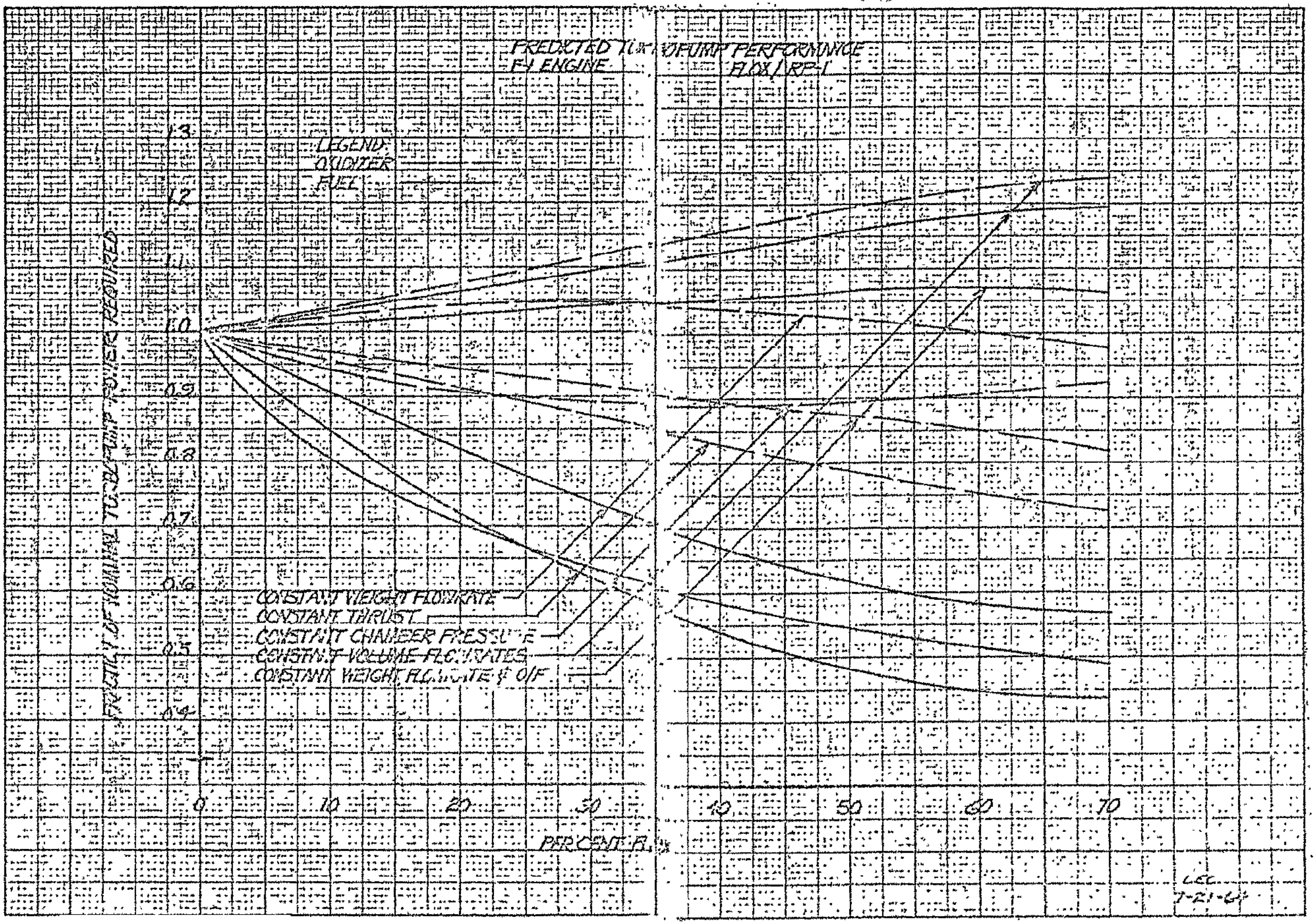
PREDICTED TURBOPUMP PERFORMANCE
F-1 ENGINE
FLOX / RP-1
LEGEND
OXIDIZER
FUEL
FRACTION OF NOMINAL TURBOPUMP POWER REQUIRED
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
CONSTANT WEIGHT FLOWRATE
CONSTANT THRUST
CONSTANT CHAMBER PRESSURE
CONSTANT VOLUME FLOWRATES
CONSTANT WEIGHT FLOWRATE & O/F
0
10
20
30
40
50
60
70
PERCENT FLOX

LCC
7-21-64

2.3.3.2 Heat Transfer Analysis

The following ground rules and assumptions apply to the heat transfer results.

(1) The existing chamber tubes were not changed in any way.

(2) The carbon layer on the hot gas side of the tubes was estimated at the different FLOX concentrations by correlating model-motor test data (using LOX/RP-1 and limited oxygen difluoride OF_2/RP-1) and full-scale F-1 LOX/RP-1 test data.

(Note: The thickness of the carbon layer is an extremely important factor in the cooling capability of the thrust chamber. The total experimental data available is limited, however, the thickness was assumed to reduce as the fluorine concentration increased. This assumption needs further experimental verification.)

(3) The mixture ratio limits quoted are for no direct chamber injection, i.e., all fuel flow is routed through the cooling system.

(Note: At lower mixture ratios, some of the fuel would undoubtedly be by-passed to minimize pressure drop.)

Figures (2-8), (2-9) and (2-10) show the thrust chamber cooling limits as determined by Rocketdyne.

(Note: Rocketdyne states that the mixture ratio limits as determined by their initial study are not absolute. A number of quick fixes are available which singly or in combination could be used to increase the allowable mixture ratios without violating the restriction of "No major thrust chamber re-design.")

The following approaches are possibilities:

(1) Change in tube material

(2) Change in tube wall thicknes

(3) Localized increases in tube coolant velocity and turbulence ("dimples or spoilers")

(4) Increased injector film cooling

(5) Possible substitution of a hydrocarbon fuel with a higher coking temperature

Incorporation of one or more of the possibilities noted above would broaden the capability of the F-1 and allow operation up to the gas generator power limit. Performance data with modified cooling are shown on the previous figures 2-1 through 2-5.

2.3.3.3 Carbon Deposition in a FLOX/RP-1 Thrust Chamber (Boeing Analysis)

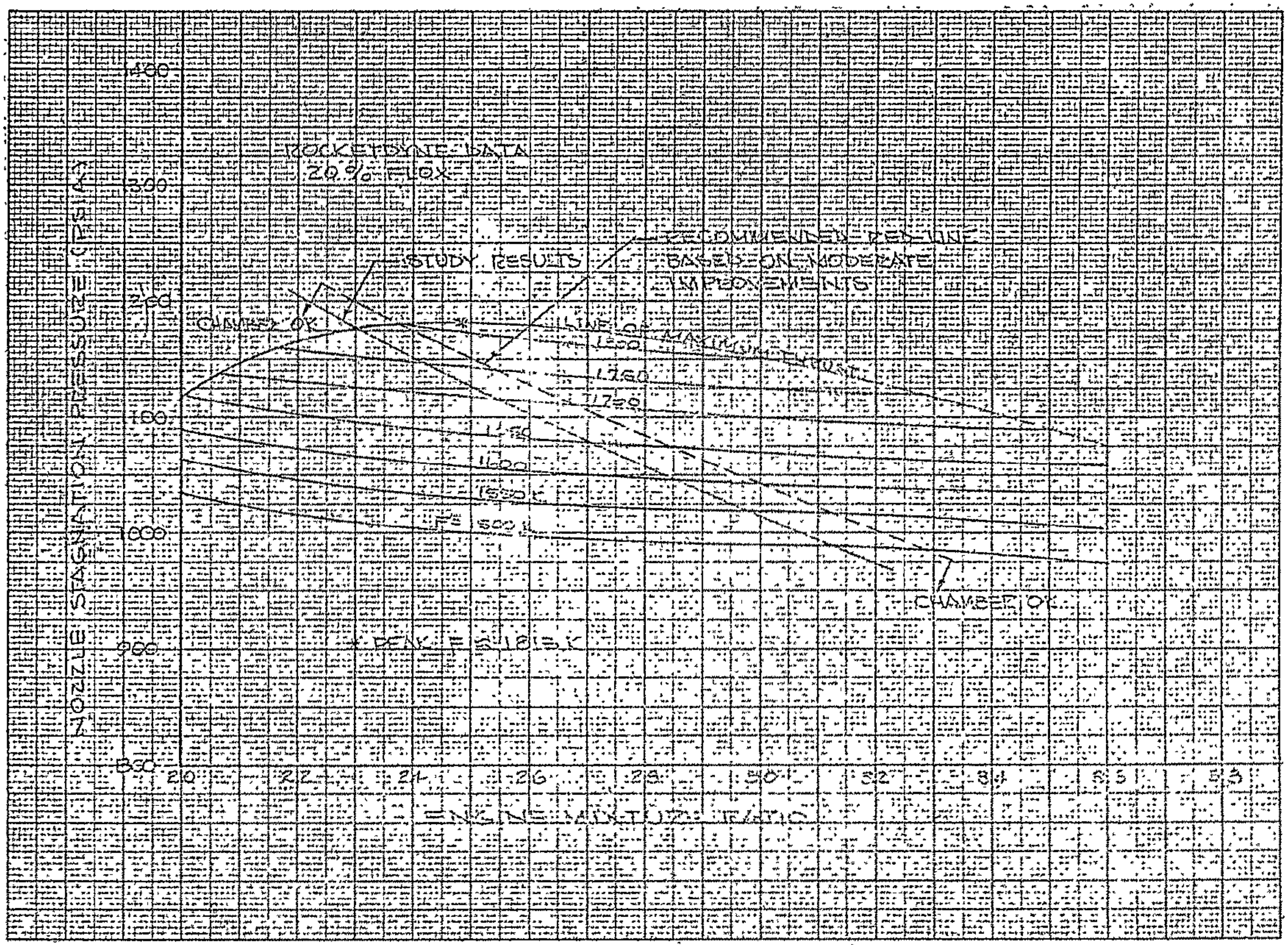

Fig. 2-8. F-1 Thrust Chamber Cooling Limit with 20% FLOX

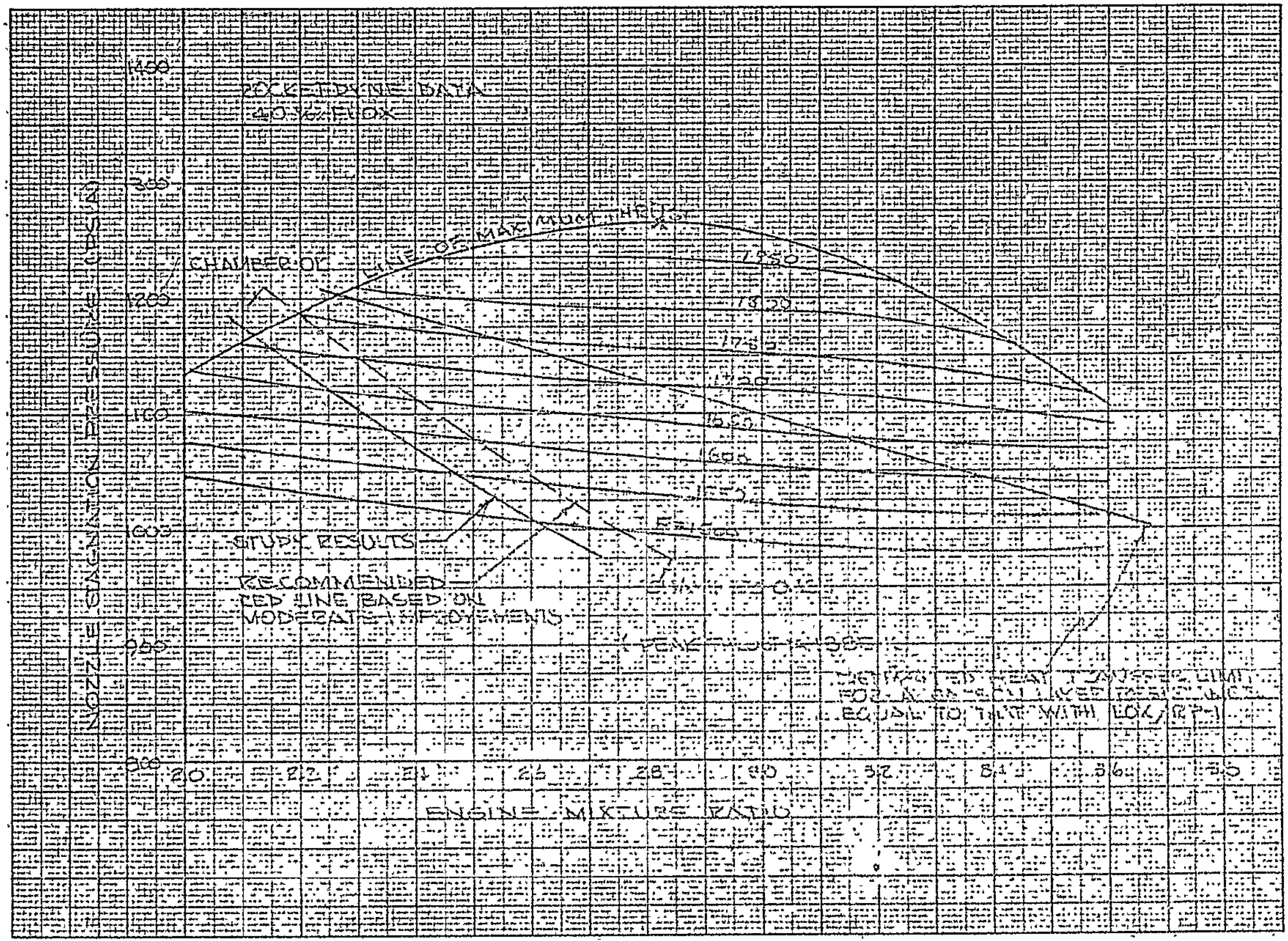

Fig. 2-9 F-1 Thrust Chamber Cooling Limit with 40% FLOX

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Sec 2 Pg 15

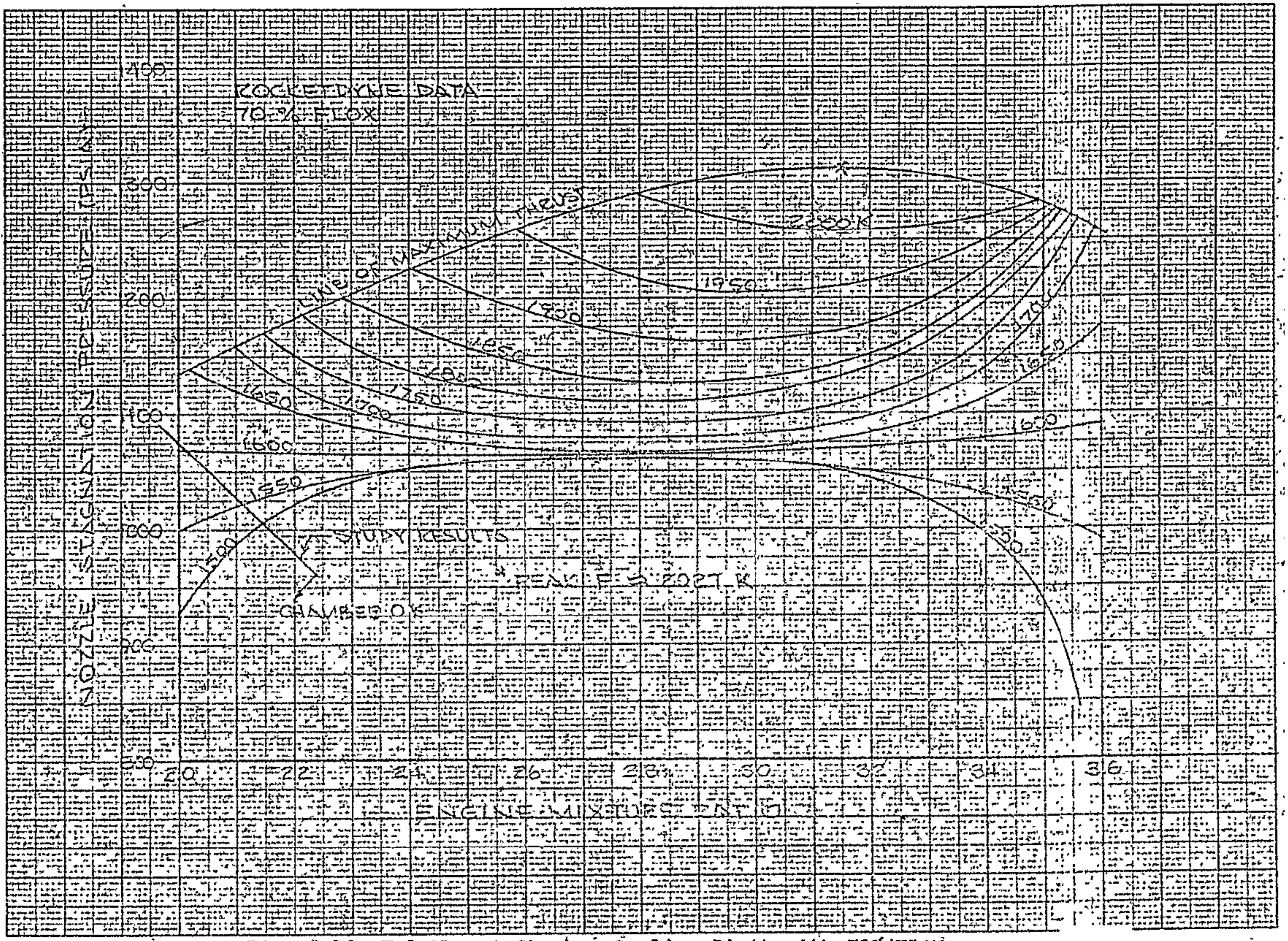

Fig. 2-10 F-1 Thrust Chamber Cooling Limit with 70% FLOX

D5-114
Sec 2

Boeing conducted a cursory analysis of carbon deposition in a FLOX/RP-1 thrust chamber. Since data are readily available for LOX/RP-1, this combination was used for comparison. It was assumed both propellant combinations are fired in identical chambers, under constant chamber pressure and at optimum mixture ratio.

There are several possible arguments, supporting either greater or lesser carbon buildup as the fluorine percentage increases, if the mechanics and thermodynamics of the combustion process are considered.

The hard, striated deposits most probably exist from thermal cracking in the liquid phase of the fuel which impinges on the chamber walls. The amount of deposit depends on the length of run with deposit weight increasing linearly with time in the initial stages. A maximum thickness is attained, however, when the rate of deposit buildup is equaled by the rate of erosion. This hypothesis has been shown to be correct by experimental data although the actual deposit thickness fluctuates around a steady state value because the deposits break off as relatively large chunks of material.

Since equilibrium is established in both propellant combinations under study, the combustion mechanism is unimportant to the analysis of deposit thickness. This is especially true since the deposit is a product of the fuel only and should not be influenced by the oxidizer makeup.

The remaining parameter which could influence deposit weights is the rate of carbon deposit erosion.

Increased pressure is known to accelerate smoke formation in combustors. Coke deposits are, in general, affected similarly; that is, a leveling-off in deposit rate has been found once the pressure is increased to two or three atmospheres. This is attributed to increased rate of erosion with increased combustion gas density. Coke deposition would be expected to increase with pressure; reach a steady state, and then decrease as pressure continues to rise. At constant chamber pressure, specified in the system study, no effect would be expected.

Rocketdyne has mentioned a rough inverse relationship between deposit thickness and fluorine percentage in the oxidizer in a gas generator combustion chamber. (See par. 2.3.3.2.) Assuming constant chamber pressure, comparison of the molecular weights of LOX/RP-1 and FLOX/RP-1 combustion products under extreme fuel rich conditions shows nearly identical values. Under near stoichiometric conditions the molecular weight of the FLOXed system combustion products is actually slightly less than that of the LOX system, indicating slightly heavier deposits for the FLOX system.

Higher combustion temperatures would tend to reduce the deposit thickness. Continued carbon buildup would reduce the heat transfer and increase the carbon surface temperature until burning commenced. As the carbon layer burned away, the heat transfer would increas thereby cooling the surface and once again allowing the layer to rebuild. The deposit thickness would, therefore, be inversely proportional to the combustion gas temperature.

Finally, if the velocities of the exhaust gases are compared, it is evident that a more erosive effect would be exerted by the FLOX propellant combination, thus reducing deposit thickness by establishing equilibrium earlier. The reduced carbon thickness would only appear in the nozzle area where the expanding gases are accelerating: no effect would appear in the combustion chamber.

No other comparisons of the two systems are available. It appears that a slight decrease in carbon thickness would result from a FLOXed system burning near stoichiometric conditions, with the effect becoming more pronounced for higher fluorine percentages. If the above hypothesis is correct, fuel coking in the coolant tubes could become a serious problem because of the dual effect of higher temperatures and lower carbon deposits.

It may be stated that under constant combustion chamber conditions the carbon deposition rate and structure for FLOX/RP-1 are identical. The only parameters which could effect deposit thickness are the combustion gas properties. A higher combustion gas temperature and velocity will increase erosive effects, thereby reducing deposit thickness. The combined effect of higher combustion temperatures and lower hot-gas side insulation may create coking problems in the interior (fuel side) of the coolant tubes.

2.3.4 Estimated NPSH Requirements (Boeing Analysis)

Operation of the F-1 engine with FLOX RP-1 propellants will probably necessitate a change in fuel and oxidizer volumetric flow rates in order to maintain a suitable engine mixture ratio. The result will be, in most cases, a change in NPSH requirements. These requirements were calculated from ideal model laws and, therefore, do not account for any changes in pump downstream resistances (orifice or line configuration changes) or real pump behavior which deviates from the ideal. Calculations were made for the following five cases:

(a) constant total weight flow rate at a mixture ratio which optimizes the engine sea level specific impulse
(b) constant combustion chamber pressure at optimum mixture ratio
(c) constant thrust at optimum mixture ratio
(d) constant volumetric flow rate of both fuel and oxidizer
(e) constant total weight flow rate at the nominal mixture ratio

As can be seen from Fig. 2-11, the NPSH requirement for each operating case decreases with increasing FLOX percentage. Therefore, reduced requirements for the pressurization system are expected when FLOX is used on the S-IC.

2.4 ESTIMATED F-1 ENGINE PERFORMANCE (BOEING ANALYSIS)

Theoretical performance calculations for FLOX/RP-1 propellants indicate that specific impulse increases with fluorine content and is maximum at a FLOX mixture of about 70 percent. This mixture of fluorine and oxygen represents the optimum propellant composition for preferential

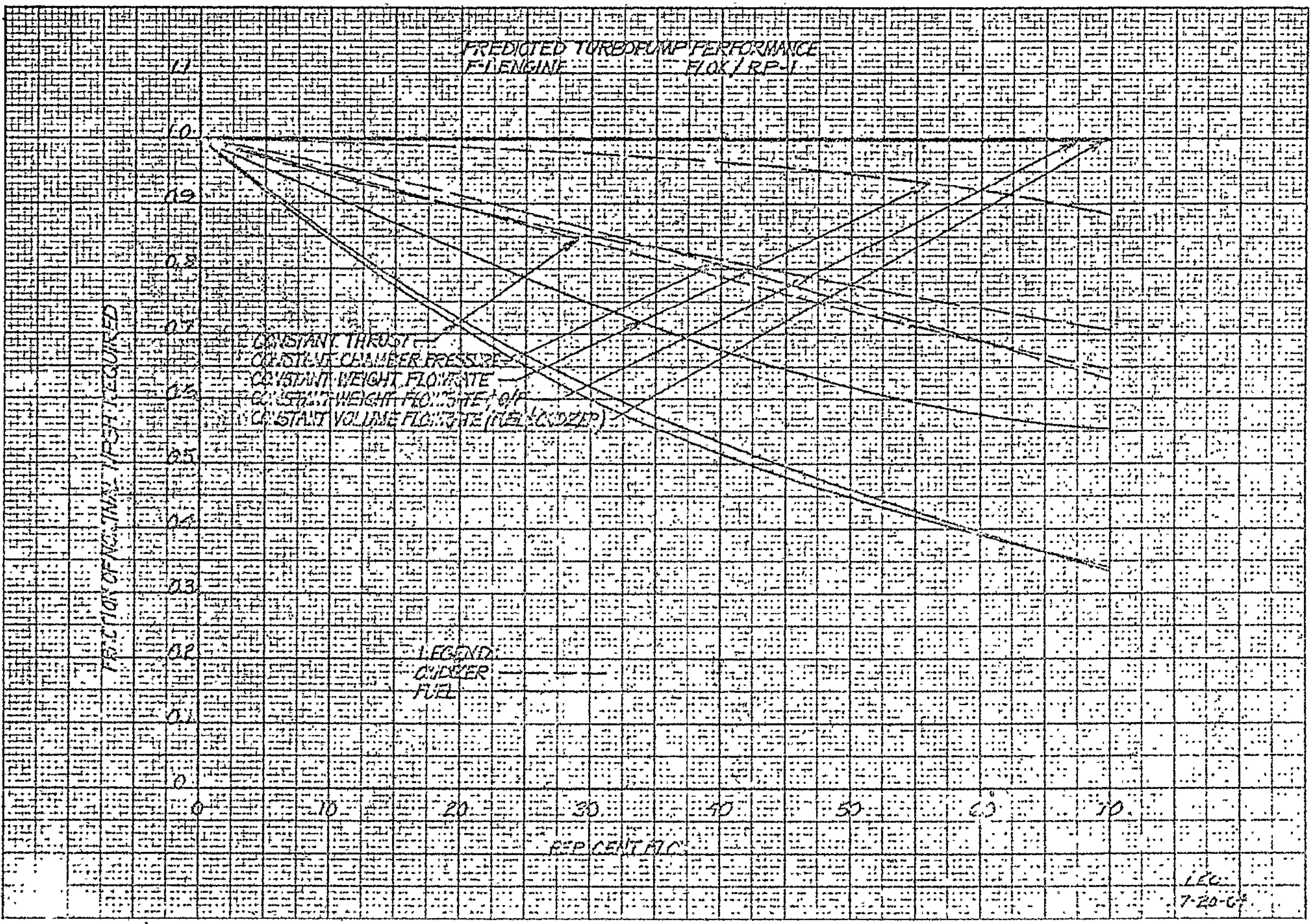

FIG. 2-1

D5-11459-1

burning of fluorine with hydrogen, and oxygen with carbon. Boeing made performance estimates for the following conditions:

(a) constant total weight flow rate at a mixture ratio which optimizes the engine sea level specific impulse
(b) constant combustion chamber pressure at optimum mixture ratio
(c) constant thrust at optimum mixture ratio
(d) constant volumetric flow rate of both fuel and oxidizer
(e) constant total weight flow rate at the nominal mixture ratio

These resulting data have been checked with Rocketdyne and NASA information and general agreement exists. They are presented here for added information.

Traditionally, a theoretical base of either frozen or shifting equilibrium composition is selected and appropriate efficiencies are applied to predict an actual engine operating trend. Boeing experience in reaction kinetics coupled with various state-of-the-art kinetic analyses strongly indicated that the performance of either LOX/RP-1 or FLOX/RP-1 propellants expanded in an F-1 thrust chamber would be very closely approximated by a complete shifting equilibrium expansion. A theoretical shifting base was, therefore, used to predict FLOX/RP-1 F-1 engine performance. The efficiencies used to correct the theoretical sea level specific impulse to expected F-1 actual performance with FLOX were obtained from data provided by Rocketdyne.

Assumptions made in the analysis include a constant sea level thrust coefficient and a gas generator mixture ratio which decreases with percent FLOX to maintain the nominal gas generator combustion chamber temperature.

Figures 2-12 through 2-17 show the results of the Boeing study referenced to the specification F-1 engine. Note that the maximum (i.e., gas generator power limit) performance case was not defined as was accomplished in the Rocketdyne study.

2.4.1 Reaction Kinetic Analysis of the Combustion Products

Some discrepancy between Boeing and Rocketdyne specific impulse predictions are apparent. As indicated, these differences, for the most part, are small, generally less than 3 to 4 seconds in regions of primary interest.

As indicated previously, a reaction kinetic analysis of the combustion products of LOX/RP-1 and 30% FLOX/RP-1 expanded in an F-1 thrust chamber is believed near shifting equilibrium flow specifically in the mixture ratio range between 2.0 and 3.2. There is a distinct trend toward frozen flow which theoretically occurs at low mixture ratios. Near frozen flow would not be expected to occur until the mixture ratio is below about 1.6 for LOX/RP-1. Until tests prove otherwise, Boeing recommends that essentially shifting equilibrium be used to predict F-1 engine performance with FLOX/RP-1 propellants.

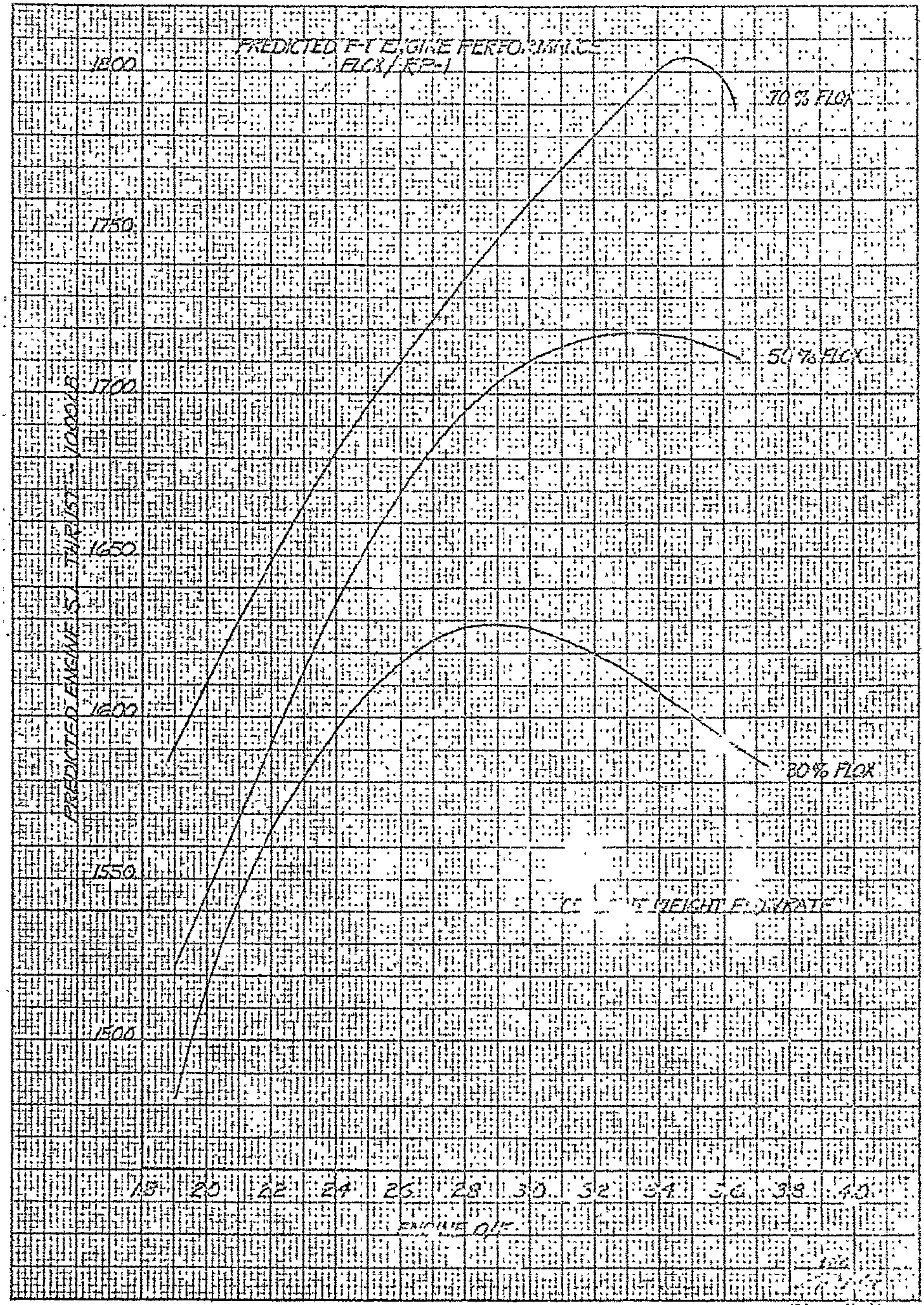
PREDICTED F-1 ENGINE PERFORMANCE
FLOX / RP-1
PREDICTED ENGINE SL THRUST ~ 1000 LB
1800
1750
1700
1650
1600
1550
1500
70 % FLOX
50 % FLOX
30 % FLOX
CO T WEIGHT F OWRATE
18
20
22
24
26
28
30
32
34
36
38
40
ENGINE O/F

Fig. 2-12

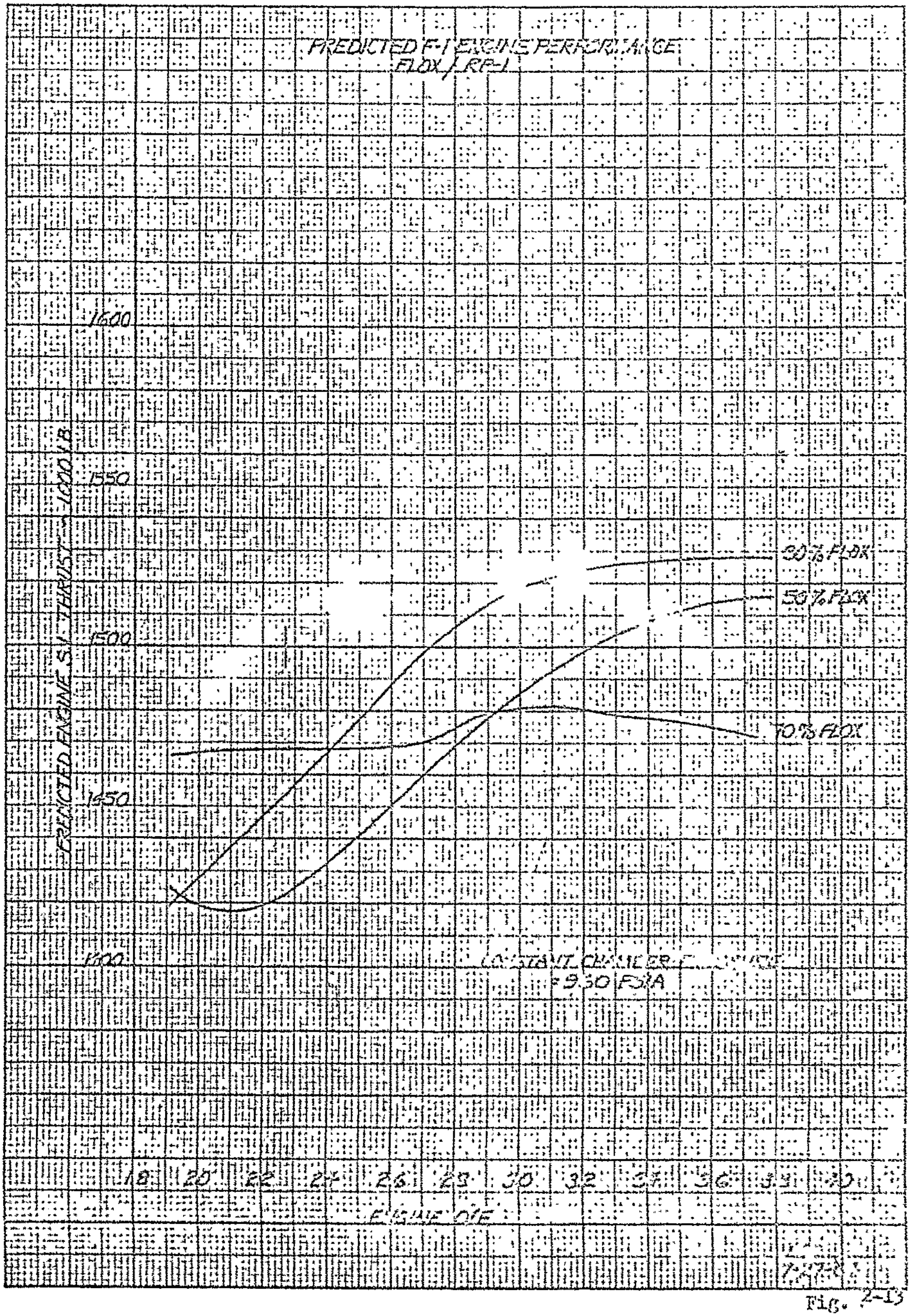
PREDICTED F-1 ENGINE PERFORMANCE
FLOX / RP-1
PREDICTED ENGINE S.L. THRUST ~ 1000 LB
1600
1550
1500
1450
1400
30% FLOX
50% FLOX
70% FLOX
CONSTANT CHAMBER PRESSURE
= 930 PSIA
18
20
22
24
26
28
30
32
34
36
38
40
ENGINE O/F

Fig. 2-13

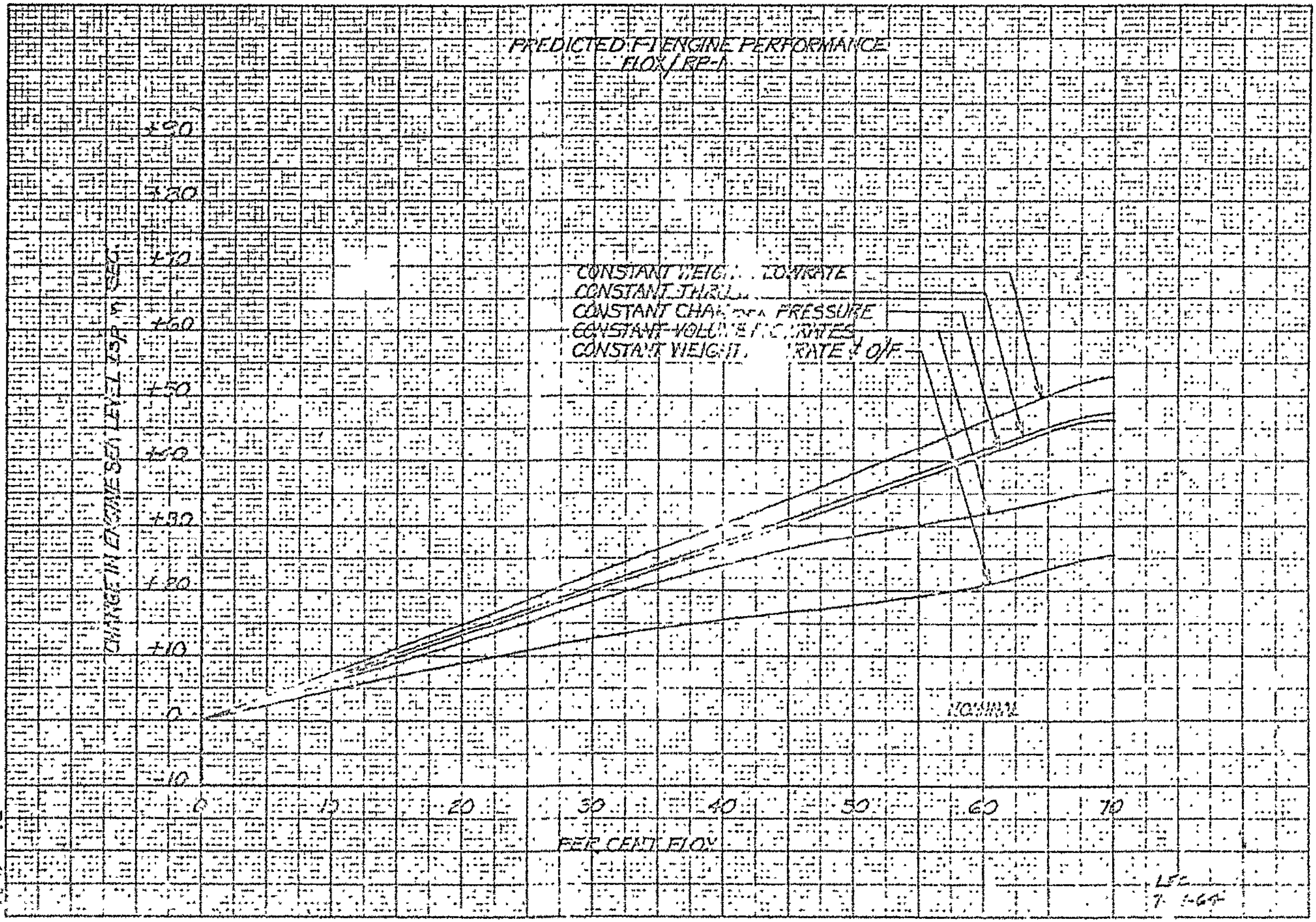

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Fig. 2-14

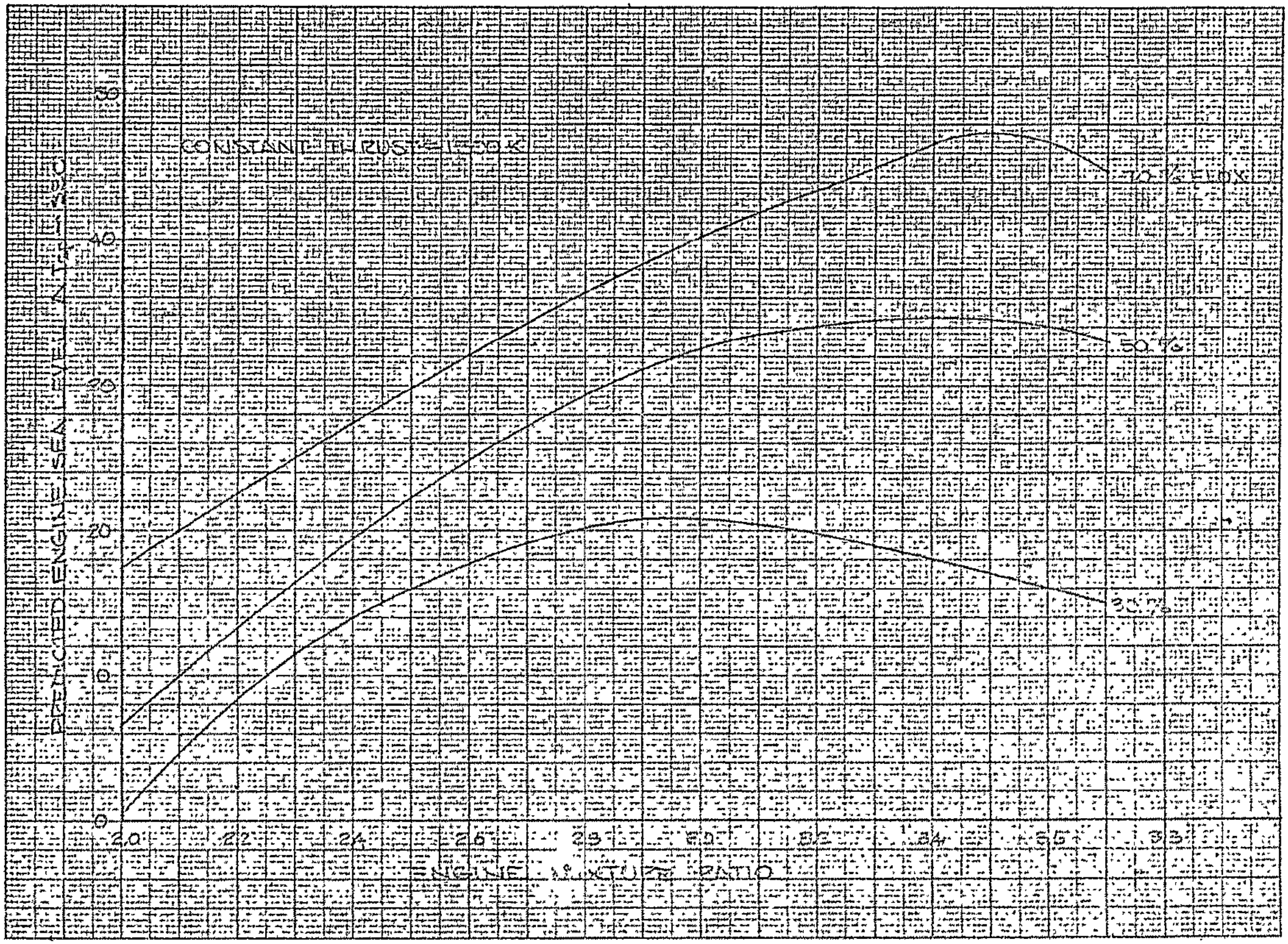

Fig. 2-15 Predicted FLOX/RP-1 Engine Performance at Constant Thrust of 1500K

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Sec. 2

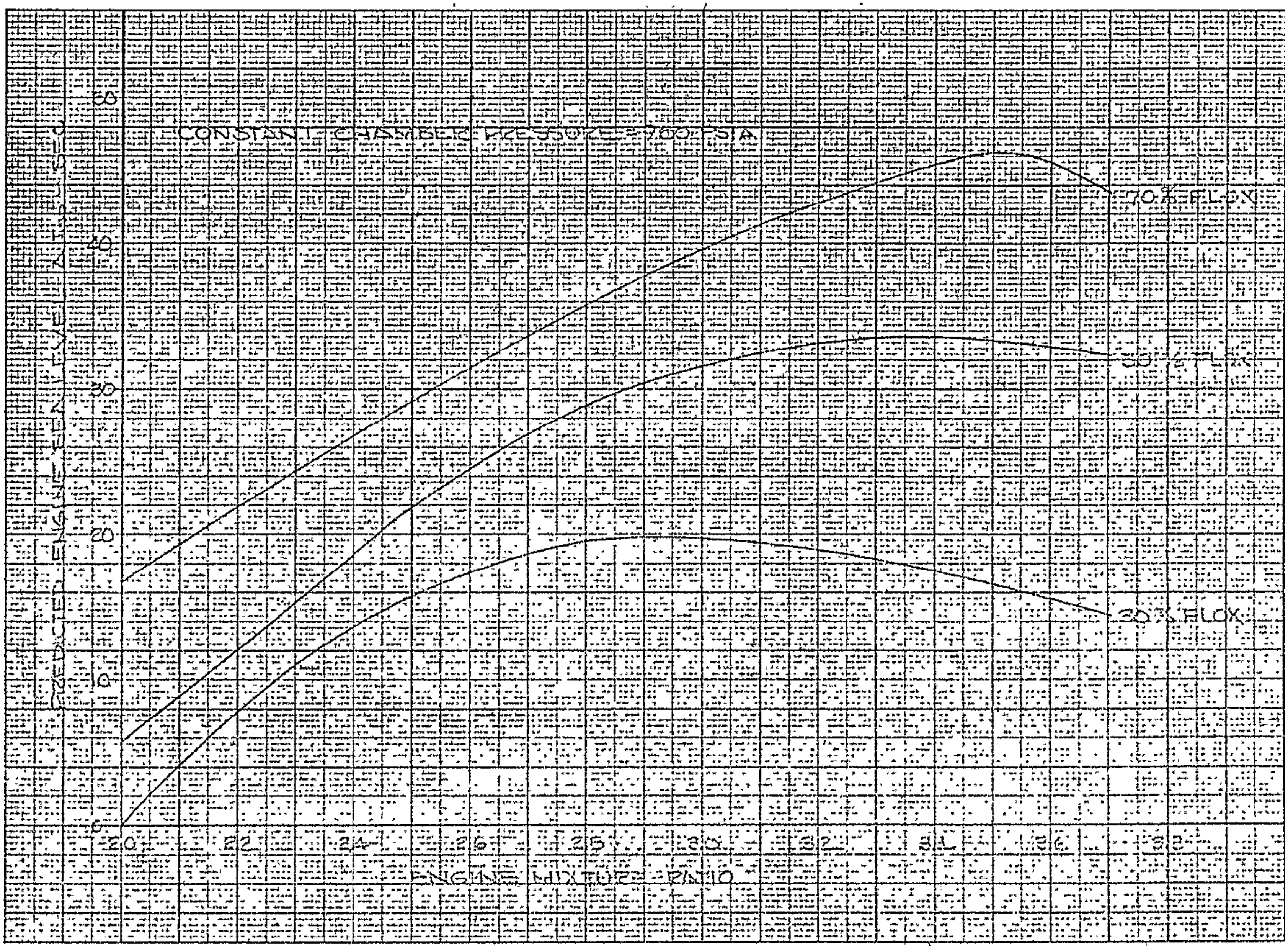

Fig. 2-16 Predicted FLOX/RP-1 Engine Performance at Constant Chamber Pressure of 960 psia

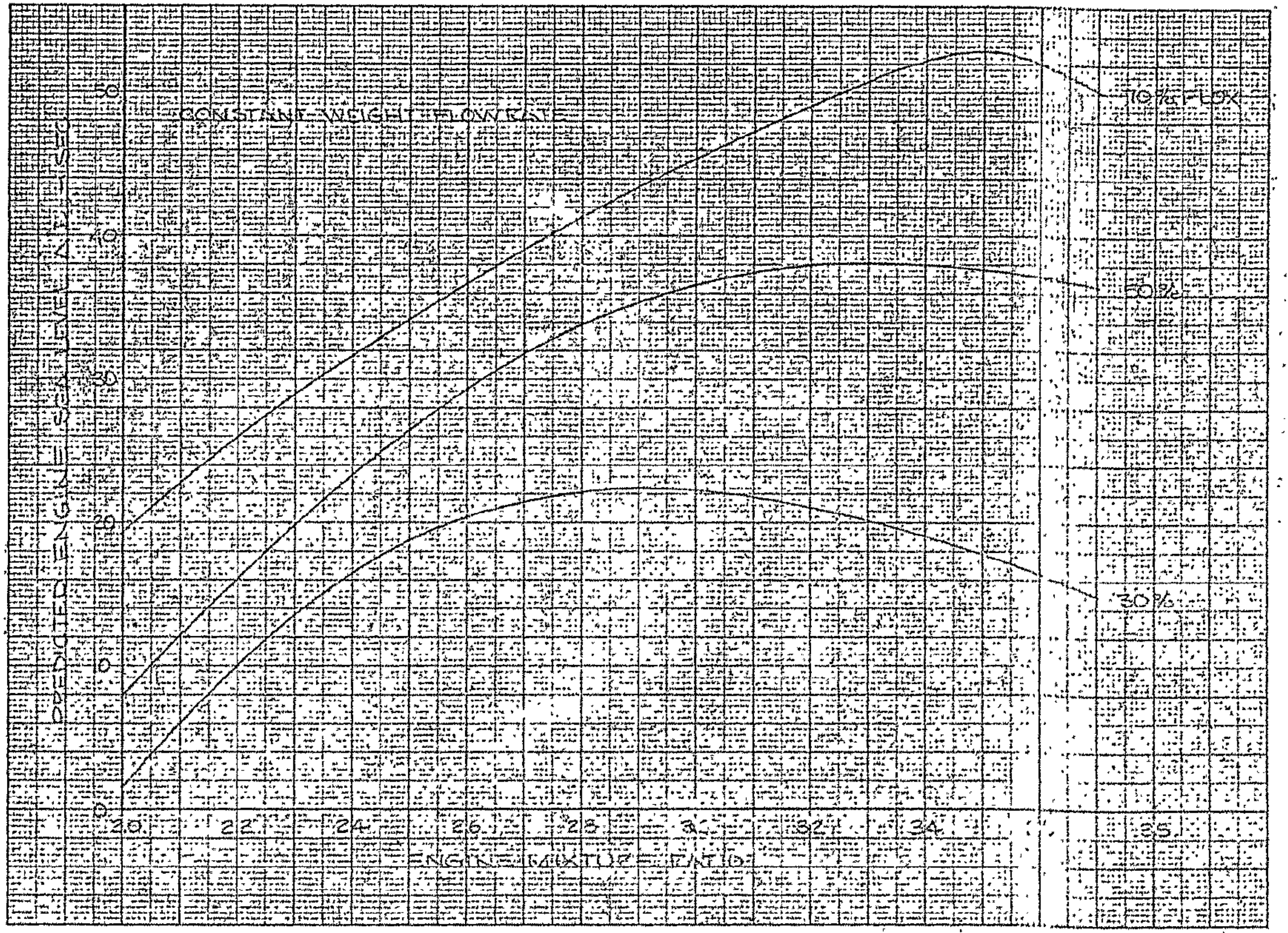

Fig. 2-17 Predicted FLOX/RP-1 Engine Performance at Constant Weight Flowrate

DS-111
Sec 2
p-26

An additional discrepancy between Boeing and Rocketdyne data is found in the theoretical specific impulse for 70% FLOX. It seems unlikely that the differences observed could be attributed to different assumptions for propellant composition or standard heats of formation. One explanation is that the Rocketdyne digital performance program possibly has a different accounting for the solid phase of carbon in the exhaust products. Again, tests appear necessary to define absolute values.

2.5 VEHICLE PERFORMANCE SUMMARY

Based on Rocketdyne's preliminary estimates of F-1 performance and combustion chamber heat transfer limits, seven engine-stage configurations were identified as logical stopping points in performance growth. These configurations range from minimum change at moderate payload increase to maximum change and maximum payload increase within the present S-IC envelope. These are as follows: (see Table 2-1)

(1) Existing 1522K engine and stage using 30 percent FLOX and off-loaded oxidizer and fuel.

(2) Existing 1522K engine with possible slight modification to stage structure - 37 percent FLOX - full oxidizer and fuel loaded to an arbitrary minimum thrust/weight ratio (1.17).

(3) Existing 1625K engine - 38 percent FLOX - full oxidizer fuel off load. (Note: The present engine may be operated at 1625K if additional structural bands are installed around the thrust chamber to withstand the slightly higher chamber pressures.) The increased thrust and resulting payload will require increased stage structure in this and all following operating modes.

(4) Modified F-1 cooling tubes - optimum propellant load (fuel off load), nominal thrust (1800K) and uprated structure.

(5) Modified F-1 cooling tubes - optimum propellant load (fuel off-load), maximum thrust (2015K) and uprated structure.

(6) Modified F-1 cooling tubes, bulkheads relocated and nominal 1800K thrust. In this and the following case, the propellant tank bulkheads have been relocated such that the optimum engine mixture ratio may be realized without off-loading the fuel tank.

(7) Modified F-1 cooling tubes - bulkheads relocated - 1985K thrust.

2.5.1 Existing Vehicle & Engine

The following paragraphs show the development of performance points described on the previous Table 2-I.

Figure (2-18) shows the theoretical payload increase vs. mixture ratio for the existing 1522K engine and vehicle. It is seen that a theoretical payload increase of 17,000 lbs. may be realized when operating at the maximum engine cooling limit and an arbitrarily selected minimum thrust/weight ratio of 1.17. This operating point coincides with a FLOX percentage of 37 percent and mixture ratio of 2.8.

If the oxidizer tank is off-loaded and fuel adjusted appropriately, a structural load equivalent to today's LOR value is assured. Performance under these conditions peaks out at 30 percent FLOX

TABLE 2-1

PERFORMANCE SUMMARY

FLOX S-IC

	THRUST	ΔI_{SP}	% FLOX	M.R.	L. WT.	W_p	% FUEL OFF-LOAD	T/W	W-% F-1	THEORETICAL ΔPL	CORRECTED ΔPL
1. EXISTING ENG & STAGE (OXIDIZER OFF-LOAD)	1522K	21	30	2.81	6.23M	4.50M	22.4	1.22	92	——	10,000
2. EXISTING ENG (FULL OXIDIZER)	1522K	24	37	2.81	6.52M	4.75M	16.0	1.17	92	17,000	14,000
3. EXISTING 1625K ENG (FULL OXIDIZER)	1625K	22	38	2.54	6.70M	4.80M	6.5	1.21	98	20,300	17,000
4. MOD. F-1 COOLING (FULL OXID) (EXIST TANKS-NOM. THRUST)	1800K	54	70	3.45	6.80M	4.99M	28.8	1.32	100	54,700	45,000
5. MOD. F-1 COOLING (FULL OXID) (EXIST TANKS-MAX THRUST)	2015K	52	70	3.25	6.88M	5.08M	21.5	1.46	113	65,600	54,000
6. MOD. F-1 COOLING OPT. BULKHEADS (NOM. THRUST)	1800K	54	70	3.35	7.21M	5.40M	0	1.25	100	61,500	51,000
7. MOD. F-1 COOLING OPT. BULKHEADS (MAX THRUST).	1935K	54	70	3.50	7.23M	5.41M	0	1.37	110	74,000	62,000

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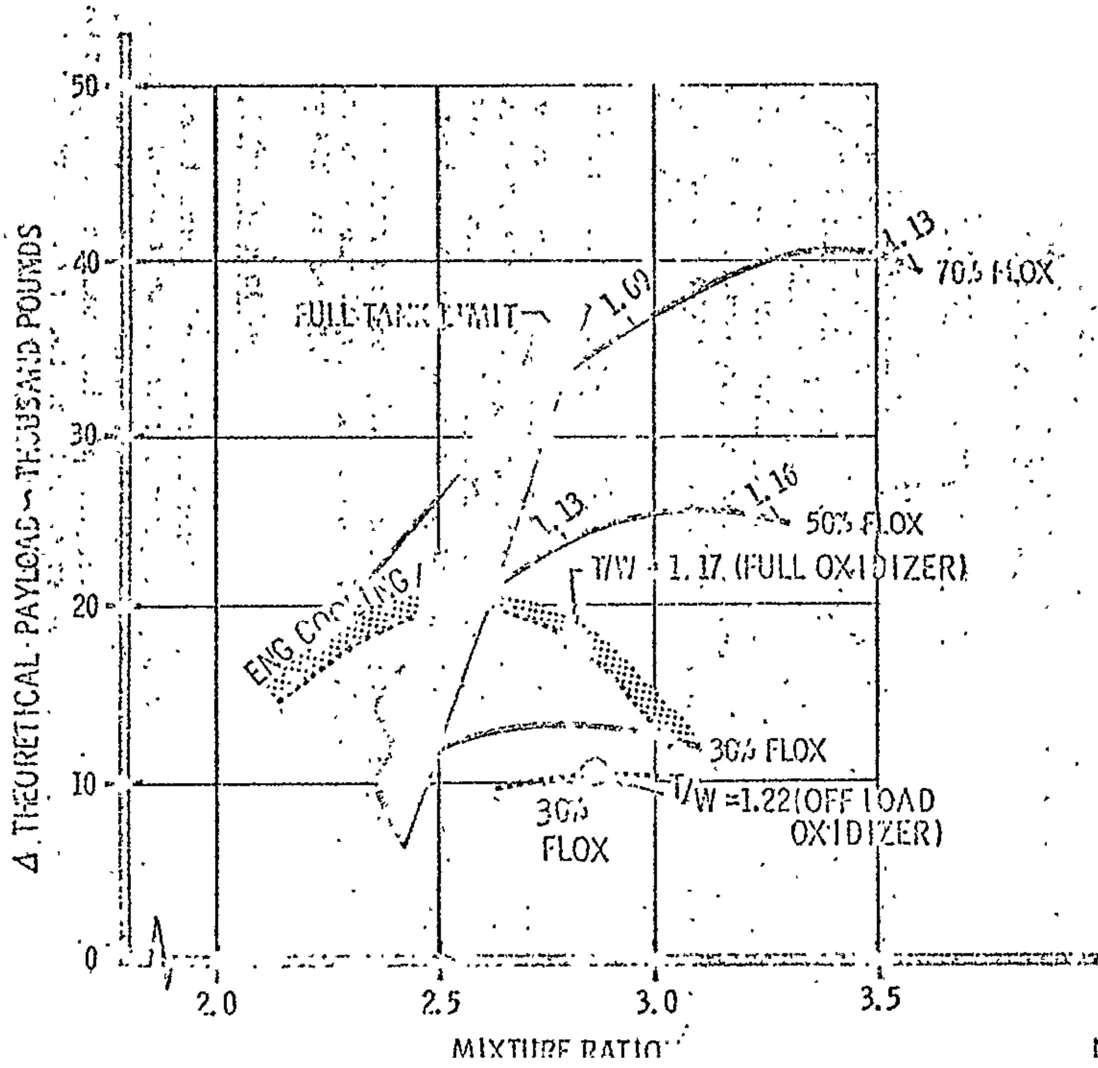
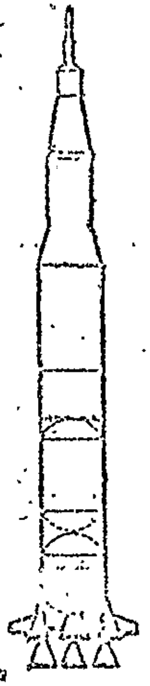
VEHICLE PERFORMANCE
EXISTING ENGINE & VEHICLE





EXISTING ENG
& VEHICLE
1522K THRUST

	OFF LOADED OXIDIZER	FULL OXIDIZER
ΔPL(CORR)	10,000	14,000 LBS
ΔWP	+50K	+ 200K
% FLOX	30%	37%
L WT.	6.23	6.52
T/W	1.22	1.17
ΔI_{SP}	21 SEC	24 SEC
$\overset{\circ}{W}$ = % OF EXIST. F-1	92%	92%

NOTE: ALL UNITS LBS EXCEPT AS NOTED

Fig. 2-18
Sec 2 2.29
D5-11641

resulting in a theoretical payload increase of slightly over 10,000 lbs. (lower curve). Theoretical payload is reduced by the amount necessary to account for the inert weight increases. These payloads are called corrected payloads and are conservatively representative of true payload increases which could be expected. The corrected payloads are tabulated in the figure.

The scope of the study was too limited to accomplish detailed loads analysis for the numerous conditions investigated. Therefore, a correction curve was developed to show payload values that are expected to be more nearly representative of what can be expected from a FLOX vehicle. The correction data are described in 2.5.5.

2.5.2 Existing Engine @ 1625K

If more of the capability of the existing engine is used with the present S-IC tanks, the thrust may be increased to 1625K. Figure (2-19) shows that a theoretical payload increase of approximately 20,000 lbs (17,000 lbs corrected) may be realized at this thrust level at the chamber cooling limit. This performance peak is at 38 percent FLOX T/W = 1.21 and mixture ratio of 2.54.

2.5.3 Modified Engine Cooling @ 1800K and 2000K

Rocketdyne has indicated that by a slight change in the thrust chamber cooling tube geometry, the chamber cooling limits may be removed. Figure (2-20) shows the performance gains when the cooling limits have been removed and the engine is operated at 1800K (nominal engine thrust) and 2000K (max. engine thrust). The theoretical payload increases at these operating points and are 54,000 lbs. and 66,000 lbs., respectively. The corresponding corrected payloads as noted in the figure are 45,000 and 54,000 lbs.

2.5.4 Modified Cooling - Relocated Bulkheads

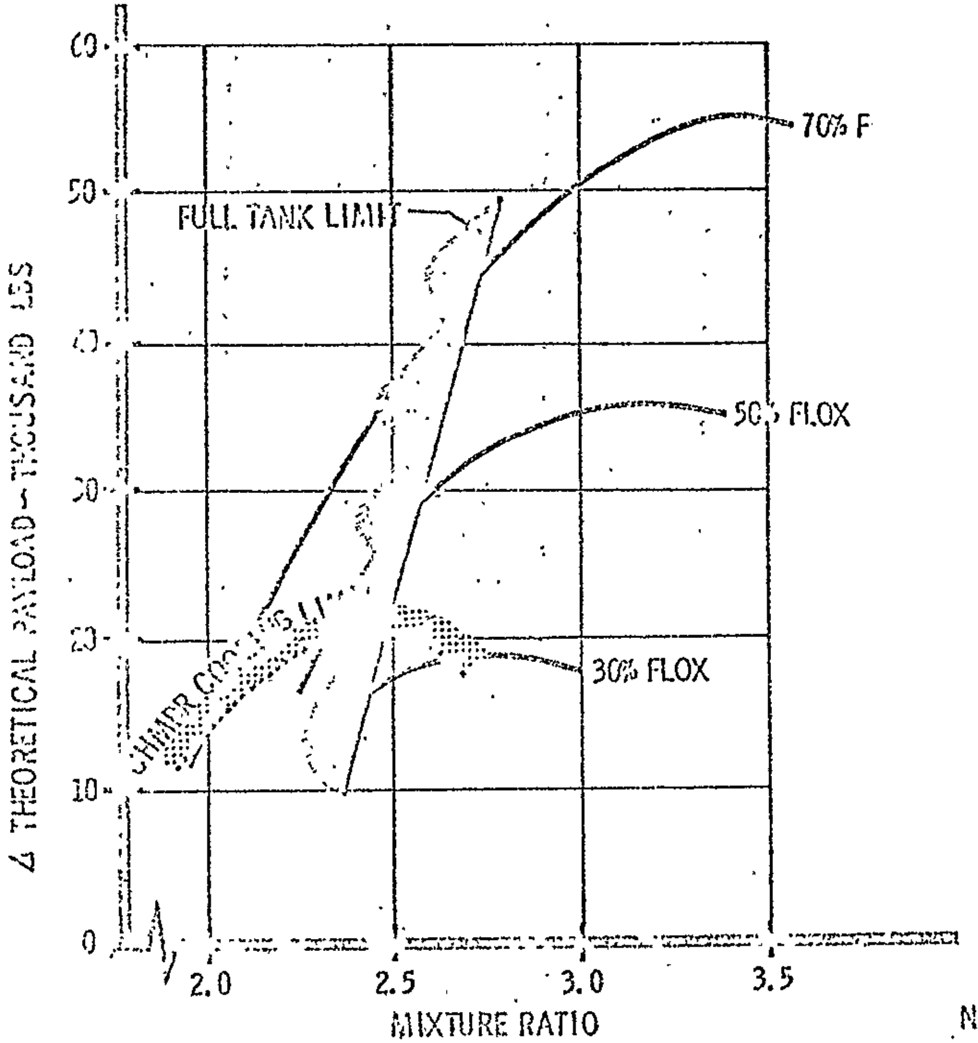
If the propellant tank bulkheads are moved such that the full tank loaded mixture ratio is equivalent to the optimum engine mixture ratio, the corrected payload increases are 51,000 and 62,000 lbs. for the nominal thrust and maximum thrust operating points, respectively.

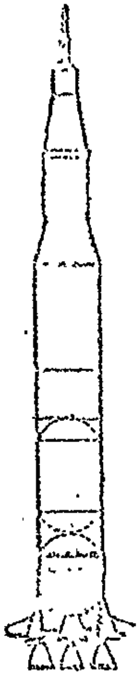
As is summarized on the previous table (2-I), performance improvement from approximately 10,000 to 62,000 lbs. payload is possible by applying FLOX to the S-IC.

2.5.5 Inert Weight Correction

As percent fluorine in the oxidizer is increased, vehicle propellant loading, engine thrust, specific impulse, optimum mixture ratio and payload increase. Because these items vary simultaneously and not necessarily in a fixed relationship, a complex series of inert weight equations would be necessary for specific performance predictions. Development of such equations was beyond the scope of the general feasibility study.

VEHICLE PERFORMANCE
EXISTING ENGINE - FULL OXIDIZER
THRUST 1625K





EXIST. ENG WITHIN
COOLING LIMITS

ΔPL (CORR)	17,000
ΔSWP	230K
%FLOX	33.5
LWT.	6.70M
T/W	1.21
ΔI_{SP}	22 SEC
THRUST	1625K
$\dot{W}$ = % OF EXIST. F-1	90%

NOTE: ALL UNITS LBS EXCEPT AS NOTED

Fig. 2-19
Sec 2, pg 31

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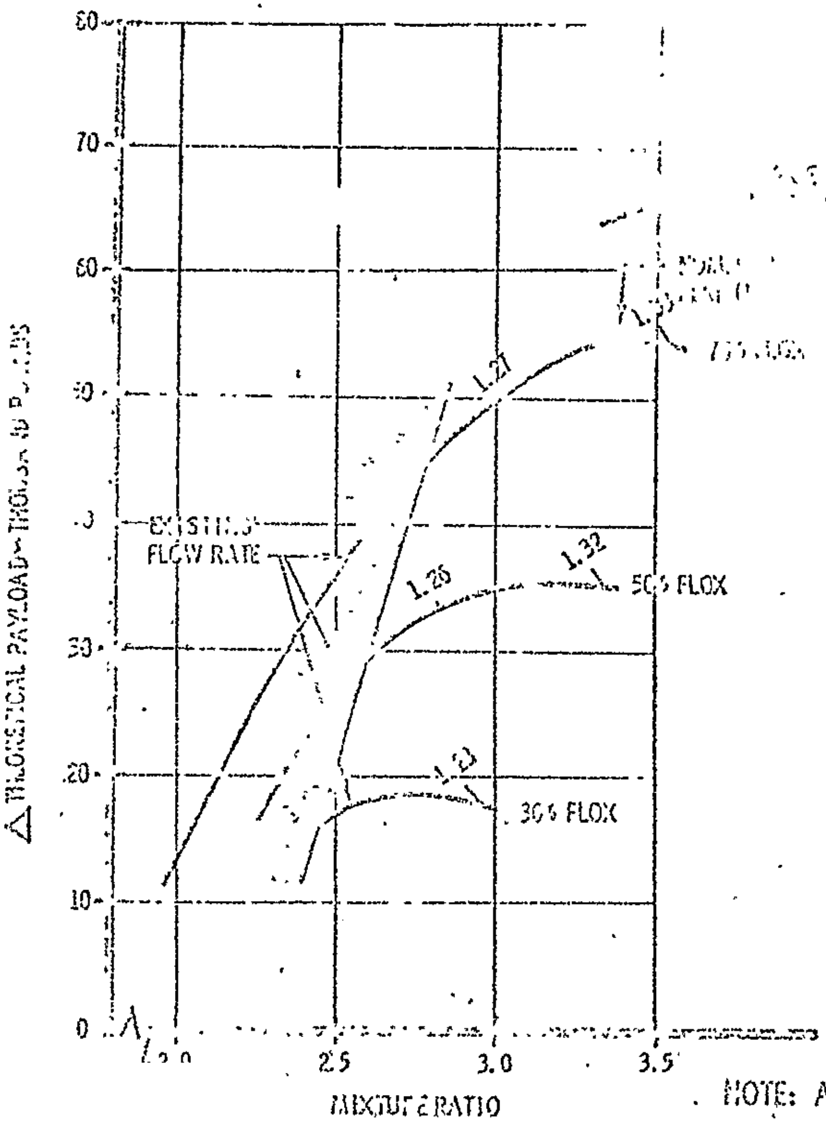
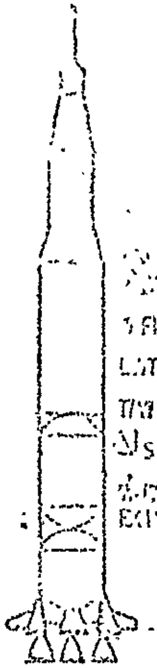
VEHICL[illegible]NCY



[illegible] TANKAGE
MODIFIED CHAMBER [illegible]



	FULL OXIDIZ[illegible] 100%	[illegible]
[illegible] (LO2R)	85,[illegible]	
[illegible]SP	4[illegible]	[illegible]
% FLOX	70%	70%
L/T	6.[illegible]	[illegible]
T/W	1.32	[illegible]
ΔI_SP	51 [illegible]	
% OF EXISTING F-1	105.5	[illegible]

NOTE: ALL UNITS LBS EXCEPT AS NOTED

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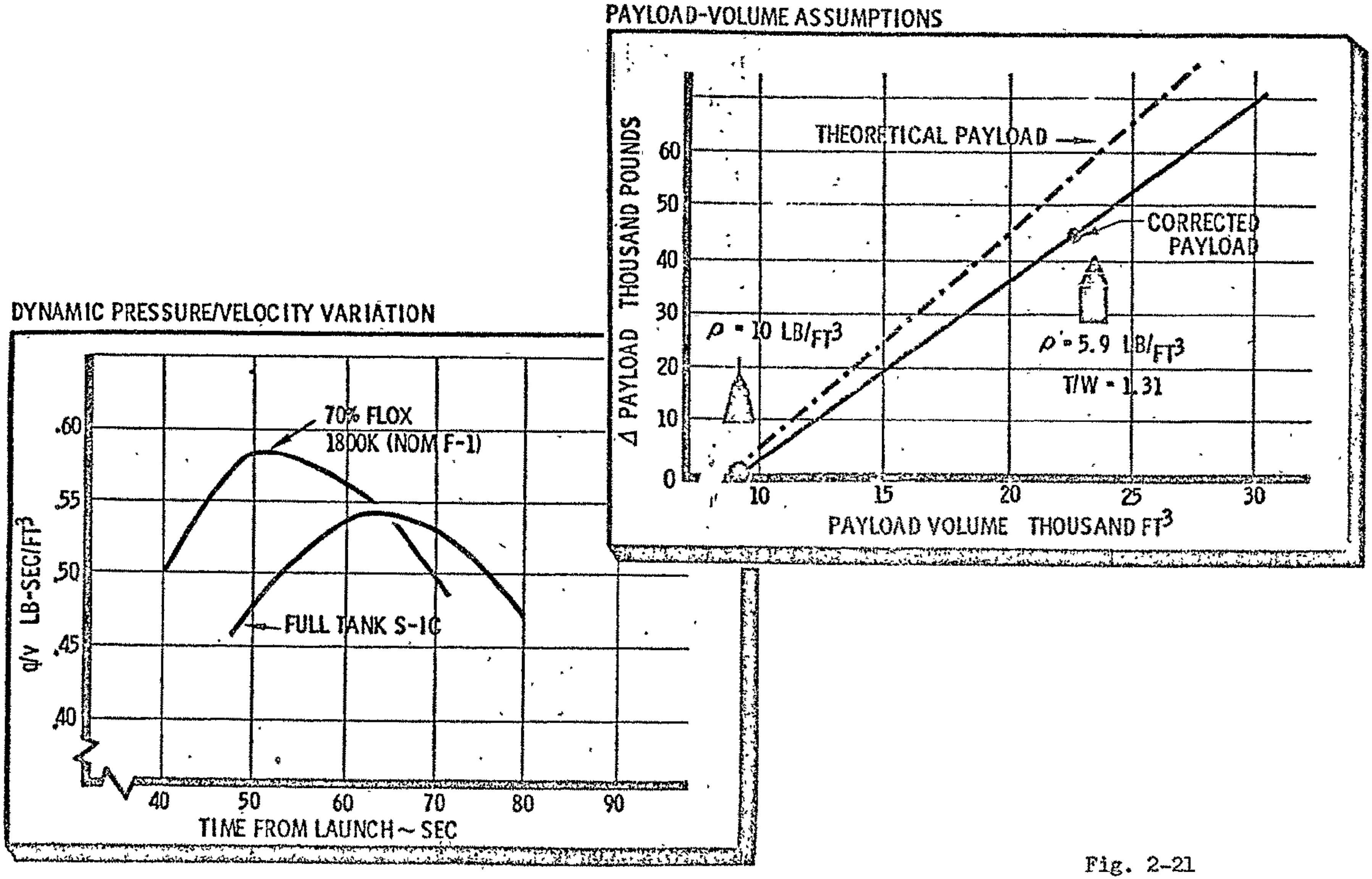
Fig. 2-20
Sec 2 Pg 32

As an option, Boeing selected two design points as references. One reference is the existing Saturn V/Apollo. The other reference vehicle is based on a specific study configuration with engine thrust at 1800K pounds and launch weight at 6.8 million pounds, i.e., configuration 4 on Table 2-1. The payload weight increase, approximately 55,000 pounds (computer run with no inert weight effects), was assumed to be contained at a total payload density of slightly less than six pounds per cubic foot. (See Figure 2-21). Examination of the trajectory showed the expected increase in flight loads (lefthand curve, Figure 2-21). Using the new loads, penalties to all three stages were developed and the effects of increased first stage thrust and propellant were defined. Performance was reiterated and the payload increase dropped to approximately 45,000 pounds. For expediency, a straight line was drawn through the two points (Apollo and configuration 4) and all other configurations were penalized accordingly. This method, as a rule, should result in conservative results especially for those configurations that have lower thrust to weight at launch.

STRUCTURAL WEIGHT EFFECTS


PAYLOAD-VOLUME ASSUMPTIONS

DYNAMIC PRESSURE/VELOCITY VARIATION

Fig. 2-21

SECTION 3

STAGE DESIGN ANALYSIS

3.0 STAGE DESIGN ANALYSIS

3.1 MATERIALS COMPATIBILITY

3.1.1 Introduction

This section contains the study results based on published literature and can be used with reasonable confidence. Final confirmation of material and design suitability, of course, will be predicated upon specific sensitivity and compatibility tests.

Essentially only minor design and compatibility problems are apparent in the S-IC. The area of major question is the potential problem associated with handling FLOX gas at elevated temperatures and then probably only when contaminants are present. Tests on an independent R&D program at Boeing-Seattle with pure fluorine indicate that contaminant reactivity is extremely great at elevated temperatures and relatively subdued or non-existent at cryogenic temperatures. The oxidizer tank pressurization system on the existing S-IC produces high temperature GOX and is routed through numerous fittings and joints, some with possibility of contamination.

As a matter of judgment, at this stage in the technology, it would appear desirable to eliminate high temperature FLOX gas from the stage. This could be done by a substitute pressurization system.

Follow-on work should include studies in this area.

Schematic diagrams of the LOX/GOX system are shown on the following pages with reference to materials of construction, environment (pressures, temperatures, and flow rates) through or near each component in the system, and probable problem areas. The problem areas have been investigated from the standpoint of materials and structural design based on data available. It was impossible to go into all phases of material and structural redesign during this phase of study, therefore, a complete examination of design changes in the problem areas is proposed for a follow-on program.

The "Components List" is referenced to the key numbers on the overall schematic (figure 3-1).

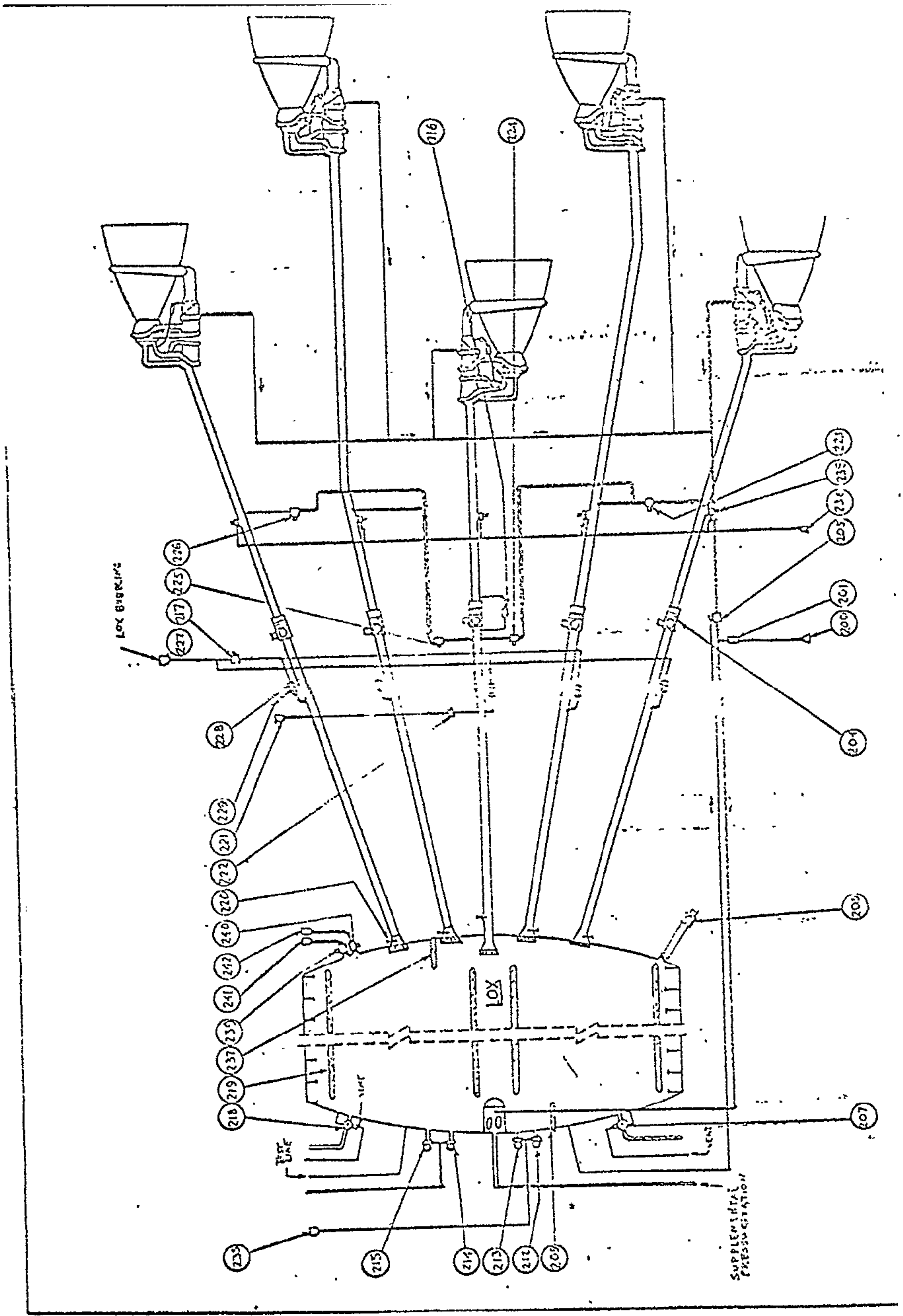
3.1.2 Oxidizer System - Components List

200 Quick Disconnect Coupling, LOX Tank Pre-pressurization

Materials:
Stainless Steel 321 or 347 (CRES)

Environment:

Pressure	1980 psia
Temperature	530°R
Flow Rate	24.5 ft/sec



OXIDIZER SYSTEM

Fig. 3-1

201 Check Valve, LOX Tank Pre-pressurization

Materials:
17-4PH, 302, 303, 304L, 440C Stainless Steel

Environment:

Pressure	1320 psia
Temperature	530°R
Flow Rate	4.0 lb/sec

203 GOX Flow Control Valve, LOX Tank Flight Pressurization

Materials:
2024 Aluminum Alloy - 17-4 PH, 17-7 PH, 301, 302, 303, 304, 305, 310, 316, 321, 347, 440C Stainless Steels, Star 'J' Stellite - Haynes Stellite #3 - Rene Material per AMS 5545 - Barium BID - Stillman Rubber Compound TH 1057 - Teflon - Kel-F - Viton per MIL-R-25897

Environment:

Pressure	1500 psia
Temperature	850°R
Flow Rate	1360 ft/sec

204 LOX Pre-valve and Flow Meter Assy

Materials:
6061, 7075 Aluminum Alloys - 17-4 PH, 302, 303, 440C Stainless Steels CRES Screws - Teflon - Seal (RACO)

Environment:

Pressure	——
Temperature	158°R
Flow Rate	38.98 ft/sec.

205 Valve Assy., Emergency Drain, LOX

Materials:
6061, 7075 Aluminum Alloys - 17-4 PH, 302, 303, 440C Stainless Steels - CRES Screws - Teflon - Seal (RACO)

Environment:

Pressure	——
Temperature	158°R
Flow Rate	5.02 ft/sec

207 Valve, Vent & Relief, LOX

Materials:
356-T6, 2024, 2219, 5052, 6061 Aluminum Alloys - 17-4 PH, 17-7 PH, 301, 302, 303, 304, 321, 347,

440C Stainless Steels - Aclar - Teflon - Acheson EC 1730 Lubricant - Kel-F, LOX Grade 300 - Tape per Federal Specification PPP-T-60

Environment:

Pressure	25.5 psia
Temperature	158-500°R
Flow Rate	256 ft/sec

209 Sensor, Level, LOX Loading - LOX Suppressed Range

Materials:
2024, 6061, 7075, 5052 Aluminum Alloys - 304, 340L Stainless Steel - Low Carbon Steel (QQ-S-636) - Teflon - LOX Compatible Lubricants per MSFC-SPEC-106 - Laminated Glass Filled Teflon - FS-1281 - Solid Extruded Teflon type TE-100

Environment:

Pressure	29.0 psia
Temperature	158-500°R
Flow Rate	----

212 Switch Pressure, LOX Pre-pressurization

Materials:
304L, 321, 347, 410 Stainless Steel - NI-Span-C (an Iron-Nickel-Chromium Alloy)

Environment:

Pressure	31 psia
Temperature	280-650°R
Flow Rate	----

213 Switch Pressure, LOX Tank Vent

Materials:
3042, 321, 347, 410 Stainless Steel - NI-Span-C (an Iron-Nickel-Chromium Alloy)

Environment:

Pressure	25.5 psia
Temperature	280-650°R
Flow Rate	

214 Switch, Pressure, LOX Tank Pressurizing

Materials:
304L, 321, 347, 410 Stainless Steel - NI-Span-C (an Iron-Nickel Chromium Alloy)

Environment:

Pressure	64.3 psia
Temperature	280-650°R
Flow Rate	----

215 Switch, Pressure, LOX Tank Vent

Materials:
304L, 321, 347, 410 Stainless Steel - NI-Span-C (Fe-Ni-Cr Alloy)

Environment:

Pressure	52.0 psia
Temperature	280-650°R
Flow Rate	

216 Valve, Check, Pre-valve By Pass - Center Suction Line

Materials:
2024, 6061 Aluminum Alloys - 302, 303 Stainless steels - Teflon

Environment:

Pressure	---
Temperature	158°R
Flow Rate	---

217 Valve, Shutoff, LOX Bubbling

Materials:
356-T6C STG - 2024 Aluminum Alloy - 416 Stainless Steel - Teflon - Kel-F

Environment:

Pressure	430 psia
Temperature	530°R
Flow Rate	20-40 ft^3/mi

218 Valve, Vent & Relief, LOX Tank

Materials:
356-T6, 2024, 2219, 6061 Aluminum Alloys - 17-4 PH, 17-7 PH, 301, 302, 303, 304, 321, 347, 440C Stainless Steels - Aclar - Teflon - Ackeson EC 1730 Lubricant Kel-F, LOX Grade 300 - Tape per Federal Specification PPP-T-60

Environment:

Pressure	25.5 psia
Temperature	158°-500°R
Flow Rate	256 ft/sec

219 Sensor, Level, LOX Measuring

Materials:
2024, 6061, 7075, 5052 Aluminum Alloys - 304, 340L Stainless Steels - Low Carbon Steel (QQ-S-636) - Teflon - LOX Compatible Lubricants per MSFC-SPEc-

106 - Laminated Glass Filled Teflon - FS-1281 - Solid Extruded Teflon type TE-100

Environment:

Pressure	----
Temperature	158-500°R
Flow Rate	----

220 Sensor, Level, Engine Cutoff, LOX Suction Line

Materials:
Borosilicate Kovar Sealing Glass Corning Glass #7052 - Kovar - 2024 Aluminum Alloy - 301, 304L Stainless Steel

Environment:

Pressure	----
Temperature	158°R
Flow Rate	38.98 ft/sec

221 Coupling, Fill & Drain, LOX - LOX Suction Line

Materials:
(CRES) 321 or 347

Environment:

Pressure	160 psia
Temperature	158°R
Flow Rate	37.8 ft/sec

222 Valve Assy, Fill & Drain , LOX - LOX Suction Line

Materials:
6061, 7075 Aluminum Alloys - 17-4 PH, 302, 303, 440C Stainless Steels - CRES Screws - Teflon - Seal (RACO)

Environment:

Pressure	125 psia
Temperature	158°R
Flow Rate	37.8 ft/sec

223 Valve Assy., LOX Interconnect NO

Materials:
6061, 7075 Aluminum Alloys - 17-4 PH, 302, 303, 440C Stainless Steels - CRES Screws - Teflon - Seal (RACO)

Environment:

Pressure	93 psia
Temperature	158°R
Flow Rate	93 ft/sec.

224 Valve Assy., LOX Interconnect NC

Materials:

6061, 7075 Aluminum Alloys - 17-4 PH, 302, 303, 440C
Stainless Steels, CRES Screws - Teflon - Seal (RACO)

Environment:

Pressure	93 psia
Temperature	158°R
Flow Rate	93 ft/sec

225 Valve Assy., LOX Interconnect NO

Materials:
6061, 7075 Aluminum Alloys - 17-4 PH, 302, 303, 440C
Stainless Steels, CRES Screws - Teflon - Seal (RACO)

Environment:

Pressure	93 psia
Temperature	158°R
Flow Rate	93 ft/sec

226 Valve Assy., LOX Interconnect NO

Materials:
6061, 7075 Aluminum Alloys - 17-4 PH, 302, 303, 440C
Stainless Steels - CRES Screws - Teflon - Seal (RACO)

Environment:

Pressure	93 psia
Temperature	158°R
Flow Rate	93 ft/sec

227 Quick Disconnect Coupling - LOX Bubbling

Materials:
(CRES) 321 or 347 Stainless Steel

Environment:

Pressure	430 psia
Temperature	530°R
Flow Rate	20-30 ft^3/min

228 Orifice, Insert, LOX Bubbling

Materials:
321/347 Stainless Steel

Environment:

Pressure	65
Temperature	530
Flow Rate	20-30 ft^3/min

229 Check Valve, LOX Bubbling

Materials:
17-4 PH, 302, 440C Stainless Steel

Environment:

Pressure	65
Temperature	530
Flow Rate	2-30 ft^3/min

235 Quick Disconnect Coupling, Mod. - LOX Tank Automatic Checkout, Pressure Switches

Materials:
Aluminum Alloy

Environment:

Pressure	---
Temperature	530°R
Flow Rate	---

236 Quick Disconnect Coupling, Max., LOX Suction - Automatic Checkout, Pressure Switches

Materials:
Aluminum Alloy

Environment:

Pressure	---
Temperature	530°R
Flow Rate	---

237 Sensor, Level, LOX Measuring, LOX Tank

Materials:
2024, 6061, 7075, 5052 Aluminum Alloys - 304, 340L Stainless Steel - Low Carbon Steel (QQ-S-636) - Teflon - LOX Compatible Lubricants per MSFC-SPEC-106 - Laminated Glass Filled Teflon - FS-1281 - Solid Extruded Teflon type TF-100

Environment:

Pressure	65 psia
Temperature	158°R
Flow Rate	---

238 Valve Assy., Fill & Drain, LOX - LOX Tank

Materials:
6061, 7075 Aluminum Alloys - 17-4, 302, 303, 404C Stainless Steels - CRES Screws - Teflon, - Seal (RACO)

Environment:

Pressure	125 psia
Temperature	158°R
Flow Rate	37.8 ft/sec

239 Valve Assy., Fill & Drain, LOX - LOX Tank

Materials:
6061, 7075 Aluminum Alloys - 17-4, 302, 303, 404C Stainless Steels - CRES Screws - Teflon - Seal (RACO)

Environment:

Pressure	125 psia
Temperature	158°R
Flow Rate	37.8 ft/sec

240 Valve Assy., Fill & Drain, LOX - LOX Tank

Materials:
6061, 7075 Aluminum Alloys - 17-4, 302, 303, 440C Stainless Steels - CRES Screws - Teflon - Seals (RACO)

Environment:

Pressure	125 psia
Temperature	158°R
Flow Rate	37.8 ft/sec

241 Coupling, Fill & Drain, LOX - LOX Tank

Materials:
6061 Aluminum Alloy - 321 Stainless Steel

Environment:

Pressure	160 psia
Temperature	158°R
Flow Rate	37.8 ft/sec

242 Coupling, Fill & Drain, LOX - LOX Tank

Materials:

6061 Aluminum Alloy - 321 Stainless Steel

Environment:

Pressure	160 psi
Temperature	158°R
Flow Rate	37.8 ft/sec.

3.1.2.1 Effect of Flucrine on Materials

Aluminum Alloys - The 2000 series alloys form the major structure of the oxidizer delivery system. They are used in the LOX tank and the LOX suction ducts. The 6000 series alloys are used for various tubing and bracketry. The 7000 series alloys are used for anti-slosh baffling and in the LOX suction ducts. All the aluminum alloys used in the booster are compatible with fluorine under all expected conditions.

Stainless Steels - Stainless steels are used in the GOX system and in almost all instrumentation. They are also used for CRFS screws throughout the system. All the stainless steels are compatible with fluorine.

Zinc and Cadmium Plating - Zinc and cadmium plating are not recommended for use in fluorine systems. The reaction between fluorine and cadmium or zinc is rapid at first and asymptotically approaches zero quickly. If the plating must be used, an increased thickness of the plating material is recommended (Type II per QQ-P-416A).

Platinum - Platinum forms volatile fluorides and is not recommended for use above 100°F. Use of this material might present a problem during passivation due to the possibility of the oxidizer tank being heated on the pad or test stand by the sun.

Silver Brazing - Silver brazing or soldering is recommended for use in fluorine system where welding cannot be accomplished; however, no flux may be used and the process should be furnace brazing.

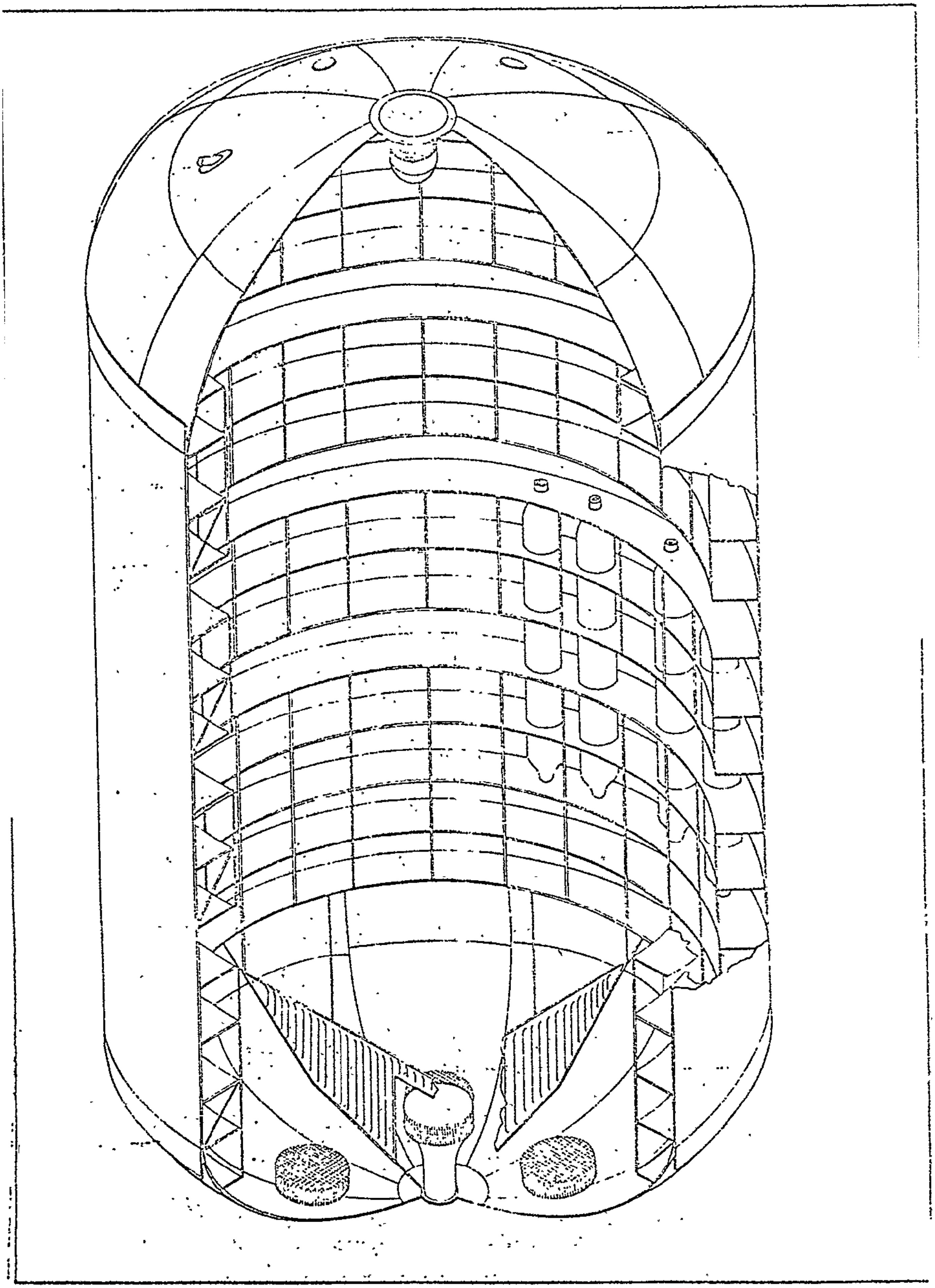
Miscellaneous Alloys - The various other metal alloys in the system are considered compatible with fluorine under the existing conditions.

Teflon - Solid fluorocarbons materials (teflon, TFE, FEP, Laminated glass filled teflon, nickel filled teflon, etc.) are compatible with liquid fluorine under the existing conditions. These fluorocarbons, however, are not compatible with gaseous fluorine and must be replaced.

Lubricants - The only lubricants that are compatible with liquid FLOX are the Kel-F lubricants. These Kel-F lubricants are, however, not advisable for FLOX use and should be avoided if possible. If it is impossible to avoid using these lubricants, they may be used very sparingly (thin films). No LOX compatible lubricants are considered for GF_2/O_2 use, and it is imperative that they be avoided.

Rubber - All rubber compounds are non-compatible with liquid or gaseous FLOX and must be avoided.

Glass - Glass, while not attacked by fluorine, is etched by hydrogen fluoride. The glass used for optical instrumentation could possibly be affected, but glass used for sealing purposes should present no problem. The concentration of hydrogen fluoride in 70% FLOX is less than 0.14 percent by weight and the temperature of liquid FLOX is far



LOX TANK

Fig. 3-2

below that of the freezing point of hydrogen fluoride. The freezing out of hydrogen fluoride should result in its removal before transfer to the booster. (A separator may be required for this purpose.)

3.1.3 LOX Tank

3.1.3.1 LOX Tank Materials List

A. LOX Tank (119) (ref. figure 3-2)

1. Gore Apex and Base, Skin, and Lower Head
   Material: 2219 Aluminum

2. "Y" Rings
   Material: 2219, T851, %852 Aluminum Alloy

3. Manhole Cover, Upper Head and Center Piece Head
   Material: 2219 Aluminum Plate

4. Ring and Cruciform Baffle Assemblies
   Material: 7079, T652 Aluminum Alloy,
   cadmium plated fasteners

5 5. Helium Bottle Installation

   a. Helium Bottle Supports, Parts
      Material: 219 Aluminum Alloy

   b. Helium Bottles
      Material: 2014 Aluminum Alloy

6. GOX Distributor Assembly

   a. Doubler Outlet Assemblies
      Material: 321, 347 Annealed Stainless Steel

   b. Outlet Jacket
      Material: Reinforced Tetrafluoroethylene (TFE)

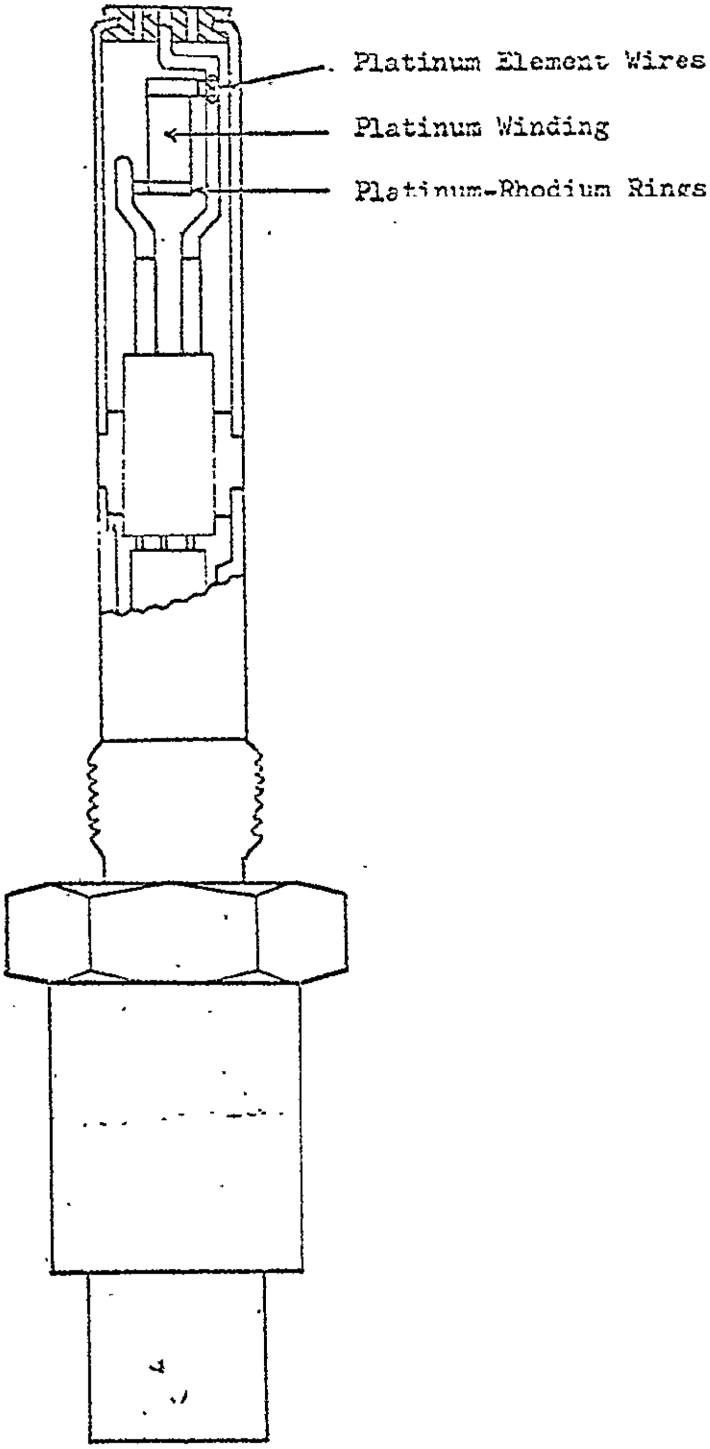
   c. Support Ring
      Material: 2219 Aluminum Alloy

B. LOX Tank Instrumentation

1. Pressure Transducers
   Material: 304L, 321, 347, 410 Stainless Steel -
   NI-Span-C (An Iron-Nickel-Chromium Alloy)

2. Temperature Transducers (ref. fig. 3-3)
   Material: 304L Stainless - Platinum -Silver Brazed
   Nichrome Wire - Teflon - Glass - Alumina - Zinc Plating

3. Cable Assemblies
   Material: Teflon insulated wire - KEL-F-90 - A286,
   302, 3 4 Stainless Steel - 2024 Aluminum



TEMPERATURE TRANSDUCER

Fig. 3-3

4. Level Sensing System (ref. Fig. 3-4)
   Material: 2024, 6061, 7075, 5052 Aluminum Alloys - 304, 340L Stainless Steel - Low carbon steel (QQ-S-636) - Teflon, LOX Compatible Lubricants per MSFC-SPEC-106 - Laminated Glass Filled Teflon - FS-1281 - Solid extruded Teflon type TE-100

3.1.3.2 Material and Design Changes Necessary

Temperature Transducer - It may be necessary to redesign the temperature transducers in the LOX tank. Platinum is in contact with fluorine and reaction will take place as noted in 3.1.2.1.

Liquid Level Sensor - The only material change that appears necessary in the liquid level sensor is the removal of LOX compatible lubricants if possible. If it is not possible to remove these lubricants, they should be treated according to 3.1.2.1.

Anti-Slosh Baffle Connector - The anti-slosh baffle connector presents a cleaning problem. There is a small crevice in the rear of the connector as noted in Fig. 3-5. This crevice can hold organic particles which would be difficult to remove with ordinary cleaning procedures and particular care should be taken in cleaning before introduction of FLOX. An alternative method for correcting this problem is redesign so as to enlarge this crevice for easier cleaning.

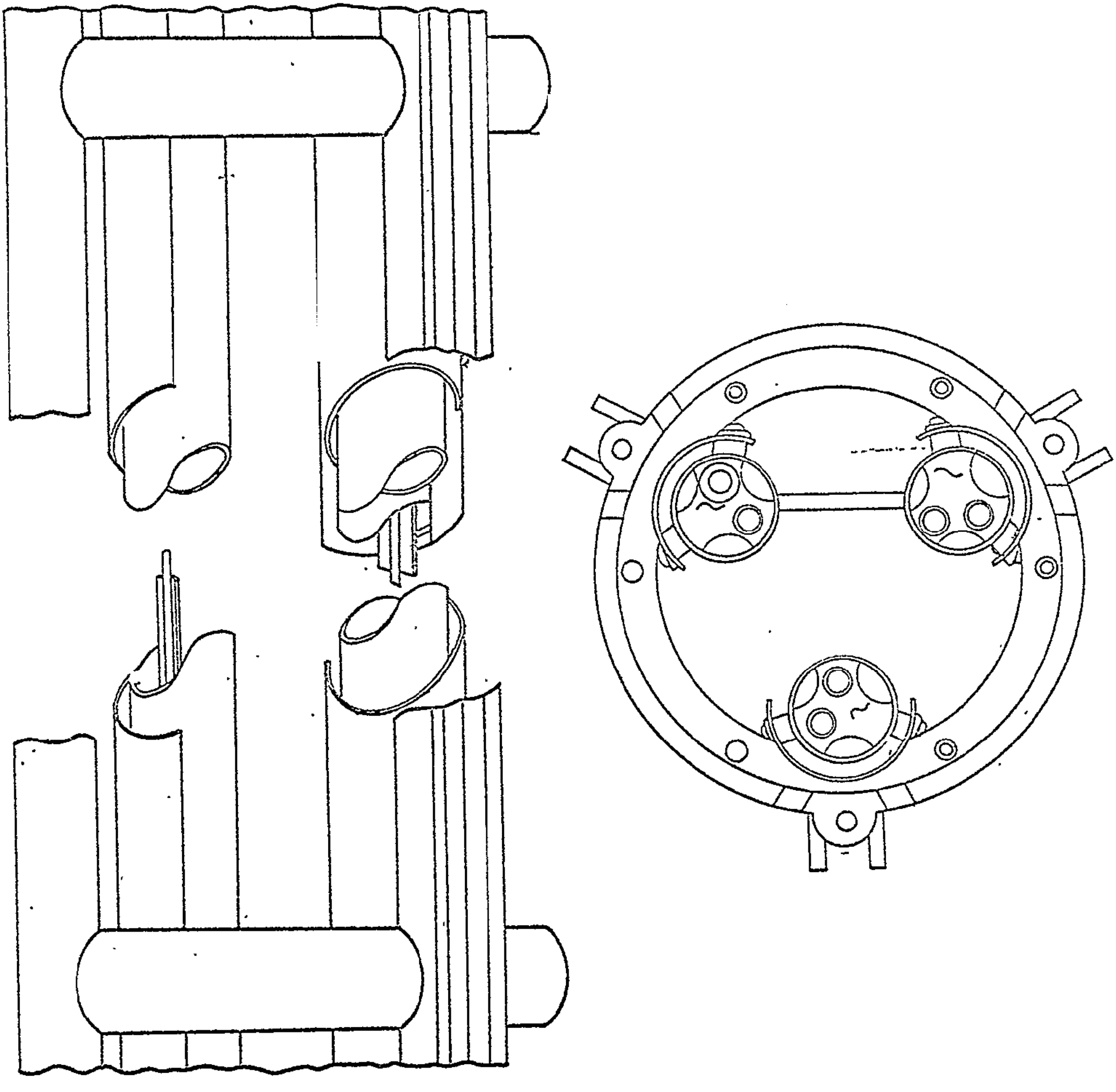
GOX Distributor Assembly - The GOX distributor assembly contains reinforced tetrafluoroethylene (TFE) which is not considered compatible with GF_2/O_2.

Cable Assemblies - Electrical cable assemblies in the oxidizer tank consist of a teflon coated wire jacketed in stainless steel braid which is over-jacketed with teflon braid. The machinery which assembles these cables uses LOX compatible lubricants for easier assembly. A possible solution to this problem would be to use solid teflon jacketing outside the steel braid (required for grounding to connectors) and fusing the teflon outer jacket through the steel braid to the teflon coating on the wire underneath at one spot in back of the connector. This would prevent FLOX from wicking up the steel braid and effectively isolate the lubricants from FLOX exposure.

3.1.4 LOX Suction Ducts - Fuel Tank (Ref. Fig. 3-6 and 3-7)

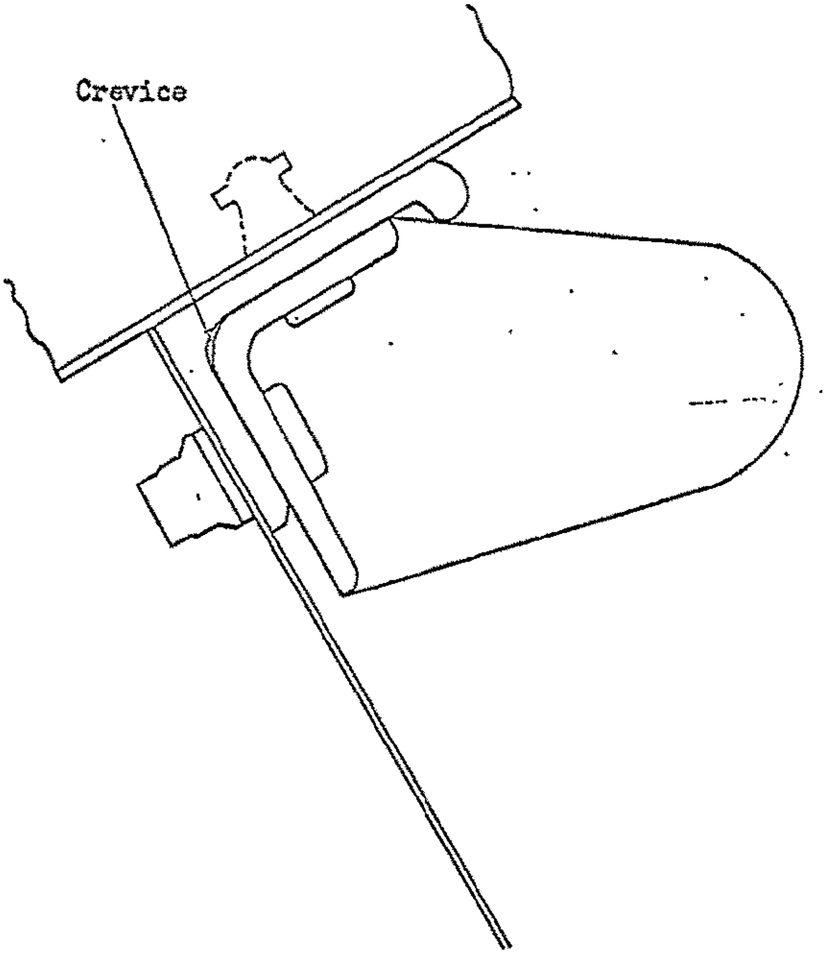
3.1.4.1 Material and Design Changes Necessary

Gimbal Joints - The gimbal joints of the LOX suction ducts present two design problems which could cause considerable difficulty. These problem areas are the convoluted surfaces and faying surfaces designed for greater flexibility. The convoluted surface will be difficult to clean under normal cleaning procedures and could entrap organic matter which could cause failure of the system. If it is possible, these convoluted surfaces should be redesigned and if this is not feasible, particular care should be taken in the cleaning



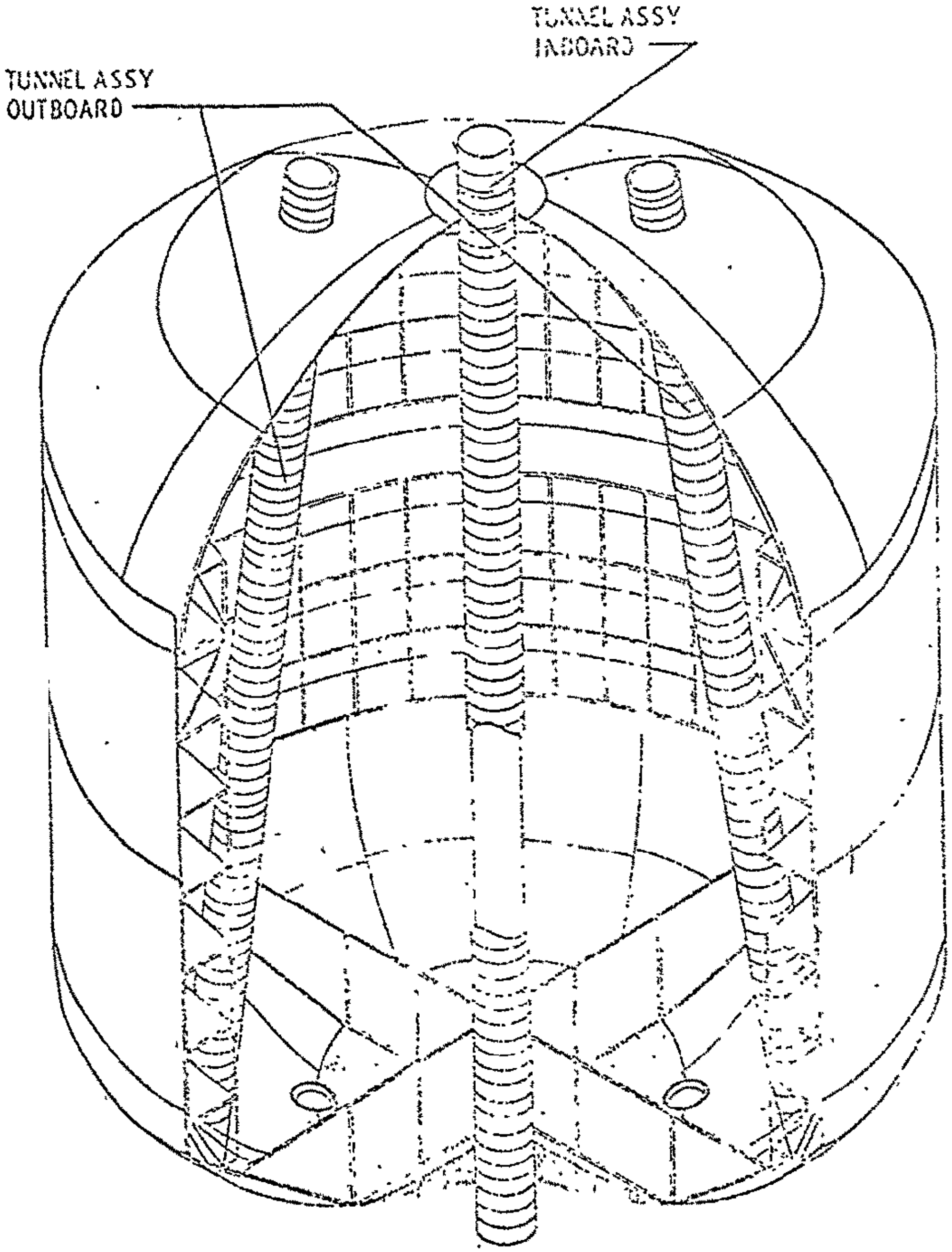
LIQUID LEVER SENSOR

Fig. 3-4



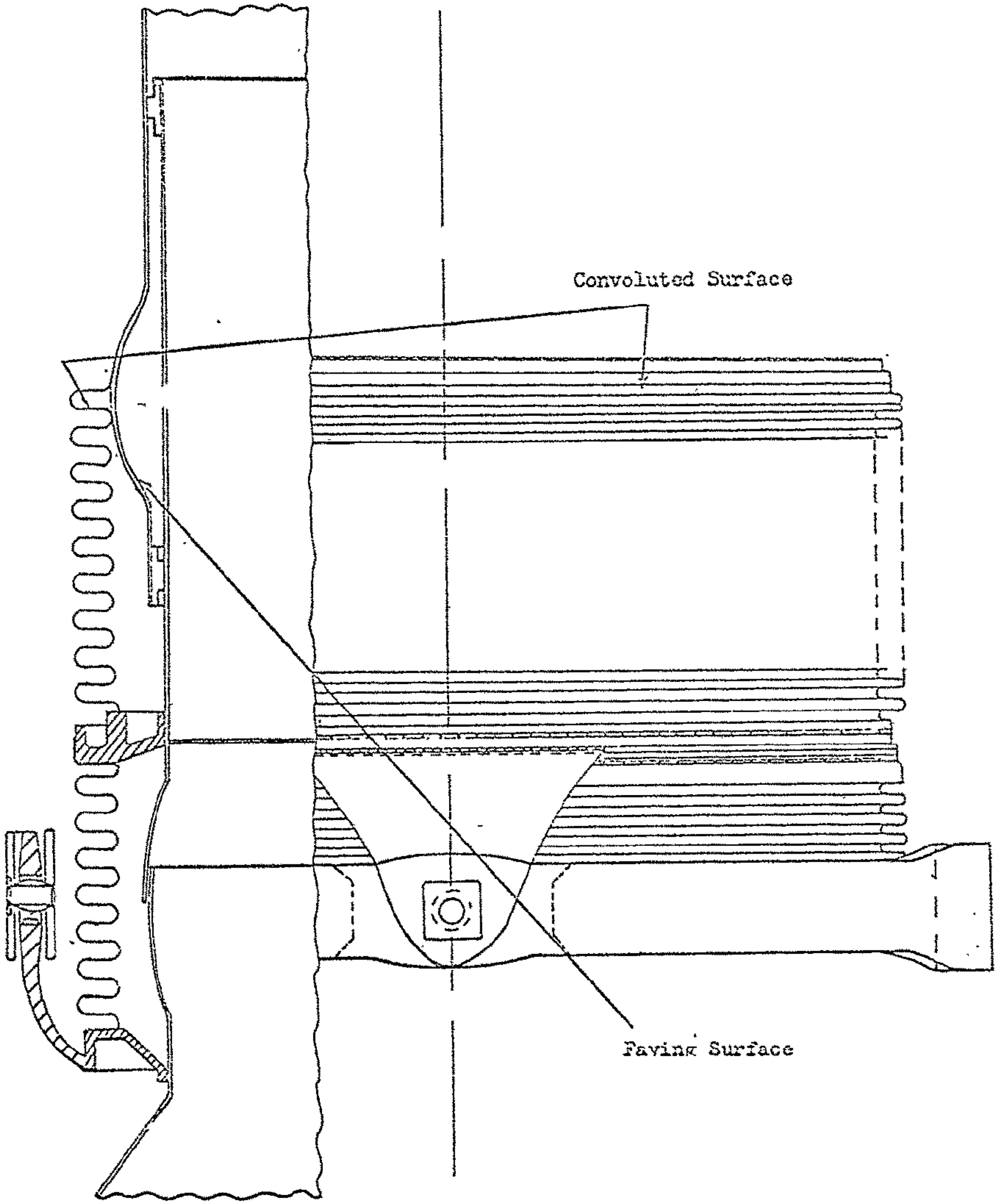
ANTI-SLOSH BAFFLE CONNECTION

Fig. 3-5



LOX SUCTION DUCTS, FUEL TANK

Fig. 3-6



TYPICAL GIMBAL JOINT, LOX SUCTION DUCT

Fig. 3-7

process. The faying surfaces could present a leakage problem where the FLOX would gasify and come into contact with materials which are not compatible with fluorine.

Flange Connection - Flange connections in the LOX suction ducts present a cleaning problem. The crevice noted in Fig. 3-8 presents a trap for contaminents and particular care should be taken in cleaning to remove these contaminants.

3.1.5 LOX Pressurization System (Ref. Fig. 3-9 and 3-10)

3.1.5.1 Material and Design Changes Necessary

GOX Flow Control Valve - The GOX flow control valve contains organic materials which make it necessary to redesign. These organics include rubber, teflon, and lubricants which are not compatible with gaseous fluorine.

Gimbal Joints - There are gimbal joints located throughout the LOX pressurization system which could cause considerable difficulty. The gimbal joints should be treated according to section 3.1.4.1.

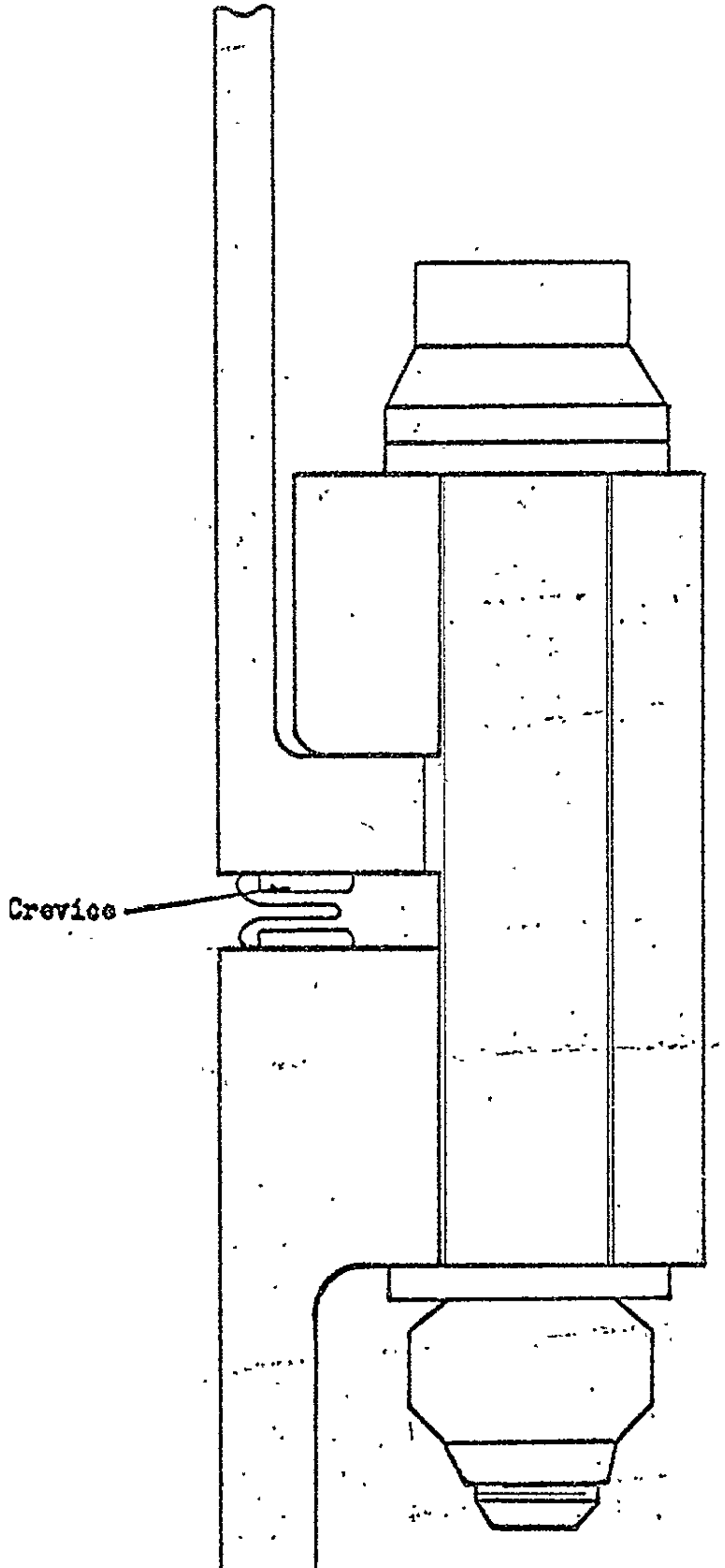
Temperature Transducers - Temperature transducers, noted in 3.1.3.1, will require redesign of platinum and organic materials. Since platinum forms volatile fluorides above 100°F, it is imperative that it be removed. The organic materials present are also non-compatible with gaseous fluorine.

3.1.6 Cleaning and Passivation

The recommended cleaning and passivation procedure for use with FLOX systems is essentially that used for LOX systems with the following additional requirements:

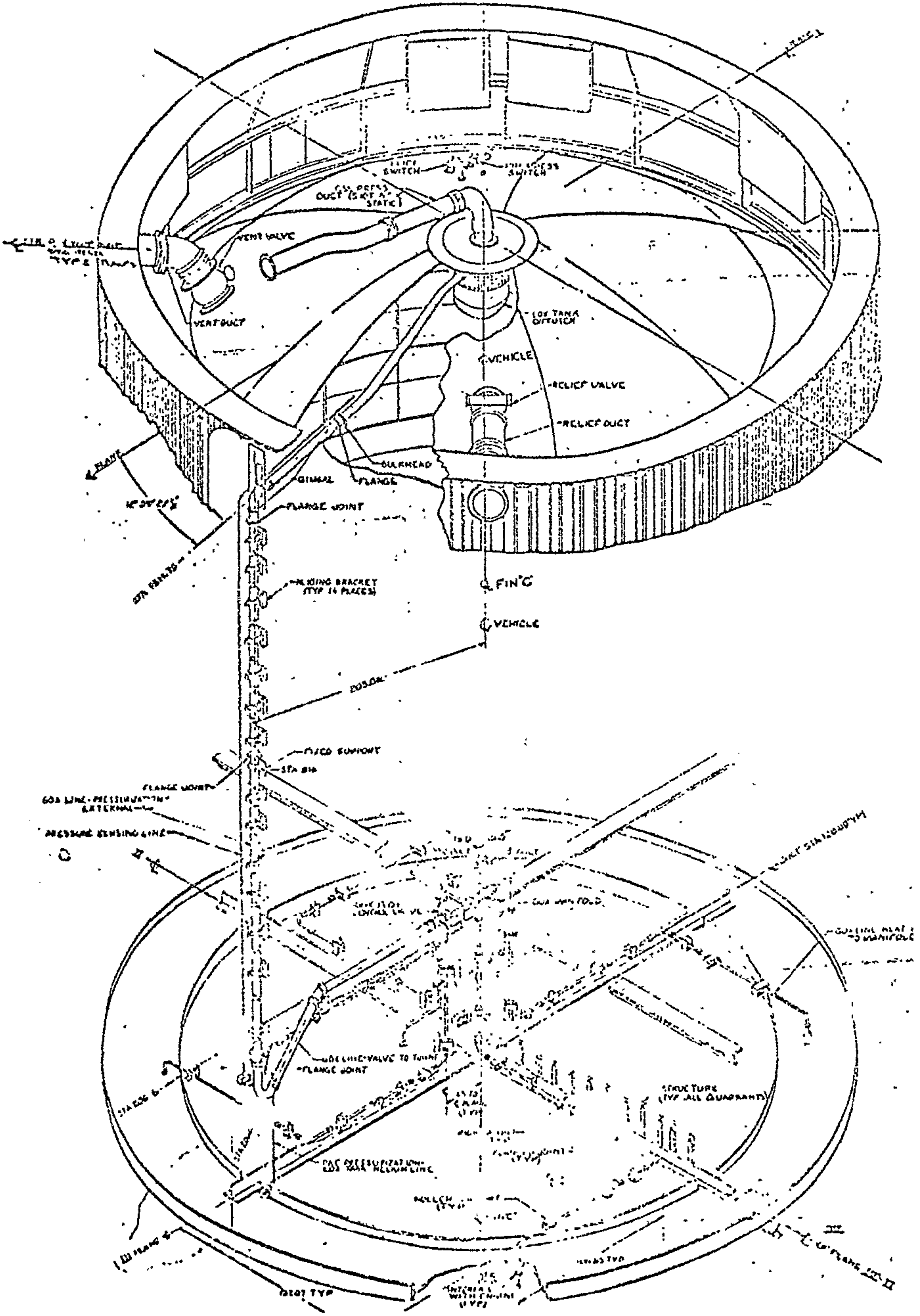
Final rinse water is removed by flushing with chemically pure acetone and drying with dry, oil-free inert gas. Parts should be processed as details if possible. Protective packaging with dry LOX clean non-particle generating materials such as Aclar should be required unless details are assembled into a closed system immediately. Dry LOX clean tongs or tools, or plastic coated gloves should be used in handling parts. When assembling components, gaskets, rings, and other such items should be new and freshly cleaned. Non-metallic materials should be immersed in a hot nitric acid solution for ½ hour prior to packaging, and wiped with acetone immediately prior to installation to remove surface impurities.

Welds, etc. should be cleaned and inspected in accordance with the standards used for LOX systems. After assembly of closed system, a water solution of non-silicated cleaner should be used, followed by a rinse with chemically pure acetone and drying and purging with oil-free dry (-65° dew point) inert gas or air. Closed systems should be kept pressurized with dry gas to prevent moist air from entering the system.



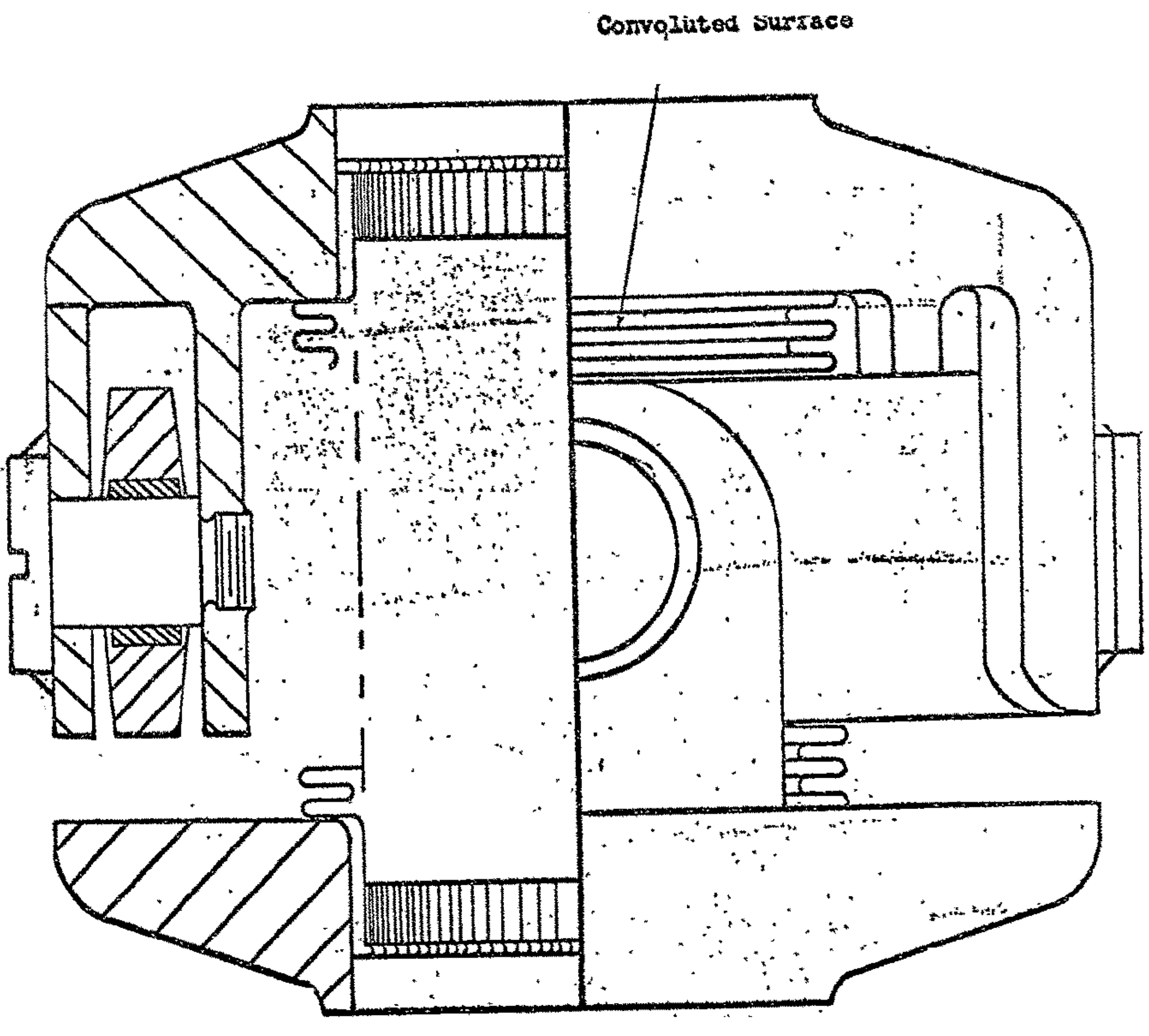
FLANGE CONNECTION, LOX SUCTION DUCT

Fig. 3-8



LOX PRESSURIZATION SYSTEM

Fig. 3-9



TYPICAL GIMBAL JOINT,
LOX PRESSURIZATION SYSTEM
Fig. 3-10

With regard to the S-IC oxidizer tank, the large faying surface area generated by slosh baffling makes the absolute exclusion of moisture of paramount importance. Consideration has been given to redesigning the baffling system to cut down the number of crevices and faying surfaces, but it is believed that this would involve many problems, and that the tank can be dried sufficiently to gain reasonable assurance that no moisture is retained in it prior to GF_2 passivation and FLOX exposure.

Prior to introduction to FLOX, the oxidizer system must be passivated with a dilute GF_2 mixture which is increased in F_2 concentration gradually until pure fluorine gas remains. This passivation must encompass the FLOX, GF_2/O_2 and engine systems. A detailed procedure for accomplishing this, including distribution systems and points of entry to the FLOX system will be presented.

The final pure fluorine gas should be maintained at a pressure of from 20 to 30 psig and held for 8 to 24 hours prior to introduction of FLOX. If the FLOX is removed, the system should be passivated for ½ hour with pure fluorine at 20 psig prior to reintroduction of FLOX.

If new, unpassivated components are required for use, these may be passivated by themselves in a manner similar to the original passivating procedure. The entire system should be repassivated for ½ hour as above after installation of the new component.

3.1.7 Conclusion

It is recommended that all non-metals be eliminated if possible in the entire system, and if it is not possible to design away from them, a minimum surface area should be available to the stream of flow. The decrease in surface area of the non-metals should increase the reliability of the system, since the speed with which the reaction occurs depends on the ratio of surface area available for reaction to the density of the materials.

The major problems appear to be in the redesign of the valves and switches in the GOX system and in the faying surfaces which exhibit crevices and convolutions. It may not be possible to design away from the creviced and convoluted areas shown; therefore, particular care should be taken in cleaning these surfaces.

It is recommended that more tests be made under conditions (pressure, temperature, and flow rate) similar to those experienced in the booster during flight in all areas of the oxidant system with metals as well as non-metals.

3.2 SPECIAL SYSTEMS DESIGN REQUIREMENTS

3.2.1 Pressurization and Vent Systems

3.2.1.1 Summary

A study was made to determine pressurization requirements for a liquid FLOX system on S-IC. The capability of the vent system under static, standby, and flight conditions was also analyzed. Existing system components were used throughout.

Results of the study indicate that pressurization requirements for the FLOX system will approximate the requirements for the existing LOX system. The capabilities of the vent system using FLOX were found to equal or exceed the performance of the LOX system.

3.2.1.2 Introduction

A study was made to determine the feasibility of replacing the LOX in the S-IC vehicle with a fluorine-oxygen (FLOX) mixture. This substitution is to be made with the minimum number of changes to present system hardware. This section reports the results of a study analyzing the requirements and capabilities of the existing pressurization and vent systems using FLOX.

3.2.1.3 Ground Rules

Because of the preliminary nature of this study and the uncertainty as to the actual percentage FLOX to be used, a complete system analysis was not conducted. In order to obtain realistic answers, the following ground rules were followed:

1. Existing system components are used throughout.
2. Performance of the F-1 engine heat exchanger with FLOX is the same as with LOX.
3. A 70 percent FLOX (fluorine by weight) mixture is considered.

3.2.1.4 Pressurization Requirements

Pre-pressurization of the FLOX tank can be accomplished with the present helium system. The increased density of the FLOX mixture results in a lower pre-pressurization requirement, and, therefore a decrease in the amount of helium necessary.

During flight, the pressurization requirements for FLOX tank will be supplied by the system presently onboard the S-IC. Figure 3-11 presents the pressure history for various pressurant flowrates. For comparison, the pressure history of the LOX tank has also been included. The results are conservative, as mass transfer has not been considered and the pressure schedule assumes maximum heat loss from the gas. For the purposes of this study, the initial FLOX tank ullage pressure was assumed equal to the LOX tank initial ullage pressure.

3.2.1.5 Vent System Capability

The capability of the present GOX vent system was analyzed for static test, standby, and flight conditions.

(a) Static Test

Operation of the vent system during static test of the FLOX vehicle will not differ appreciably from the present configuration. Due to the similarity between the properties of LOX and FLOX and the use of a common pressurant (GN_2), it was assumed that static operation was not a problem area.

(b) Standby Conditions

Figure 3-12 presents the capability of the vent system using 70 percent FLOX during standby. The requirements and capability of the GOX system are indicated for comparison. As can be seen from the figure, the capability of the system using FLOX exceeds that of the present GOX system. Vent requirements for the FLOX configuration during standby have not yet been determined.

(c) Flight Conditions

Flight capability of the vent system is presented in Figure 3-13 for a 125-second condition. The present GOX capability is presented for comparison. As under standby conditions, the vent system is capable of passing more FLOX than GOX.

The requirements for the FLOX configuration have not yet been determined. However, comparison of Figs. 3-11&3-13 indicates the vent system is capable of venting all the gas that is required for pressurization.

3.2.1.6 Conclusions

The following conclusions were reached during this study:

(1) The pressurization requirements for the FLOX tank will be similar to, but less than, the requirements for the present LOX system.

(2) The present vent system will pass a higher flowrate of FLOX than GOX.

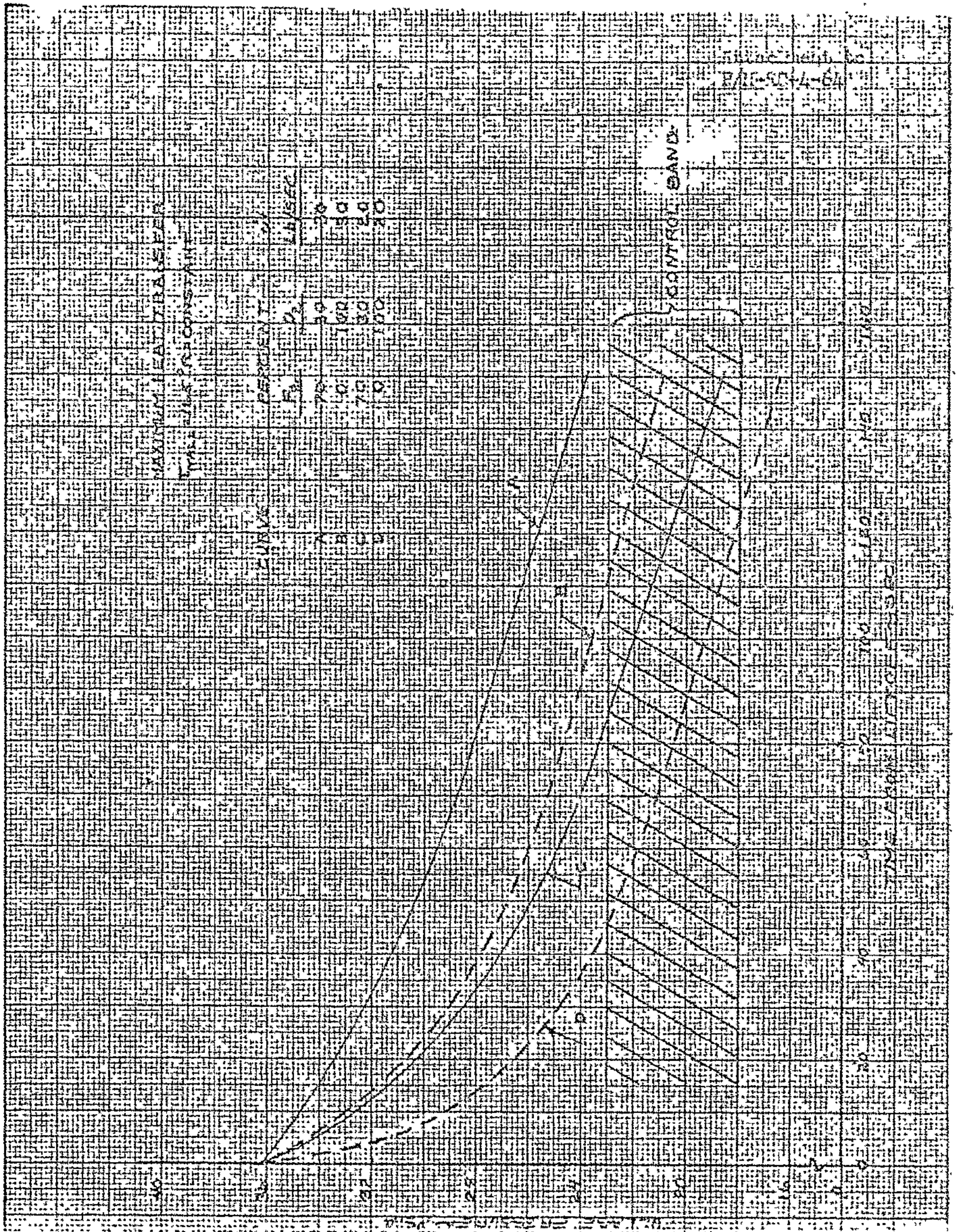
(3) FLOX vent system requirements will be similar to the present LOX system requirements; this conclusion is based primarily on the similarity of properties.

(4) Modifications to the existing heat exchanger may be required to permit passage of less than 20 lbs/sec of pressurant without overheating the piping system.

(5) From a pressurization and vent system viewpoint the existing systems' capabilities, excluding heat exchanger, are adequate.

3.2.1.7 Recommendations

It is recommended that during the second phase of this program the following areas be examined in a more rigorous manner as time and manpower permit:



				REVISED	DATE	APPROXIMATE FLOX TANK ULLAGE PRESSURE HISTORY	D5-11464-
CALC							Figure 3-13
CHECK							
APR						THE BOEING COMPANY	PAGE 27
APR							Sec 3
DWG	G.T.C.	7/21/4					

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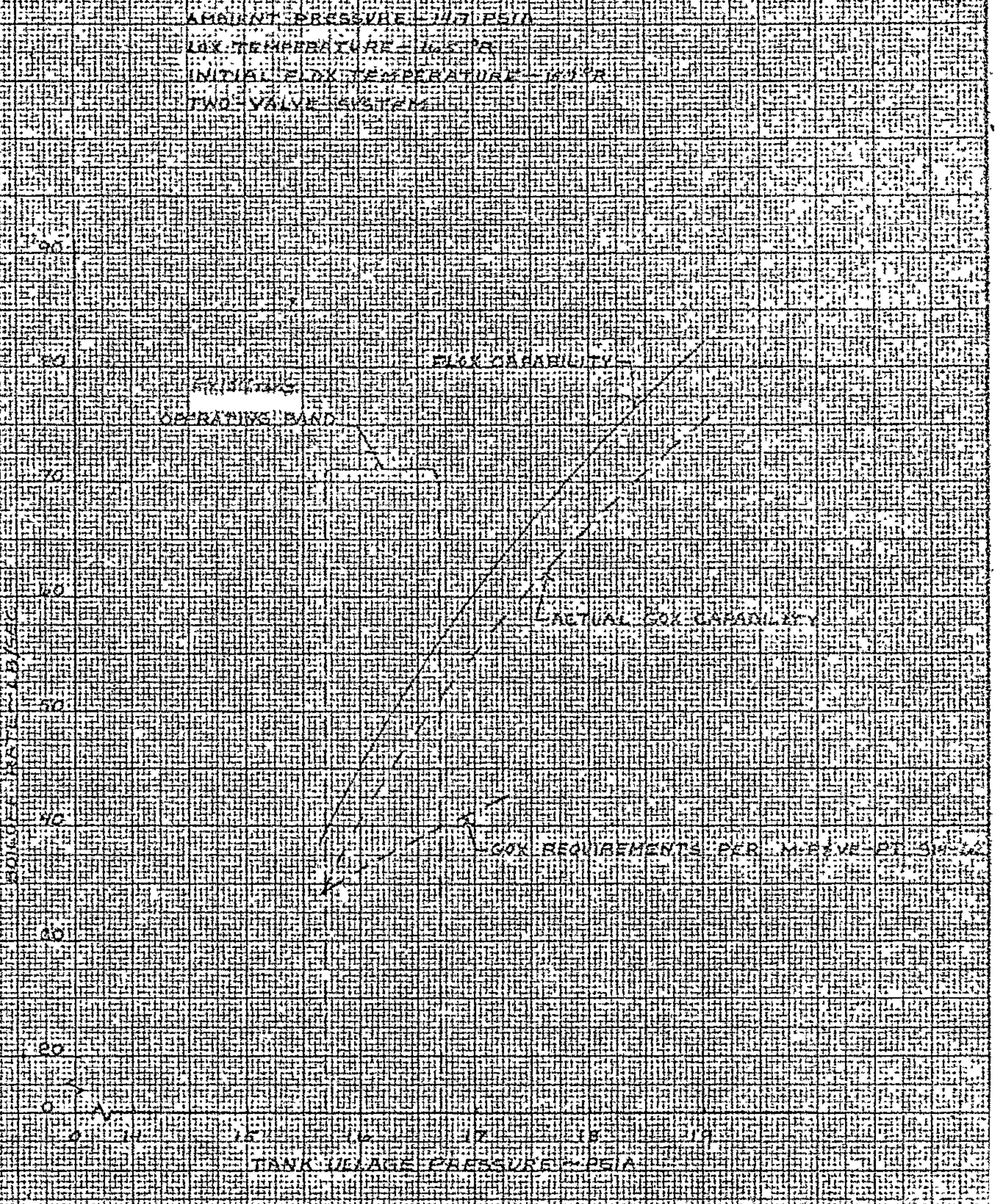

CALC			REVISED	DATE
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APR				
DWG	G.T.C.	7/21/4		

STANDBY CAPABILITY OF GOX
VENT SYSTEM USING 70% FLOX

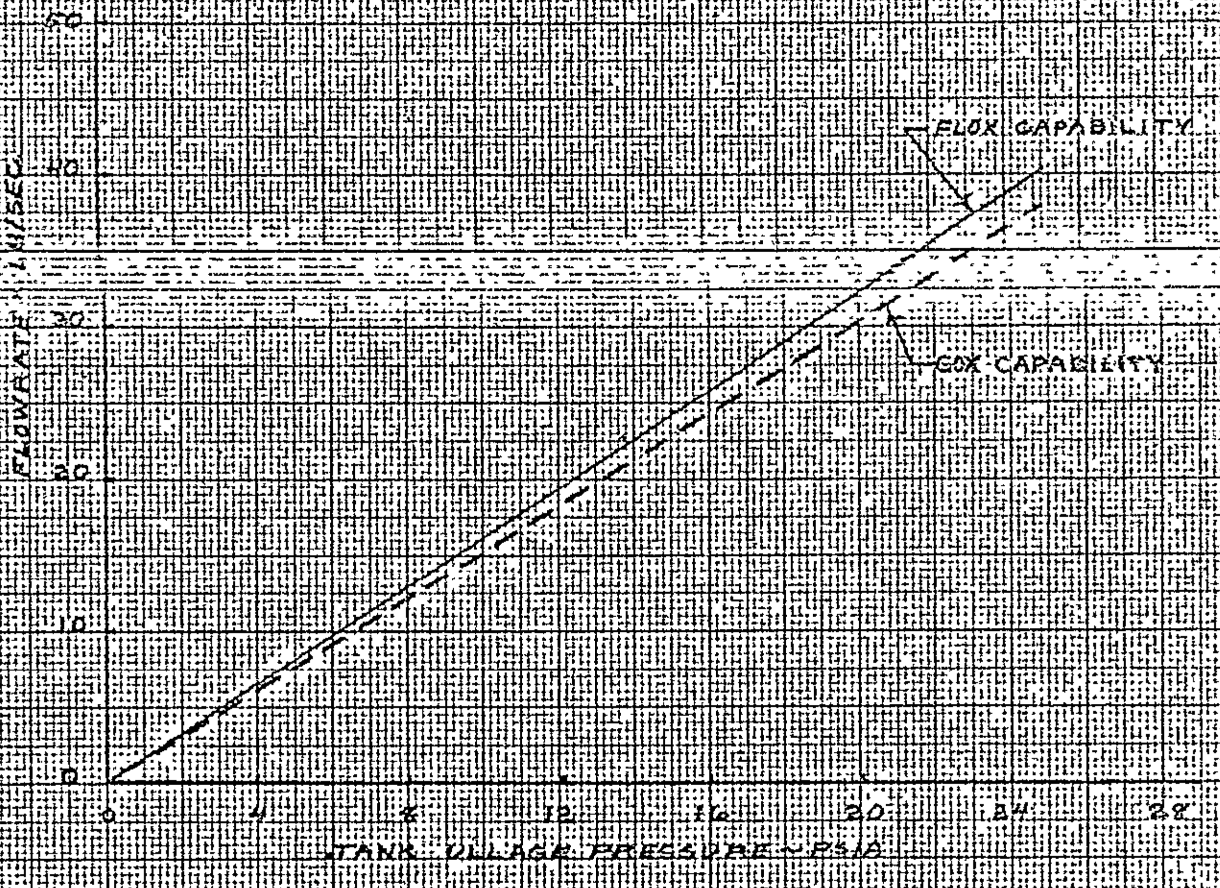
THE BOEING COMPANY

Figure 3-1

PAGE 28
Sec 3

Attachment to
P/S-RC-4-64

TIME = 125 SEC.
AMBIENT PRESSURE = 0.01 PSIA
GAS TEMPERATURE = 480 °R
ONE-VALVE SYSTEM



			REVISED	DATE		
CALC					FLIGHT CAPABILITY (τ=125 SEC) OF GOX VENT SYSTEM USING 70% FLOX	D5-11464-1
CHECK						
APR						Figure 3-1
APR					THE BOEING COMPANY	PAGE 29
DWG.	G. T. C	7/21/14		–		

(1) Performance of F-1 engine heat exchanger with FLOX in the GOX coils.

(2) FLOX pressurization requirements with revised heat exchanger performance data.

(3) Effect of FLOX vapors on vent system capability during static test.

(4) Actual requirements of vent system using FLOX.

3.2.2 Effect of Engine Ignition System Removal

When considering fluorine in LOX for S-IC oxidizer, weight and reliability advantages that are possible due to the hypergolic characteristics of FLOX/RP-1 should also be considered.

It would be possible to remove the following equipment from the present stage configuration if ten percent or more fluorine in LOX is used as the S-IC oxidizer.

	Weight
Engine G.G. pyrotechnic igniters and associated electrical wiring and armored harnesses.	9.0 pounds
Engine hypergol cylinders, hypergol cartridges (less hypergol fluid), ignition monitor valve assemblies and associated plumbing.	257.3 pounds
Stage electrical wiring and cables associated with G.G. ignition, G.G. ignitor monitoring and hypergol monitoring.	75.0 pounds
Stage weight savings	341.3 pounds

A stage start reliability increase is also predicted for FLOX/RP-1 due to the requirement for a less complex start sequence. The present start sequence requires an igniter burn through signal from both the G.G. igniters before the start sequence can continue and requires complex sequencing of the start control fluid through the ignition monitor valve to assure that fuel valves will not open before thrust chamber ignition. The referenced reliability table indicates that 9 out of 1,000 S-IC starts would be aborted by G.G. or skirt igniter malfunction and 2.5 out of 1,000 S-IC starts aborted due to hypergol system malfunction. The reliability of the ignition monitor valve is not given in the referenced table but its elimination is also considered a reliability improvement.

3.3 MAXIMUM LOADING PERMISSABLE WITH FLOX/RP-1 ON THE S-IC STAGE

In loading the S-IC to maximum capacity, when minimum ullages are specified, fuel density variations must be accounted for. This is true not only when both tanks are loaded to capacity, but also when only one is fully loaded and the other off loaded. Although the total loading values of Table 3-1 were determined for both tanks full, they will also suffice for any condition wherein only one tank is full.

Loading values given are total propellants including build-up and hold-down, unusable residuals, etc. Although propellants not available for mainstage will change slightly with changing FLOX concentration, the exact value for these cannot be obtained until a loaded mixture ratio is determined. Until this time the total loading values of Table 3-1 should be reduced by 157,920 pounds to obtain the propellants available for mainstage. This will also apply when one tank is off loaded.

3.4 THERMAL ENVIRONMENT

A preliminary study to evaluate the effects of the addition of FLOX to the S-IC oxidizer on the stage thermal environment has been completed. The results of this study are as follows:

Aerodynamic Heating - Since the addition of FLOX does not materially affect the vehicle thrust to weight ratio, it is expected that any changes in the aerodynamic heating rates will be small and will cause no major problem.

Base Heating - The addition of FLOX to the propellant will result in an increase of both the convective and radiant heating in the base area. These changes will be dependent upon the percent concentration of FLOX. A summary of these changes is presented in Table 3-2.

Based upon these preliminary estimates, it appears that the increases in base heating rates will be appreciable for FLOX levels of 30-70% and should be investigated in more detail. However, no insurmountable problems appear to exist.

MAXIMUM S-IC TANK LOADINGS WITH FLOX

% FLOX	Fuel Density	Maximum Loaded Propellants Prior to Ignition		
		Oxidizer	Fuel	Total
0	48.6 lbs/cu.ft.	3,296,725	1,399,370	4,696,095
	50.1	3,252,767	1,443,328	4,696,095
	51.6	3,206,789	1,489,306	4,696,095
30	48.6	3,579,473	1,395,145	4,974,618
	50.1	3,532,497	1,442,121	4,974,618
	51.6	3,485,395	1,489,223	4,974,618
50	48.6	3782,471	1,395,707	5,178,178
	50.1	3,736,825	1,441,353	5,178,178
	51.6	3,688,955	1,489,223	5,178,178
70	48.6	4,000,369	1,392,867	5,393,236
	50.1	3,952,620	1,440,616	5,393,236
	51.6	3,904,013	1,489,223	5,393,236

Table 3-1

FLOX EFFECTS ON BASE HEATING

Percent FLOX	Sea Level Radiation	Base Region Maximum Recirculated Gas Recovery Temp.	Base Region Recirculated Gas Heat Transfer Coefficient	Recirculation Begins
0	1.00	3050.°R	1.00	70 sec.
30.	2.22	3720.	1.08	70 sec.
50.	2.73	3920	1.06	71 sec.
7 70.	1.52	3400.	0.88	75 sec.

Table 3-2

SECTION 4

OPERATIONAL FEASIBILITY ANALYSIS

4.0 OPERATIONAL FEASIBILITY ANALYSIS

4.1 FLOX EFFECT ON GROUND SUPPORT EQUIPMENT FOR SATURN V/S-IC

4.1.1 Introduction

4.1.1.1 Purpose

Since a considerable performance gain appears to be possible with the use of a liquid oxygen - liquid fluorine (FLOX) mixture as the oxidizer in the S-IC stage, the effect on the Ground Support Equipment must be evaluated in order to determine the feasibility and cost effectiveness of its use. This section has been included in this report to outline the major ground support equipment functions which are affected by the use of FLOX and to assess the problems associated with each function.

4.1.1.2 Method

In order to determine the effect of FLOX on the Ground Support Equipment, operational flow charts were constructed for the S-IC stage The top flow chart is shown in Figure 4-1. This flow chart shows the major events from manufacturing to launch from Merritt Island Launch Area (MILA). The problems associated with each event have been listed below the blocks. It can be seen from Figure 4-1 that the major portion of the FLOX effect on the Ground Support Equipment occurs during the static firing at Mississippi Test Facility (MTF)and during the launch at MILA.

A lower level flow chart was then constructed for the static firing at MTF and is shown in Figure 4-2. The major problems associated with the static firing were shown as blocks on this chart. Each block is shown connected to the main event trail. These problem blocks are subsequently used as the basis for the expansion of this section. Figure 4-3 shows the general layout of Mississippi Test Facility.

A lower level flow chart was constructed in the same manner for Merritt Island Launch Area and is shown in Figure 4-4. Figure 4-5 shows the general layout pf one launch pad at Merritt Island Launch Area.

Each problem block from the Figure 4-2 and 4-4 flow charts has been expanded using knowledge and data from many of the references to form the remaining parts of this section of the report. Each of the problem blocks has been expanded as follows:

X.X.X.X.1 BACKGROUND INFORMATION on the operation and the effect of the use of liquid fluorine or FLOX on the operation.

X.X.X.X.2 PRESENT FACILITIES AT MISSISSIPPI TEST FACILITY OR AT MERRITT ISLAND LAUNCH AREA used to perform the operation. In some cases the operation may be new because of the use of liquid fluorine or FLOX.

FLOW CHART FLOX EFFECT ON GSE

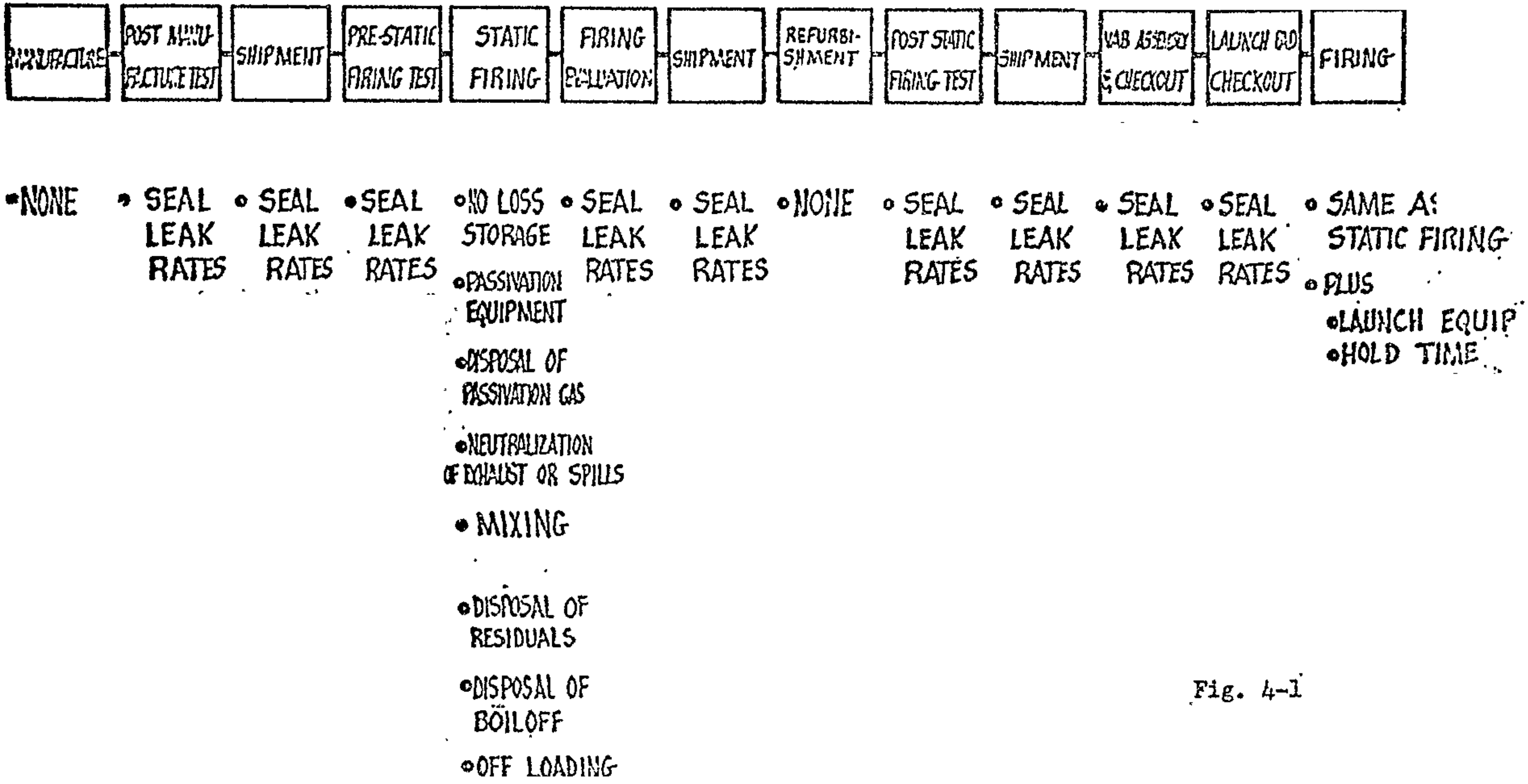


Fig. 4-1

D5-11464-
Sec. 4 Pg 3

FLOW CHART FLOX EFFECT ON GSE FOR STATIC FIRING AT MTF

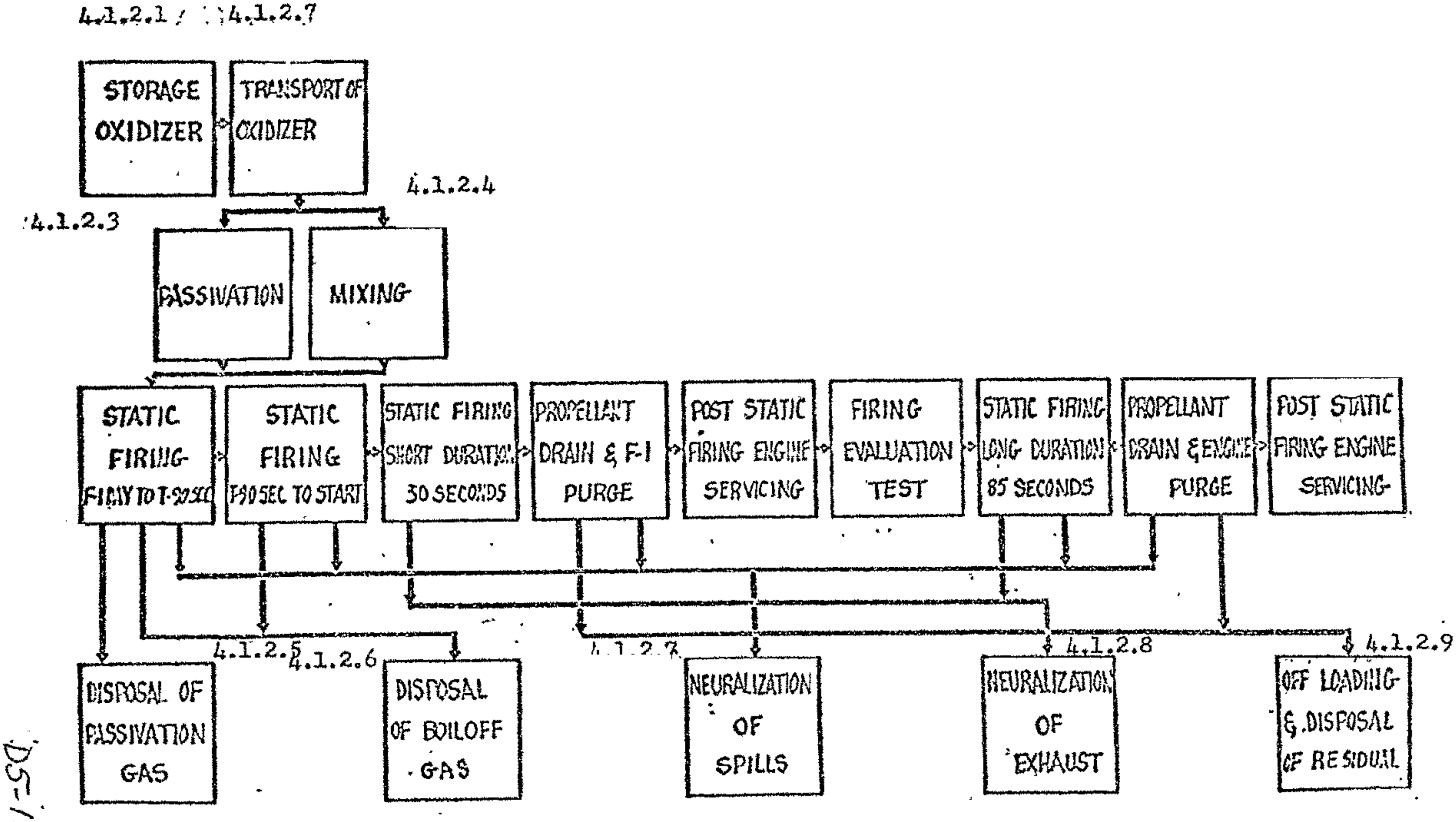
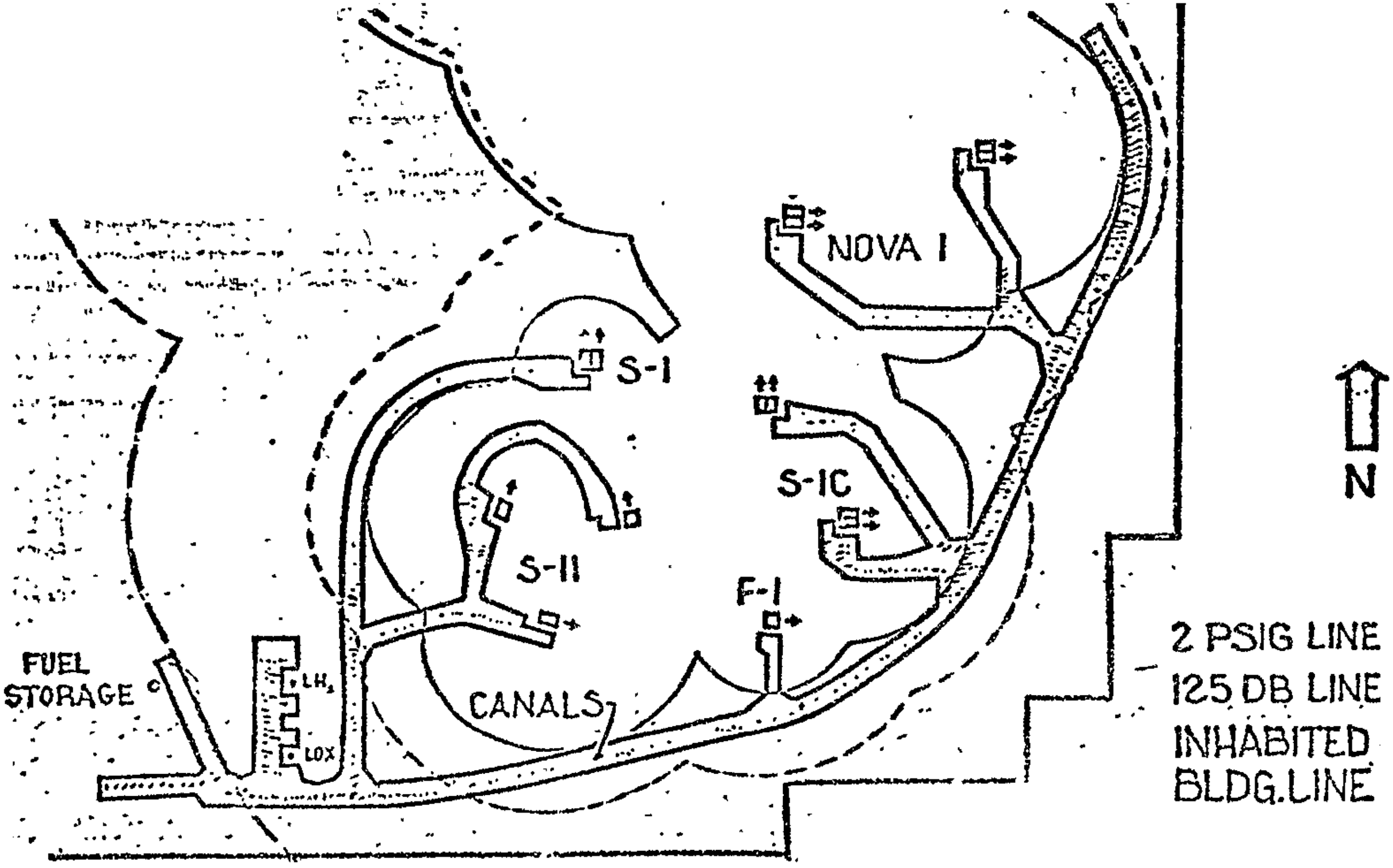


Fig. 4-2

Sec 4 Pg. 4
D5-11444-1

MISSISSIPPI TEST FACILITY



SCALE: 1" = 1000

FLOW CHART FLOX EFFECT ON GSE FOR ACTUAL FIRING AT MILA

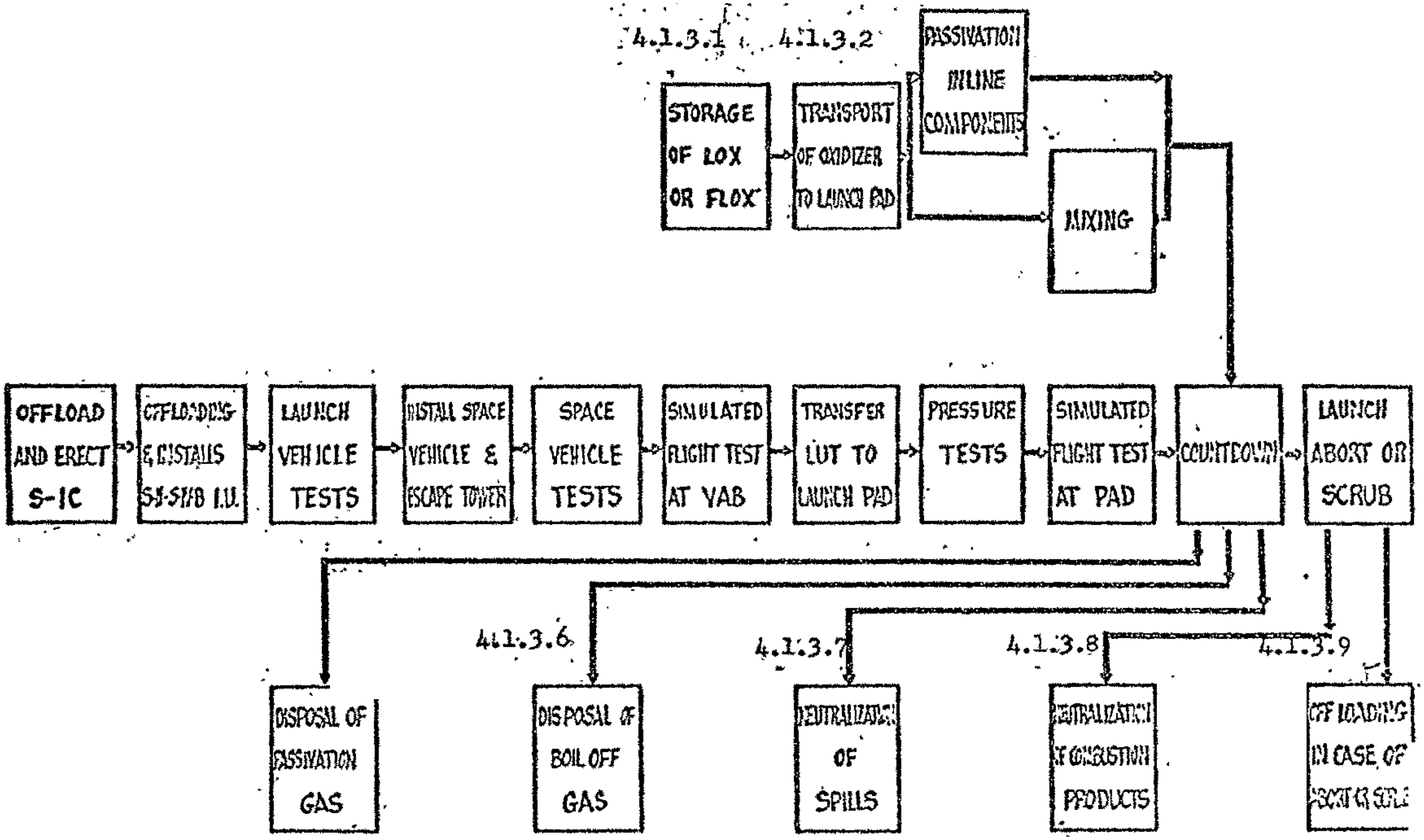
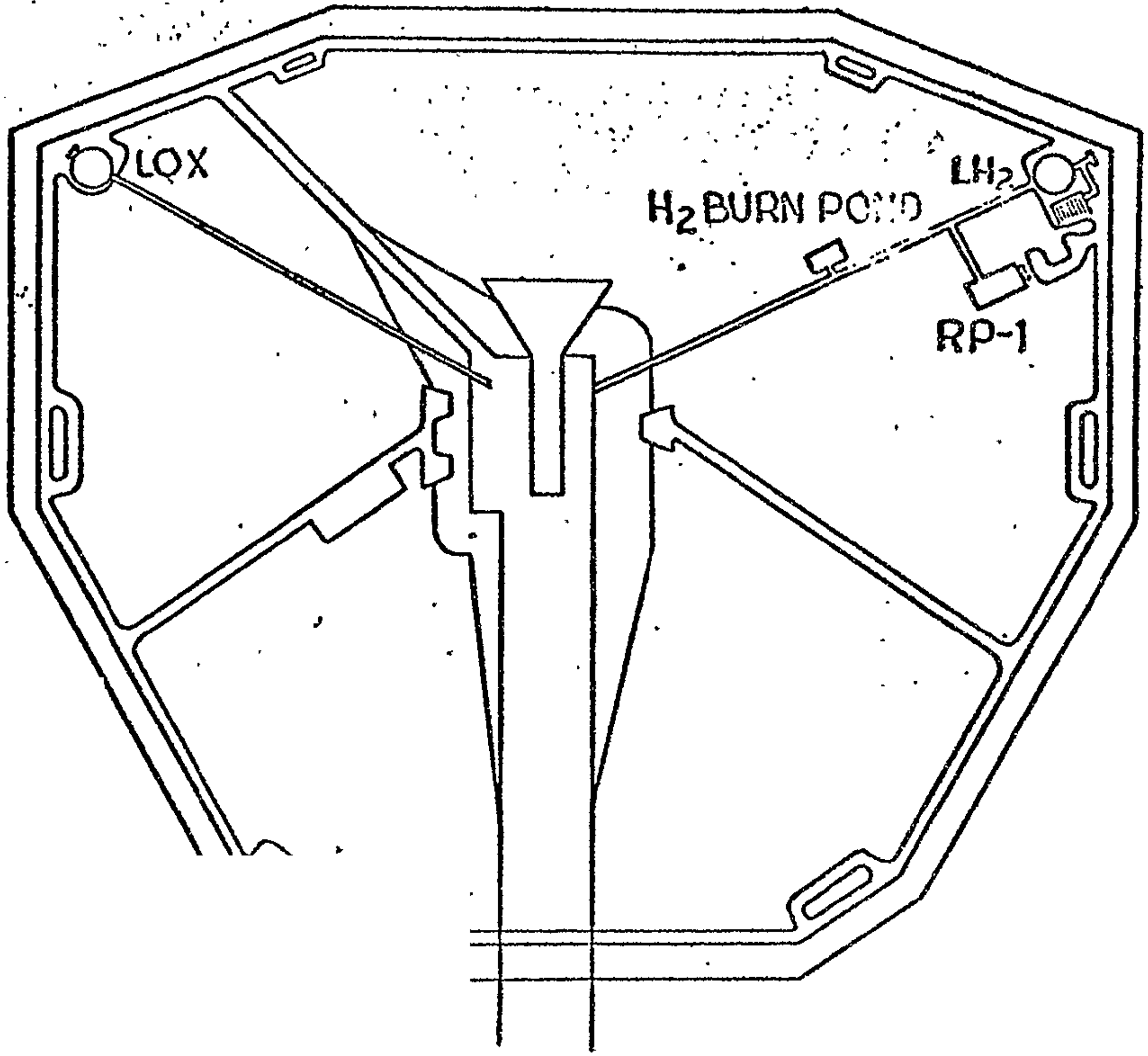


Fig. 4-4

MILA - LAUNCH COMPLEX 39

CRYOGENIC SUPPORT



X.X.X.X.3 FACILITY CHANGES AND/OR ADDITIONS needed to carry out the operation. Initially alternate methods should be locked at. Problem areas should be outlined.

4.1.1.3 Summary

This portion of the FLOX study has been pursued with the intention of defining potential GSE problem areas, determining the effects on facilities used in the ground support system, recommending several possible solutions for each problem, and defining the economic factors involved.

The problems peculiar to the FLOX oxidizer are not unique since a variety of ways exist to solve such problems as mixing, storage, disposal of combustion products and boil-off gases. The problem is more specifically to choose the best and most practical method for use on the Saturn S-IC/V. Additional trade-off and economic studies, which are not included in this report, must be completed before firm decisions can be made. It is not anticipated that any great changes to existing facilities will have to be initiated either at MILA or at MTO. The major equipment additions will most probably be a chemical reactor to neutralize fluorine or hydrogen fluoride gases and a condenser to liquify the large quantities of boil-off gases from the booster storage tank. Water deluge facilities at the firing sites appear to be adequate for treatment of all fluorine spills except the most catastrophic. Storage facilities presently used for liquid oxygen can probably be converted for use with fluorine and oxygen mixtures. Additional studies will be required in this area to determine feasibility. Mixing of cryogens and maintaining of proper mixture composition is not expected to cause undue difficulty. Precise quality control procedures should hold the mixture tolerances within a reasonable limit (estimated as ± 1%). Transfer and handling of FLOX can be accomplished with existing plumbing, valves and pumps, if materials compatibility is confirmed.

Economics poses a somewhat different problem and the solution will depend to a large extent on definition of broad categories such as number of launches, payload, final vehicle configuration, and optimum fuel to oxidizer mixture ratio. As this information becomes available, trade-off studies for GSE hardware can be carried out which will define the final system configuration.

4.1.2 Problems at Mississippi Test Facility

4.1.2.1 Central Storage of Liquid Fluorine or FLOX

4.1.2.1.1 Background Information

Large liquid fluorine storage facilities can be classed in three distinct groups. These are the liquid nitrogen jacketed tanks, the externally condensed tanks and the internally subcooled tanks. Each group can be augmented with several types of commercial insulations, radiation shields, or a vacuum. Liquid nitrogen jacketed tanks are considered zero loss systems since no fluorine is allowed to escape to the atmosphere by any technique of venting, cool down, or tank filling operations. However, externally condensed tanks and internally subcooled tanks can be designed for no loss if the systems are designed for maximum gas evolution anticipated during cool down or fill operations. Many factors must be considered in designing a liquid fluorine storage facility including installation cost, operating and maintenance costs, fluorine cost and consumption rates, and refrigerating cost and consumption rates.

Liquid Nitrogen Jacketed Tanks

Liquid nitrogen jacketed tanks are designed with three walls. The liquid fluorine is stored in the inner most container. The space between the inner and middle containers is filled with liquid nitrogen. The space between the middle and outer containers is evacuated and/or filled with an insulating material and/or radiation shields. Liquid nitrogen exists at a saturation temperature, corresponding to a pressure of 14.7, of 139.3° R and fluorine exists as a liquid up to 153.1° R. Thus the liquid fluorine cooled by the liquid nitrogen exists in a subcooled state. However, since the liquid nitrogen exists at a lower temperature than liquid fluorine, a greater temperature difference exists between the nitrogen and atmosphere causing a greater heat leak to the system and thus higher consumption of liquid nitrogen than the other two systems. This type of tank also represents an initial investment of approximately 30 percent more than the externally condensed or internally subcooled tanks and has a higher consumption. However, the liquid fluorine enters a subcooled tank and does not escape to the atmosphere.

Externally Condensed Tanks

Externally condensed tanks are designed with two walls. The liquid fluorine is stored in the inner most container. The space between the two containers is evacuated and/or filled with an insulating material and/or radiation shields. The temperature difference between the tank and the surroundings is 3% less than in the case of the liquid nitrogen jacketed tank. This causes a 3% smaller heat leak to the system but the heat leak causes some of the liquid fluorine to boiloff. This boiloff is collected and condensed outside the tank and then returned to the storage tank in the liquid form. This system can be designed to be a no loss system but is more economically designed as a minimum loss system. This means some fluorine is vented during fill and cool down periods and the condenser is designed for steady state operation of the tank.

Internally Subcooled Tanks

Internally subcooled tanks are designed with two walls. The liquid fluorine is stored in the inner tank. The space between the two tanks is evacuated and/or filled with an insulating material and/or radiation shields. The temperature difference between the tank and the surroundings is again less than the liquid nitrogen jacketed tank but it is higher than the externally condensed tank since the liquid fluorine is subcooled. The liquid fluorine is subcooled by a liquid nitrogen coil within the storage tank. This system has a higher nitrogen consumption rate than the externally condensed tank. This system can be designed to be a no loss system but is more economically designed as a minimum loss system. The subcooler coil must be placed vertically in the tank to subcool the entire contents when the tank is only partially filled.

Insulation Materials

There are a vast number of insulating techniques developed and used in the cryogenic field. The following represent various techniques: vacuum; vacuum plus metallic radiation shields; vacuum plus powders such as perlite, santocel, and metallic filled powders; vacuum plus "super insulation" consisting of a series of metal foils separated by low-conductivity glasses, etc.; and non-vacuum, blanket or foamed plastic insulations. Only the first two techniques are completely compatible with fluorine should leakage occur. The final design must consider cost versus purpose and potential hazards.

Tank Size, Shape and Location

The use of liquid fluorine dictates careful consideration of tank size and location since catastrophic failure of a tank could release large quantities of toxic products into the area. Economics dictates size and shape of the tanks. Storage facilities must be designed to neutralize and/or dispose of spills to the extent that personnel and other equipment are not damaged. The most economical storage size and shape is large and spherical. A compromise between the above requirements must be reached to adequately provide for liquid fluorine storage.

1.2.1.2 Present Facilities at Mississippi Test Facility (See Reference 1)

Present Liquid Oxygen Receiving Storage at Mississippi Test Facility

The liquid oxygen receiving storage facility at MTF will be a 460,000 gallon double-walled insulated sphere with a usable capacity of 400,000 gallons. The innter tank will be stainless steel or aluminum with a design stress determined by adding a minimum of 25 PSIG gas pressure to the maximum static head of liquid. The design temperature will be +130°F to -423°F to permit possible future storage of liquid hydrogen. The outer tank will be designed for an internal pressure of 0 PSIA if vacuum insulated and for an external pressure of 14.7 PSIA plus 0.8 over-pressure. The design temperature will be +130°F to -20°F. The loss rate at an ambient temperature of 70°F will not exceed 0.15 percent per day.

Present Liquid Oxygen Barges at Mississippi Test Facility

The liquid oxygen barges at MTF will be six 105,000 gallon double-walled insulated cylinders with usable capacities of 95,000 gallons each. These cylinders will be located on barges capable of being moved through the canal system. (See Figure 4.3). The inner tanks will be stainless steel or aluminum with a design stress determined by adding a minimum of 50 PSIG gas pressure to the maximum static head of liquid. The design temperature will be +130°F to -423°F. The outer tank will be designed for an external pressure of 14.7 PSIA plus 2.0 PSI overpressure. The design temperature will be +130°F to -20°F. The loss rate at an ambient temperature of 70°F will not exceed 0.15 percent per day.

Present Liquid Hydrogen Receiving Storage at Mississippi Test Facility

The liquid hydrogen receiving storage facility at MTF will be a 565,000 gallon double-walled, powder and vacuum insulated sphere with a usable capacity of 500,000 gallons. The material shall be stainless steel. The loss rate at an ambient temperature of 70°F shall not exceed 0.10 percent per day. The rest of the specifications will be similar to those of the liquid oxygen receiving storage facility.

Present Cost Estimate Summary

Liquid Oxygen Storage System	
460,000 gallon gross storage tank	$1,092,000
Liquid Oxygen Barges	
105,000 gallon barges	$1,890,000
6 @ $315,000	
Liquid Hydrogen Storage System	
565,000 gallon gross storage tank	$ 709,000

4.1.2.1.3 Facility Changes and/or Additions

The storage facility for the oxidizer must be chosen based on the total operation. FLOX is being considered for use in the S-IC because it is a versatile oxidizer and can be used in different concentrations based on the mission. This will require that the storage facility be designed to handle FLOX in concentrations up to 100% LF_2. Based on this study, the concentration of LF_2 does not effect the storage facility with respect to materials. The only change is in the thermodynamic characteristics of the mixture such as boiling temperature, vapor pressure, heat of vaporization, etc. The tank design should be based on the worst case.

Of the three tank designs discussed in the background information, the liquid nitrogen shielded tank has the best operating characteristics, but also has the highest initial cost and the highest liquid nitrogen consumption rate. The internally subcooled tank represents a smaller initial investment, some design problems, and a slightly lower liquid nitrogen consumption rate for the same operating characteristics. The storage tank with the recondenser has the advantage of low initial investment, lowest liquid nitrogen consumption rates, and the fact that present facilities can be modified for this type of storage.

Another consideration in designing the storage facility is the fact that because of the toxic nature of the boil off gases from the loaded S-IC stage, they will have to be disposed of or recondensed. If recondensation is chosen for these gases, this recondensing facility will be sufficiently large to handle the storage boil off rate since the stage boil off rate will be many times that of the storage facility. The present situation must also be considered at Mississippi Test Facility. The oxidizer is transported in the stored condition from the central storage area to the test stands on MSFC barges. These barges must be modified also to handle FLOX.

The engineering problems associated with liquid fluorine or FLOX storage can be solved but an economic analysis will have to be conducted to determine the optimum method to be used.

4.1.2.2 Transfer of Liquid Fluorine or FLOX to the Test Stand

Background Information

The transfer of liquid fluorine or FLOX is highly dependent on the initial conditions of the liquid fluorine or FLOX. If the storage facility keeps the liquid in a subcooled condition more heat leak can be allowed during the transfer process. If the storage facility keeps the liquid at or very near to the boiling point expensive low heat leak (insulated and nitrogen, shielded) and low friction (large diameter) transfer lines must be constructed. Transfer distances and flow rates must be considered since heat leak is a function of both of these parameters. Another factor in handling a highly corrosive fluid such as fluorine is that gases formed must be disposed of or recondensed. The transfer lines are generally divided into two groups, the nitrogen shielded, and the unshielded. Each group can be augmented with several types of commercial insulations, radiation shields or vacuum. The same economic factors must be considered when designing transfer lines that were discussed in 4.1.2.1.1.

Liquid Nitrogen Jacketed Lines

Nitrogen jacketed lines are designed similar to nitrogen jacketed tanks. The liquid fluorine is transferred through the inner most of two or three lines. The space between the inner and the next line is filled with liquid nitrogen. This keeps the liquid fluorine in a subcooled (140° R) state with a vapor pressure of 5 PSIG. This condition is obtained by maintaining the storage tank at 140° R with a liquid nitrogen shield or by passing the liquid fluorine through a liquid nitrogen subcooler prior to entry into the transfer line. There is no heat flow between the liquid nitrogen and the liquid fluorine. Therefore, heat is only transferred from the atmosphere to the liquid nitrogen. Vaporized liquid nitrogen is vented to the atmosphere and the liquid nitrogen is replenished. The heat transfer from the liquid nitrogen to the atmosphere is shown in Figure 4-6. If the liquid nitrogen shield is augmented with insulation, Figure 4-6 also gives an indication of the order of magnitude of the decrease in heat transfer. It must be noted that the insulation used for the plot in Figure 4-6 was polystyrene foam and other insulations will give different values. With a plot similar to Figure 4-6, the nitrogen consumption can be calculated knowing the heat of vaporization of liquid nitrogen and the length of the transfer process. No fluorine is allowed to be vented to the atmosphere during this process and thus no disposal or recondensing techniques have to be considered.

Unshielded Transfer Lines

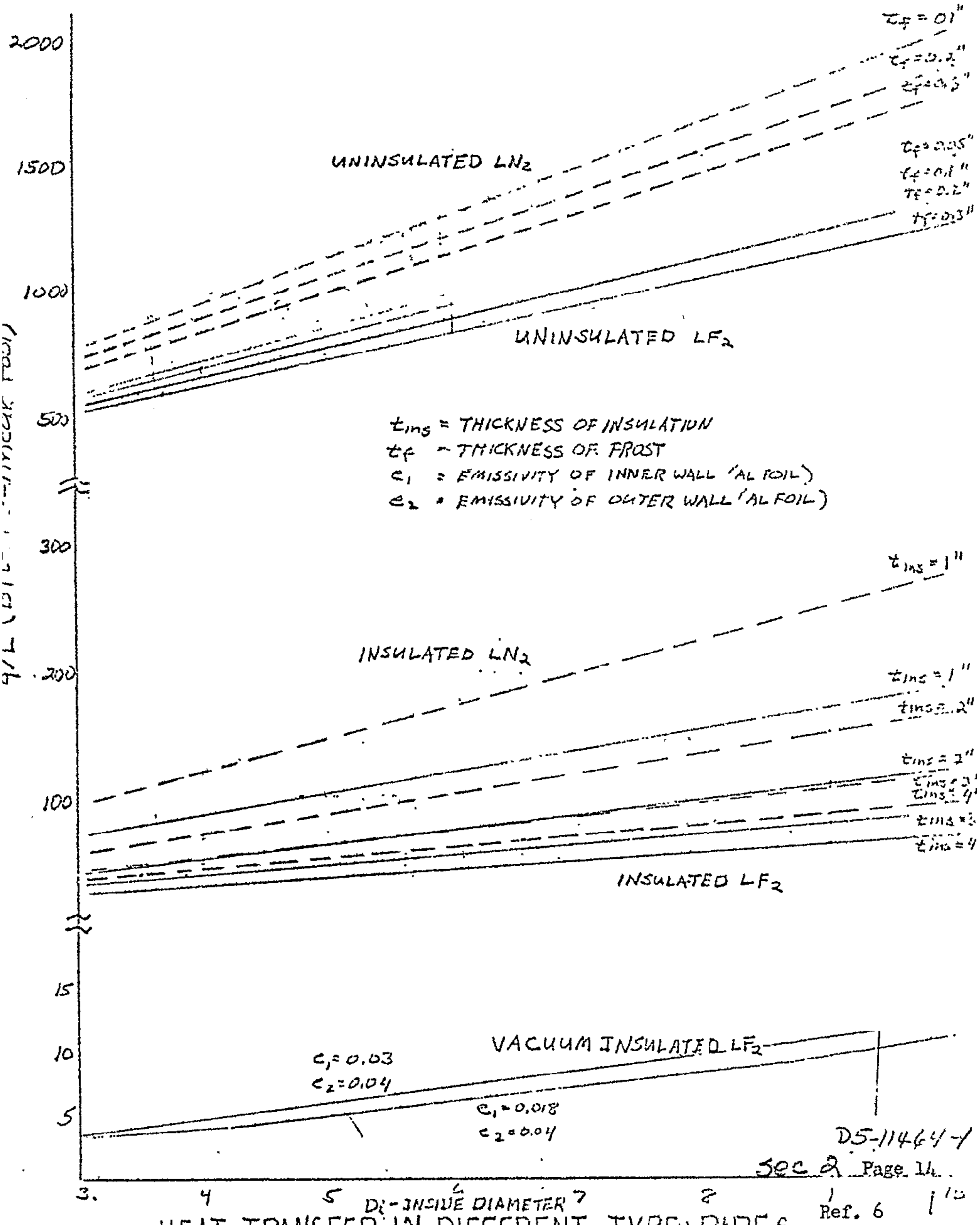
Unshielded transfer lines generally present the problem that unless the line is very short the heat leak to the liquid fluorine will be sufficient to boil some of the fluorine. This fluorine gas then must be vented to the atmosphere, disposed of, or recondensed. The problem can be partially solved by the storage facility. If the liquid fluorine is in a subcooled state when it starts the flow process, the heat leak to the fluorine will have to raise the temperature of the fluorine to its boiling point before the liquid can begin boiling. Again the line can be augmented with insulation to reduce the heat leak to the liquid fluorine. Figure 4-6 shows the heat leak to uninsulated and insulated liquid fluorine lines. It must be again noted that the insulation used for this plot was polystyrene foam. While an unshielded transfer system represents a savings in installation cost and also has a smaller heat leak than a nitrogen shielded transfer system, it must be noted that if the fluorine gas must be disposed of or recondensed, additional cost would be involved.

Vacuum Insulated Transfer Lines with Radiation Shielding

Vacuum jacketed transfer lines are constructed with the liquid fluorine line enclosed in an evacuated outer line. The surfaces of the pipes are wrapped with aluminum to reduce the emissivity of the pipe walls which reduces the heat leak. This method of transfer reduces the heat leak substantially as shown in Figure 4-6 but again increases the installation cost.

Fittings

Several fitting designs exist and this document will not attempt to go into the detailed design of any of them. The preferred method for joining nearly permanent lines is by welding since these joints require no maintenance after they are installed. Where the fitting cannot be made permanent, the recommended fittings include: Swagelok type fittings, aircraft type AN flared tube



HEAT TRANSFER IN DIFFERENT TYPE PIPES

Ref. 6
Fig. 4-6

fittings, and flanged gasketed fittings. Threaded fitting should not be used in fluorine service. The data on quick disconnects is limited but no major problems are anticipated.

Valves

There are two general categories into which valves fall; packed and packless. Packed valves use a sealing technique with fluorine compatible materials. They have been successfully used with gaseous fluorine and with liquid fluorine when in use with extended stems and housings. Packless valves use fluorine compatible metals for bellows or diaphram type seals. Packless type valves have the advantage of more reliable sealing and the disadvantage of pressure and stroke limitations. Packed valves can be used at higher pressures but the sealing materials such as chevron seals of tetra fluoroethylene polymer (Teflon) are usually not compatible with liquid fluorine under dynamic conditions. This requires that the packing be placed in a position where it will be in contact only with gaseous fluorine. This can be accomplished by extending valve body or stem or by utilizing finned body extension. Application to shutoff valves and throttling valves is more frequent than to pressure regulating and relief valves because of higher leakage rates.

Transfer Pumps

Centrifugal pumps appear to be best suited for liquid fluorine service. The main advantage is the minimum or lack of rubbing surfaces which precludes the destruction of the protective fluoride coating. Other advantages include minimum maintenance, ease of maintenance, low initial cost, minimum size, absence of fluctuating line stress, and operability under a wide variety of conditions. The main disadvantage is that a centrifugal pump must be primed before it is started. Positive displacement pumps have good pumping characteristics but rubbing surfaces in contact with the fluorine eliminate them from consideration. A problem common to all pump designs is fluorine compatible shaft seals.

.1.2.2.2 Present Facilities at Mississippi Test Facility (See Reference1)

Present LOX Transfer at Mississippi Test Facility

As discussed in Section 4.1.2.1.2, LOX is actually transferred in a stored condition by barge from the central storage facility to the general location of the test stand. This eliminates the major portion of the piping problem. However, piping is still used at the central storage and at the test stand. For liquid oxygen the piping is uninsulated suitable for the operating pressures and -423°F. Where practical, the system will be completely welded. All valves will be flanged. Only factory-made buttweld fittings shall be used. All valves will be of extended bonnet construction capable of maintaining a temperature in the packing gland above 40° F at 60° F. ambient temperature and -423 fluid temperature. Valve packing shall be Teflon chevron rings or Teflon impregnated asbestos. Leakage across the valve seats will not exceed 1 standard cubic centimeter per minute per inch of nominal valve diameter, or 0.5 standard cubic centimeters per minute externally when pressurized with nitrogen to the system operating conditions. The pumps will be the direct drive, centrifugal type with packing material suitable for handling liquid oxygen. All wetted surfaces will be satisfactory for minus 300°F operation. Pumps and motors will be mounted on a common base and be suitable for outdoor installation.

Present LH_2 Transfer at Mississippi Test Facility

As discussed in Section 4.1.2.1.2, LH_2 is actually transferred in a stored condition by barge from the central storage area to the general location of the test stand. This eliminates the major portion of the piping problem. However, piping is still used at the central storage area and at the test stand. For liquid hydrogen the piping will be vacuum jacketed with maximum heat leak per unit length and per joint to be specified in detail during final design. All shop-fabricated portions of the piping shall be furnished with their vacuum-jackets permanently evacuated and sealed. Each isolated portion of the line shall be provided with two seale connections located one at each end of the outside pipe. The internal pipe will be suitable for operating pressures of the system and -423° F temperature. The system will be completely welded, including all valves and in-line instruments, except main components such as tanks, pumps, filters, etc., which will be flanged. Where valves are adjacent to main components and will not require additional flanges, the valves will be flanged. Only factory-made buttweld fittings will be used. All valves for liquid hydrogen will be globe, butterfly, or ball-type, vacuum-jacketed or wrapped, and of extended bonnet construction capable of maintaining a temperature in the packing gland above 40° F at 60° F ambient temperature and -423° F fluid temperature. Where practical, all valves will have buttweld ends for the liquid and jacket connections. The heat leak will not exceed 46 BTU/hr per inch of nominal valve size as measured at liquid nitrogen temperature. Valve packing will be Teflon chevron rings or Teflon impregnated asbestos. Leakage across valve seats will not exceed one standard cubic centimeter per minute per inch of nominal valve diameter, or 0.5 standard cubic centimeters externally, when pressurized with nitrogen to the system operating pressure at liquid nitrogen temperature.

Present Cost Estimate Summary

Liquid Oxygen Storage System Transfer Pumps	$ 64,000
Piping, flexible connectors, valves, filters, etc.	[illegible]
Controls and Monitors	46,000
Liquid Oxygen Barges LOX pumps 18 @ $15,000	270,000
Piping, fittings, valves, etc. 6 x $41,000	246,000
Controls and Monitors	26,000
Liquid Hydrogen Storage System	
Piping, flexible connectors, valve, filters, etc.	280,000
Controls and Monitors	49,000

4.1.2.2.3 Facility Changes and/or Additions

The transfer of FLOX at MTF is simplified by the fact that the transfer distances are relatively small and the cost would not be excessive to replace the uninsulated existing LOX transfer lines with some type of insulated or vacuum jacketed lines. These new insulated or vacuum jacketed lines could be identical to the existing liquid hydrogen transfer lines. The minor change would reduce the FLOX boiloff during transfer by a factor of nearly one hundred. On the other hand, an economic analysis may show that the extra FLOX boiloff caused by these short uninsulated lines is not significant enough to warrant replacing them.

The valves presently used are compatible with fluorine or FLOX usage. Some testing will be required to substantiate the compatibility at the actual flowrates and pressures. Also the connections are generally welded except where non-permanent installation is required and then flanged connections are used. This is ideal for fluorine.

Pumps present the greatest problem since rubbing surfaces must be eliminated in order to protect the passivation of the equipment. Testing will have to be conducted to insure the compatibility of the pumps with fluorine operation.

In conclusion, the transport of liquid fluorine or FLOX present no large problems. Testing should be conducted to verify compatibility of valves, filters, pumps, etc.

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4.1.2.3 Passivation of All In-Line Components

4.1.2.3.1 Background Information

Cleanliness and passivation is the most important key to safe and successful operation with fluorine or FLOX. Although material selection is extremely important, the surface cleanliness of the equipment can be equally important. The surface finish must be free from voids, slag, or chips. Leaks in a system are often caused by moisture which reacts with the fluorine and causes burnouts. These hazards can be overcome by immaculate cleaning of components in a system and by passivation or treatment of the cleaned system with diluted low-pressure fluorine gas, followed by pressurization of the system with concentrated high pressure fluorine gas. This should precede the introduction of liquid fluorine. The thought behind passivation is that metals form a thin protective fluorine film on their surface which protects them from corrosion. In addition, residual contaminants react with the fluorine to form inert products.

Cleaning Procedures

Each user of liquid fluorine has a different cleaning procedure. The cleaning procedures of three fluorine users will be outlined below. The methods are not conflicting but merely different means to the same end.

NASA uses soap and water, steam cleaning, and air or inert gas purging to remove heavy dirt, foreign particles and coatings. This is followed by a 10-20 percent nitric acid wash and water rinse. Acetone is used to remove residual rinse water.

An inert gas purge follows the acetone. The part is then wrapped, purged with inert gas, and if practical, evacuated at room temperature. Before use, the part should be subjected to pressure tests using filtered dried inert gas.

Bell Aircraft scrubs the interior surfaces in methylene chloride with a bristle brush. The acid pickling solution is applied with a bristle brush for several minutes until any rust, and oxide coatings are dissolved. Residual acid is removed from crevices by flushing thoroughly with water for 10 minutes. This process is followed by steam cleaning and oven-baking at 250° F. for 8 hours. The cleaning and pickling procedures adopted by Bell are designed to remove foreign matter,metal oxides, and welding and brazing fluxes before passivation of the system with fluorine gas. The pickling process is conducted in two steps; a mild or conditioning pickle for relatively clean surfaces to remove normal surface oxides, contaminants, and foreign metal particles resulting from normal handling and manufacturing processes, and a de-scaling pickle to remove heavy scale, oxides, and welding flux. The latter should be used sparingly as it may attack the base metal.

Rocketdyne Division of North American disassembles the part as far as possible and vapor degreases the parts. The parts are then immersed in a cleaning detergent solution, then distilled or deionized water, then a neutralizing solution, and then deionized water again. The residual water is removed with clean acetone and the parts are then dried with oil-free nitrogen or helium. Additional drying can be obtained by baking the parts in a dust-free oven at 250° F for one hour or by placing the parts in a vacuum for 8 hours.

Passivation Procedures

All passivation procedures are generally in agreement. They consist of introducing dilute fluorine gas into the system and slowly increasing the concentration and pressure. Different users suggest different methods of diluting the fluorine including nitrogen and helium. The pressure is normally increased from 0 PSIG to working pressure in about one hour and held at the working pressure from one to two hours.

4.1.2.3.2 Present Methods and Facilities at Mississippi Test Facility

Present Cleaning Specifications

Present cleaning methods are outlined in MSFC-SPEC-164, "Cleanliness of Components for use in Oxygen, Fuel, and Pneumatic Systems, Specifications for." The discipline set forth for liquid oxygen system is no more severe than that necessary for FLOX or LF_2 systems. FLOX or LF_2 systems will necessarily have to be passivated in addition to cleaning.

Present Passivation Facilities at MTO

None.

4.1.2.3.3 Facility Changes and/or Additions

Since passivation is an entirely new operation, new equipment will have to be designed to accomplish the operation. The new equipment will be required to vaporize fluorine or FLOX and supply it to all systems which will be in contact with the fluorine or FLOX during the static test operation. Passivation can be accomplished using either fluorine or FLOX but in both cases will have to be varied in fluorine concentration and pressure. The exact location and size of the equipment will be determined by the design work itself.

The present LOX cleaning procedures are adequate to prepare the equipment for the actual introduction of the passivation gas.

In conclusion, there are no problems associated with passivation that cannot be solved in the actual design work.

4.1.2.4 Mixing

4.1.2.4.1 Background Information

Mixing entails a number of separate problems which include how the operation is to be carried out, where it is to be accomplished and finally, quality control of the end product. Since oxygen and fluorine are readily miscible in all proportions, it would appear that mixing can be accomplished very easily in the storage vessel itself.

An alternate method for blending the cryogens would be to store oxygen and fluorine separately and carry out the mixing operation in the lines during the loading procedure. Disadvantages to this method are readily apparent. A large central FLOX storage will be required to store off-loaded propellants in case of mission abort. Since this is the case, it appears more reasonable to use the mixed storage concept. Another advantage of the mixed storage method is that the percentage tolerances can be adjusted to a fine degree of accuracy and can then be "frozen" at the desired composition for a long period of time in a closed system storage tank.

The success of the mixing operation, in the final analysis, depends on how accurately fluorine and oxygen can be mixed sample tested for percentage. At the present time, there is no commercially available product which can directly measure percent fluorine in a given sample. There is, however, a device which can determine the percentage oxygen in FLOX to within ± 1 percent. The fluorine in the sample by chemical process, is first converted to gaseous chlorine to prevent etching of the detector's glass components. Percentage O_2 is measured by determining the change in magnetic field caused by the presence of oxygen and percent fluorine is, of course, the difference between this number and 100 percent. Further investigation will be required to determine if the device has the required reliability for use in the Saturn system. If a more accurate method becomes necessary, standard procedures of "wet" chemical analysis are available and details can be found in reference 7 for both oxygen and fluorine. Detection of small quantity or trace contaminants such as hydrogen fluoride (HF), carbon tetrafluoride (CF_4), and hydrocarbons can readily be carried out by use of infrared-spectrometry and standard chemical methods listed in reference 8.

4.1.2.4.2 Present Facilities at Mississippi Test Facility

At present, there are no special mixing devices available at MTO. If mixing is carried out in the existing storage tank, no additional equipment requirements are anticipated.

4.1.2.4.3 Facility Changes and/or Additions

Because mixing can most practically and economically be accomplished in the oxidizer storage tanks, the only foreseeable problem would be concerned with stratification or separation of phases, should the "FLOX mixture be allowed to remain dormant for a considerable period of time. Additional testing is necessary in this area to see if such a problem really exists. However, the increase in reliability of end-product composition should more than off-set any deleterious effects caused by stratification which can be minimized by existing methods such as gas bubbling, mechanical mixing or placement of metal strips to promote heat transfer to all tank areas.

The measurement of oxygen, fluorine and trace materials should be carried out by the infra-red and paramagnetic equipment. The standard or "wet" quantitative methods are more cumbersome and not readily adapted for use in the field.

4.1.2.5 Disposal of Passivation Gas

4.1.2.5.1 Background Information.

There are a number of methods for treatment of the residual passivation gas. The first is to chemically reduce the gas to a relatively inert by-product such as carbon tetrafluoride. This can readily be carried out by reacting the fluoride with solid carbon, anhydrous ammonia or through combustion with hydrocarbon gas. The former utilizes a reactor vessel as shown in Figure 4-7a. The gases enter the system at point A, where a servo-valve can regulate the quantity of gas into the reaction chamber. The chamber is lined with firebrick and is surrounded by a cooling water jacket to prevent chamber burnout. The product is carbon tetrafluoride which is inert and can be vented directly to the atmosphere. The stoichiometric quantity and cost of carbon needed to completely reduce the fluorine is given below:

$$C_{(S)} + 2F_2 \qquad CF_4$$

$$\text{LB. } F_2 \times \frac{\text{Mole } F_2}{38 \text{ LB } F_2} \times \frac{1 \text{ Mole C}}{2 \text{ Moles } F_2} \times \frac{12 \text{ LBS}}{1 \text{ Mole C}} = \frac{.158 \text{ LB Carbon}}{\text{LB } F_2}$$

$$\frac{.158 \text{ LB (c)}}{\text{LB } F_2} \times \frac{\$.14}{\text{LB}} = \frac{\$.022}{\text{LB } F_2}$$

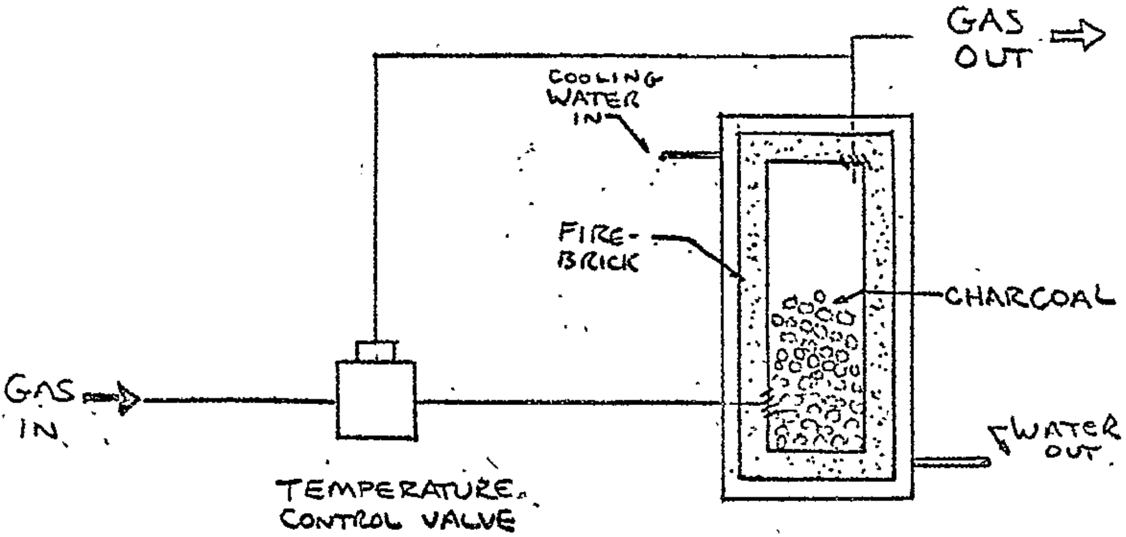
The second method utilizing liquid anhydrous ammonia (NH_3) as the reducing agent is shown in Figure 4-7b.

The exhaust gases containing a mixture of F_2, HF, enter the system at point A. The stream is then mixed with the stoichiometric amount of vaporized ammonia (NH_3) before introduction into the reaction chamber. The design of the reactor will depend, in large part, upon the quantity of gases to be treated and the degree of concentration required for the product at the stack outlet. The catalyst, which is made from alumina (AL_2O_3) and covered with finely divided nickel or platinum, promotes the reaction between ammonia and fluorine as follows:

(1) $4NH_3 + 3F_2 \text{ Catalyst } \quad 2NH_4F + 4HF + N_2$

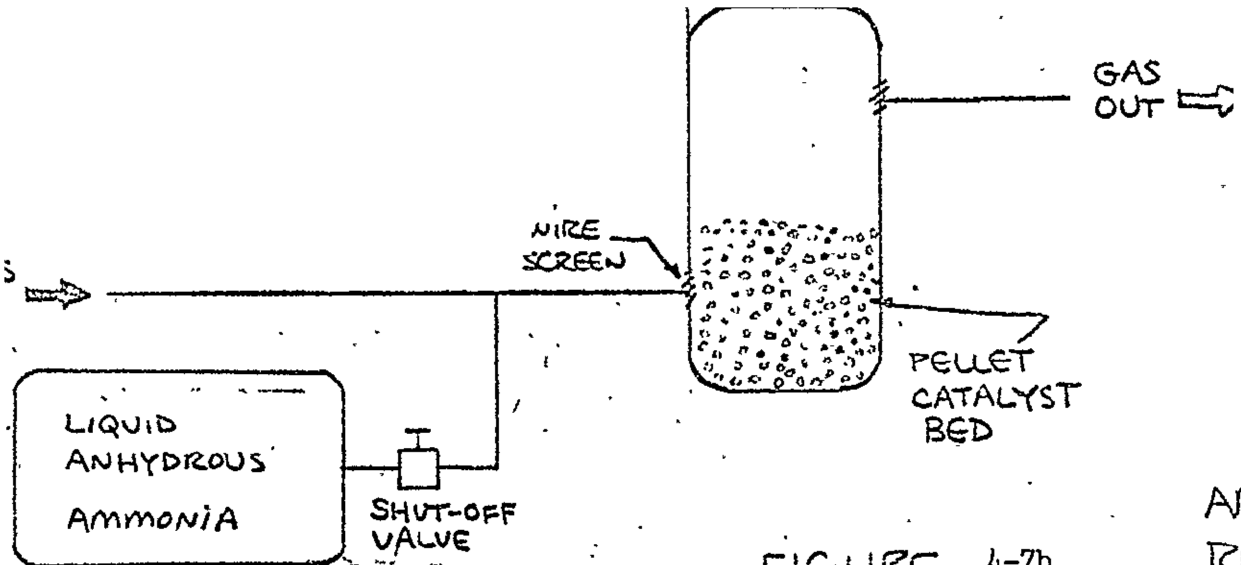
(2) $HF + NH_3 \text{ Catalyst } \quad NH_4F$

Stoichiometric quantity and cost of ammonia needed to treat the fluorine is given below:



CHARCOAL REACTOR

FIGURE 4-7a



AMMONIA REACTOR

FIGURE 4-7b

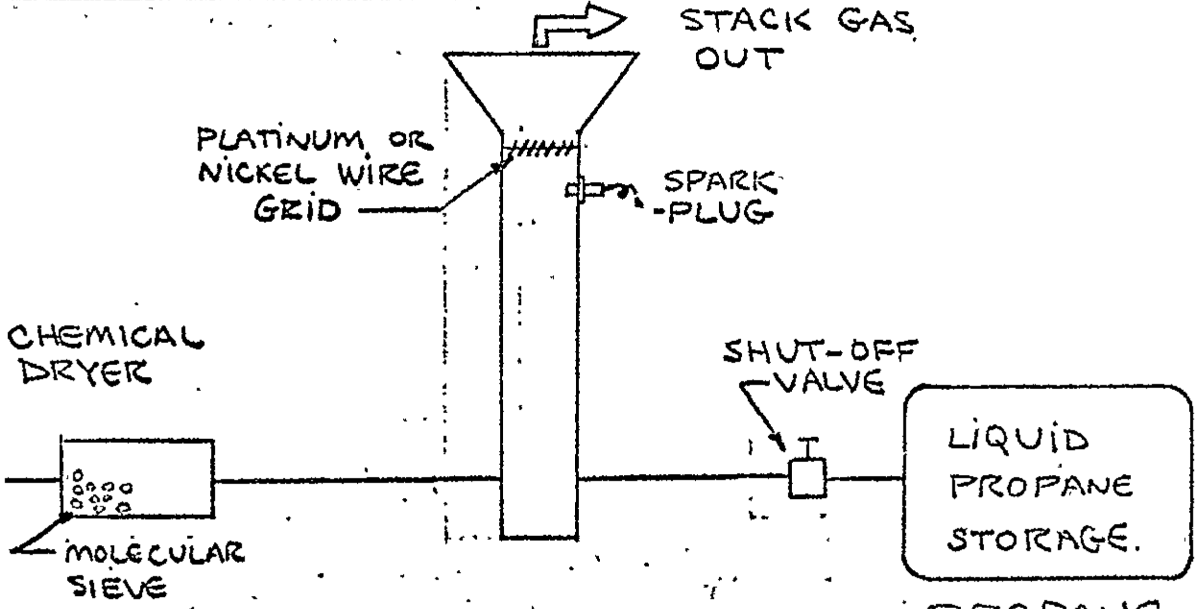


FIGURE 4-7c

PROPANE BURNER

$$(1)\ 1\ \text{LB F}_2 \times \frac{\text{Mole F}_2}{38\ \text{LBS F}_2} \times \frac{4\ \text{Moles NH}_3}{3\ \text{Moles F}_2} \times \frac{17\ \text{LBS NH}_3}{1\ \text{Mole NH}_3} = \frac{.596\ \text{LB NH}_3}{\text{LB F}_2}$$

$$(2)\ 1\ \text{LB F}_2 \times \frac{\text{Mole F}_2}{38\ \text{LBS F}_2} \times \frac{4\ \text{Moles HF}}{3\ \text{Moles F}_2} \times \frac{1\ \text{Mole NH}_3}{1\ \text{Mole HF}} \times \frac{17\ \text{LBS NH}_3}{1\ \text{Mole NH}_3} =$$

$$\frac{.596\ \text{LB NH}_3}{\text{LB F}_2}$$

Total NH_3 required = 1.192 LBS.

$$\frac{1.192\ \text{LBS NH}_3}{\text{LB F}_2} \times \frac{\$.20}{\text{LB NH}_3} = \frac{\$.239}{\text{LB F}_2}$$

The rate and efficiency of the reaction can be controlled by the amount of ammonia available and by controlling the bed temperature The waste gases can then be vented to the atmosphere or absorbed by water.

The third method reduces fluorine by combustion with a hydrocarbon fuel such as propane (See Figure 4-7c).

The untreated gases enter the system at a point where moisture is removed in a chemical dehydrator. The chemical desiccant utilized would be Linde Molecular Sieve 4AXW or equivalent. Downstream propane is mixed in stoichiometric amount with the gas. The mixing must be accomplished far enough upstream so that a uniform mixture is realized at the wire grid. Combustion is initiated by a simple spark mechanism and the reaction proceeds as follows:

$$10F_2 + C_3H_8 \qquad 3\ CF_4 + 8\ HF$$

The rate and efficiency of the reaction can again be controlled by limiting the concentration of the hydrocarbon fuel and/or the temperature of the reactants. The exhaust gases can then be scrubbed with water to remove the hydrogen fluoride and vent to the atmosphere. Calculations for stoichiometric amount and cost of fuel required are given as follows:

$$1\ \text{LB F}_2 \times \frac{1\ \text{Mole F}_2}{38\ \text{LB F}_2} \times \frac{1\ \text{Mole Propane}}{10\ \text{Moles F}_2} \times \frac{44\ \text{LBS}}{1\ \text{Mole Propane}} \qquad \frac{.105\ \text{LB Propane}}{\text{LB F}_2}$$

$$\frac{.105\ \text{LB Propane}}{\text{LB F}_2} \times \frac{\$.55}{\text{LB Propane}} = \frac{\$.057}{\text{LB F}_2}$$

A final method for disposal of the passivation gas would be to re-condense the gas and return the liquid to the storage tank. The relatively small quantity of gas involved and the high probability of contamination suggests this method not be considered.

4.1.2.5.2 Present Facilities at Mississippi Test Facility

At present, no provision for construction of reactor vessels, combustors or re-condensors at MTO has been made. There are no major design difficulties in designing any of these items, so that elimination of any of the above described methods on this basis alone would not be anticipated.

4.1.2.5.3 Facility Changes and/or Additions

A detailed economic analysis will be necessary to pin-point the best disposal method. However, combustion with a hydrocarbon seems to be more favorable since larger gas quantities can be handled, maintenance is less complicated and the operation is in general much simpler than the other methods.

4.1.2.6 Disposal of Boil-Off Gases

4.1.2.6.1 Background Information

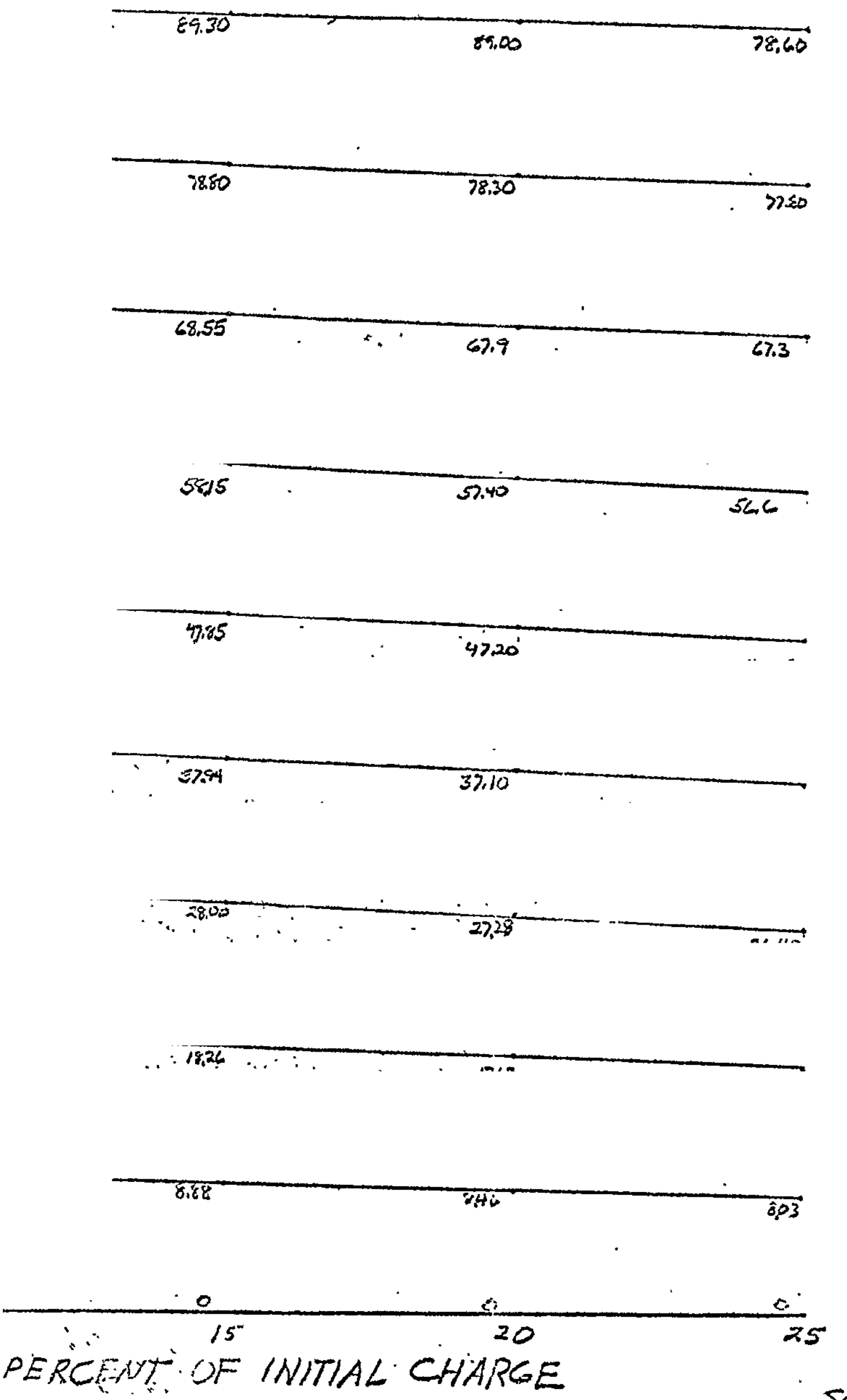
The handling of boil-off gases can be classified into the following general categories: (1) uncontrolled venting to the atmosphere, (2) chemical neutralization, and (3) re-condensation with recovery of fluid. Unlimited boil-off to the atmosphere presents a number of problems which involve protection of personnel, equipment and the maintenance of a constant composition mixture in the booster storage tank. Because of fluorine's greater volitility, the vapor products will contain a greater proportion of the halogen than will the liquid in the tank. Figure 4-8 shows the depletion of fluorine with total boil-off and points out the difficulty of maintaining a homogenious mixture. Although direct venting to the atmosphere appears to be the most economical method for handling boil-off gases, it may well prove to be impractical as a workable method if proper mixture tolerance cannot be maintained.

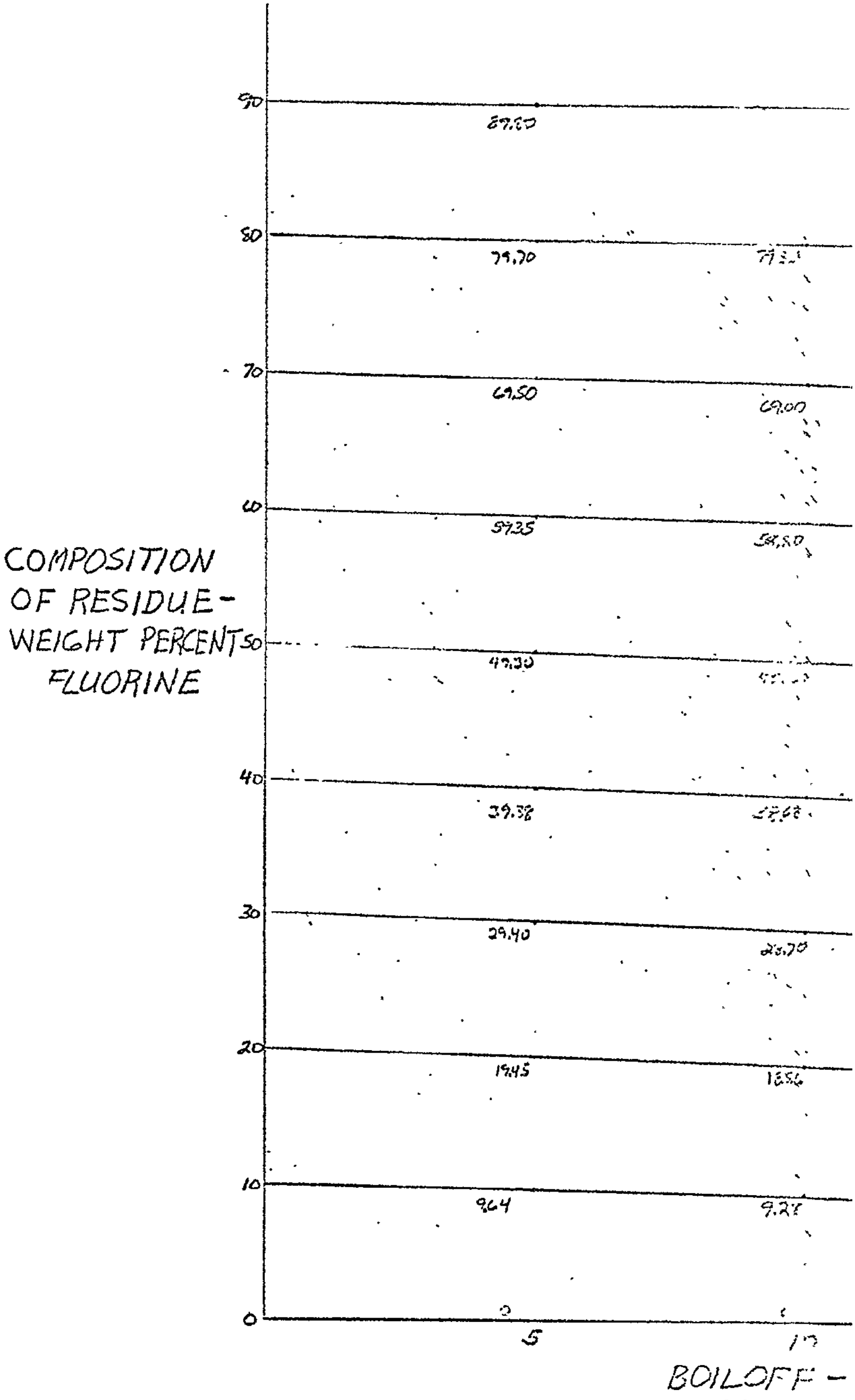
Figures 4-9 and 4-10 show boil-off rates as a function of mixture composition.

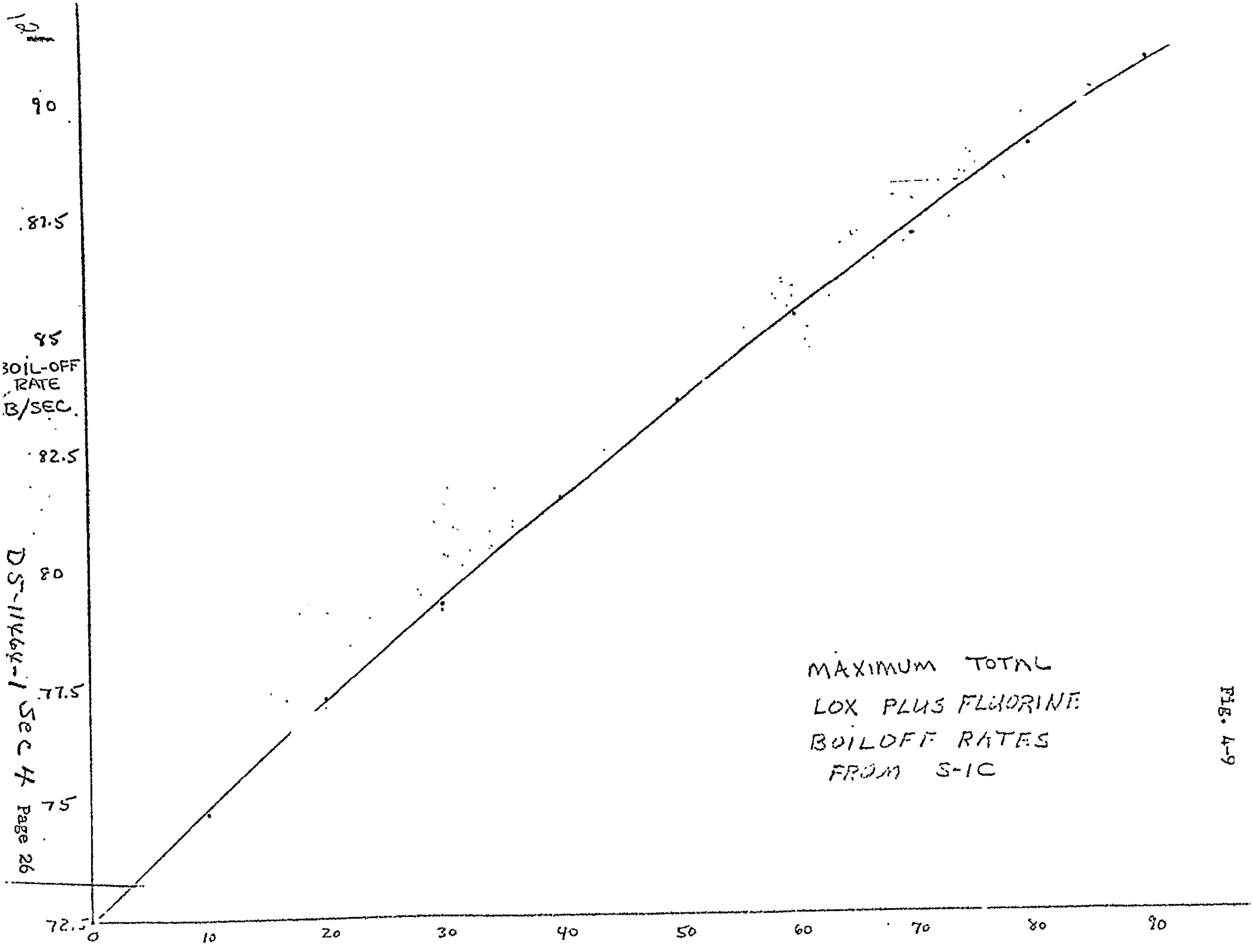
The following is a sample calculation for one point on the boil-off curves.

Assumptions:
- (a) Heat leak into the LOX storage tank is approximately equal to the heat leak into a FLOX tank of the same configuration.
- (b) Raoult's Law is obeyed, i.e., boil-off is perfect gas.
- (c) Boil-off rates from MSFC memo PVE-PTP-64-M39 are valid
- (d) Total FLOX pressure is 1 ATM.

Sample calculation for 30 percent fluorine. (Boiling temp. 88.3°K)


89.30
89.00
78.60
78.80
78.30
77.80
68.55
67.9
67.3
58.15
57.40
56.6
47.85
47.20
37.94
37.10
28.00
27.28
18.26
8.88
8.46
8.03
0
0
0
15
20
25
PERCENT OF INITIAL CHARGE


COMPOSITION OF RESIDUE - WEIGHT PERCENT FLUORINE
90
80
70
60
50
40
30
20
10
0
89.80
79.70
69.50
59.35
49.30
39.38
29.40
19.45
9.64
0
79.3
69.00
58.50
38.68
28.70
18.56
9.28
0
5
10
BOILOFF -



MAXIMUM TOTAL
LOX PLUS FLUORINE
BOILOFF RATES
FROM S-IC

FIG. 4-9

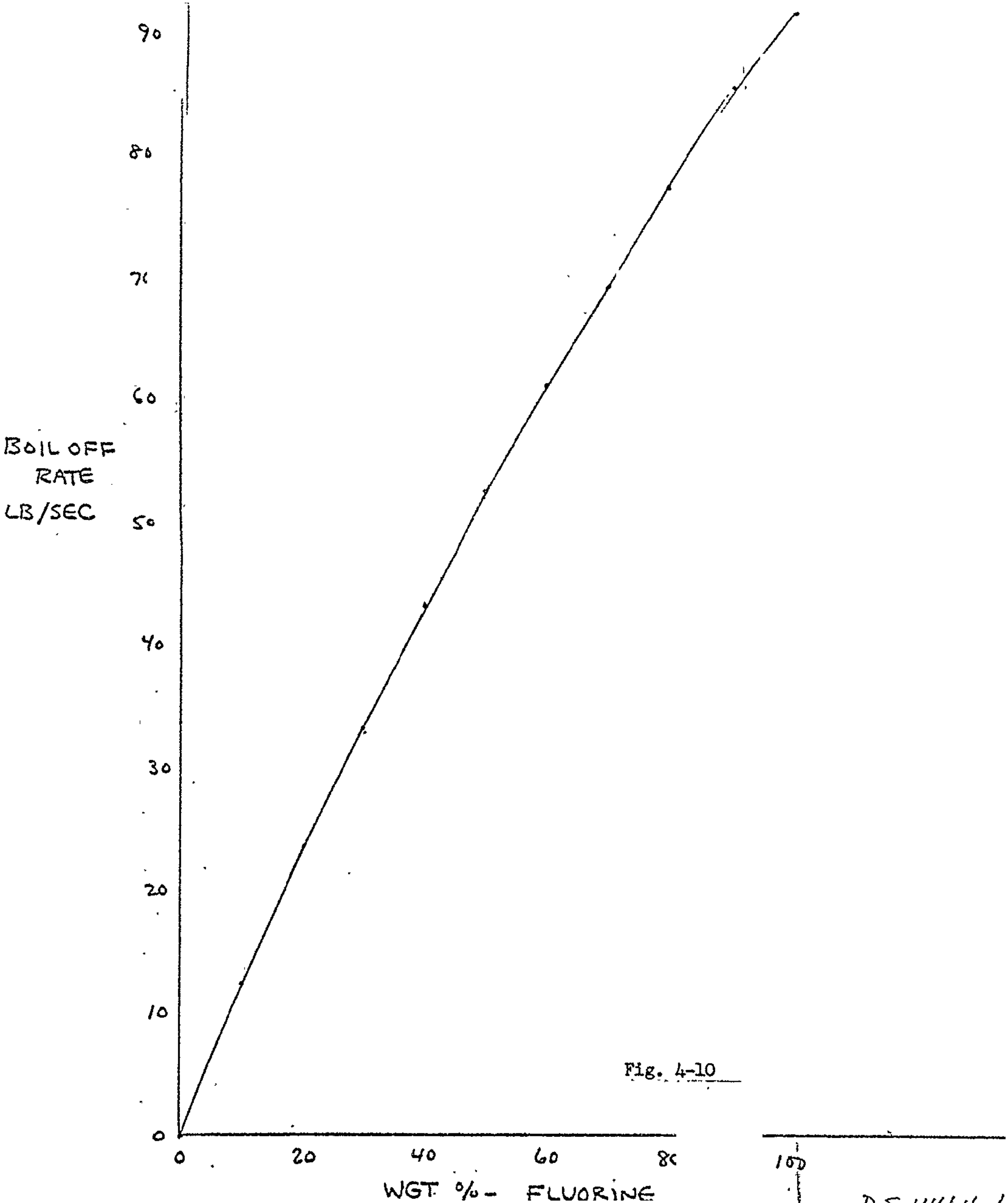

90
80
70
60
50
40
30
20
10
0
BOIL OFF RATE LB/SEC
0
20
40
60
80
100
WGT %- FLUORINE

Fig. 4-10

(1) Max. Heat Leak

$$\frac{72.5 \text{ LBS LOX}}{\text{Sec.}} \times \frac{91 \text{ BTU}}{\text{LB}} = 6600 \frac{\text{BTU}}{\text{Sec.}}$$

(2) Convert weight percent to volume percent.

Basis: 100 LBS Mix

$$\text{Moles F} = \frac{30 \text{ LBS (F)}}{28 \text{ LBS/Mol}} = .79$$

$$\text{Moles O} = \frac{70 \text{ LBS (O)}}{32 \text{ LBS/Mol}} = 2.19$$

$$\text{Mole Fraction F: } \frac{.79}{2.98} = .265$$

(3) Raoult's Law

(a) Vapor pressure of F_2 at 88.3° K is 1090 mm.

(b) Volume fraction $F_2 = \frac{1090 \text{ mm}}{760 \text{ mm}} \cdot (.265) = .38.$

(4) Convert volume percent to weight percent

$$.28 \text{ Moles } F_2 \times \frac{38 \text{ LB}}{\text{Mol}} = 14.45$$

$$.62 \text{ Moles } O_2 \times \frac{32 \text{ LB}}{\text{Mol}} = 19.85$$

$$\text{Wgt. fraction } F_2 = \frac{14.45}{34.} = .42$$

(5) Calculate total boil-off rate, X.

$$\frac{6600 \text{ BTU}}{\text{Sec.}} = \frac{70.7 \text{ BTU}}{\text{LB } F_2} (.42 X) + \frac{92.4 \text{ BTU}}{\text{LB } O_2} (.58 X)$$

$$X = 79.2 \text{ LBS/Sec.}$$

(6) Fluorine boil-off rate

$$y = 79.2 \frac{\text{LB}}{\text{Sec.}} \left(\frac{.42 \text{ LB } F_2}{\text{LB}}\right) = 33.2 \frac{\text{LB}}{\text{Sec.}}$$

If an extended hold period is experienced, and delays of more than an hour are not uncommon, then a suitable method for handling the large quantity of boil-off gases must be found. Chemical neutralization utilizing the methods of paragraph 4.1.2.5 are technically feasible, but would have to be more closely investigated, especially in the area of economics, before a firm decision can be made as to their worth. The last category appears to be the most promising at this time and presents a number of related alternatives:

(1) Reliquefy boil-off products and return liquid directly to the booster tanks,
(2) Reliquefy boil-off products and return liquid to central storage or,
(3) Transfer boil-off products to an off-site liquefaction facility.

The first and second suggestions differ mainly in placement of the equipment of condensation; in the case of the former close to the launch complex and in the latter in the proximity of the storage facility. Each has one major advantage over the other, since one would reduce pumping costs and equipment while the other would eliminate the need for a system of recondensation at the launch site. The third method would entail the largest initial capital outlay to build a liquefaction plant to handle not only the boil-off products from the booster, but also to produce liquid fluorine to cover the needs of the Saturn as well as other propulsion systems utilizing this element.

4.1.2.6.2 Present Facilities at Mississippi Test Facility

MTO presently contains no facilities capable of handling the large quantities of boil-off gas from a booster storage tank.

4.1.2.6.3 Facility Changes and/or Additions

Since economics play such a dominant role in the final choice, it will be extremely difficult to analyze each method until detailed information regarding number of planned launches, optimum FLOX mixture composition and final vehicle configuration is made available. In fact, the analysis should probably be carried beyond the scope of the Saturn FLOX Program to determine what, if any, future needs are envisioned for fluorine in the Aero-Space industry. Should sufficient quantities be used in the coming years, it would probably be most economical to let private industry build and operate a liquefaction facility close to the firing site. On the other hand, considering only the immediate needs for a Saturn booster, using FLOX, then either a boil-off gas condensor or a storage tank condensor would probably be the best solution.

4.1.2.7 Neutralization of Spills

4.1.2.7.1 Background Information

Several methods for neutralization of relatively small quantities of fluorine (less than 50 Lbs) have been described in paragraph 4.1.2.5 and will not be considered here. For larger or bulk quantities neutralization can generally be classified under the following categories: (1) controlled, (2) uncontrolled, and (3) emergency. For controlled reactions, the fluorine should be channeled into a run-off pool where suitable chemical treatment can be initiated. Metallic fluorides, sodium hydroxide, sodium carbonate and steam or water fog have all been mentioned in the literature as possible methods for disposal. The primary disadvantage being one of economics when bulk quantities of materials are involved and in some cases additional treatment is required where toxic or corrosive by-products are formed.

If circumstances permit, some fluorine may be neutralized in an uncontrolled fashion,i.e., through boil-off, reaction with atmospheric moisture and any available fuel such as soil or foliage. Because of fluorine's high reactivity and volatility neutralization should take place in a reasonable length of time. However, the danger inherent in this operation should be countered with a portable water supply or chemical neutralization in case the reaction gets out of hand. The path of the run-off chemicals, usually metallic fluorides, should be checked to see that no drinking water supplies, streams or wild life is being affected. The state or local statutes governing pollution should also be checked before uncontrolled fluorine disposal is permitted.

Emergency disposal can best be carried out by treatment with large quantities of water (deluge) or by treatment with soda ash ($Na_2 CO_3$). Several tests have been conducted (See reference 2) using $Na_2 CO_3$ to form the relatively stable sodium fluoride (NaF). The chemical system presents more handling problems than the use of water including the problem of residue disposal. The tests, which have treated nearly a ton of material, have been reasonably successful.. The results show that the chemical method appears to neutralize the fluorine more rapidly than does water.

A water deluge system appears to be the least complicated and, since provisions are available at the firing sites, would seem also to be the most economical. Treatment of fluorine spills with water has the advantages of ease of application and universal availability of the neutralizing agent. The reaction of water with fluorine forms hydrofluoric acid which is diluted to safe levels with an excess of water. Adequate drainage should be provided solely for use with fluorine components and, if possible, all run-off should be collected in large run-off pools where further neutralization can be made. The reaction between fluorine and water is a violent one, however, regulation of spray quantities will keep the reaction under control. A finer water spray tends to be more effective as a neutralizer and at the same time dampens the violence of the reaction.

4.1.2.7.2 Present Facilities at Mississippi Test Facility (See References 1 & 3

The present facilities at MTF which could be used for neutralization of spills are the existing water deluge systems. These deluge systems are present at the central storage areas, the transfer areas, at the test stand, and at the flame deflector.

The storage area water deluge system is presently designed to provide 0.45 GPM per square foot over the surface of all hydrogen storage vessels. This deluge water pressure during maximum flow conditions shall not be less than 25 PSIG at the highest nozzle.

Sprays controlled manually by a quick opening valve shall be provided at each barge, truck, and rail car main transfer connection. Four spray nozzles of the sweep spray type shall be provided and oriented to deluge the area under each connection point. The sprays shall deliver approximately 500 gallons per minute at each transfer connection.

At the test stand a total of 215,000 gallons per minute are supplied to various positions. These include 15,000 GPM at Elevation 140.00 for motor sprays, 30,000 GPM at Elevation 155.00 for engine deluge sprays, 30,000 GPM at Elevation 160.00 for lower tank bulkheads sprays, 50,000 GPM at Elevation 195.00 for load platform and hold down structure sprays, 69,000 GPM at various elevations for stand structures sprays, 20,000 GPM at Elevation 285.00 for upper tankage sprays and 1000 GPM for the derrick.

The deflector at the test stand is supplied with a total of 400,000 GPM. The water is distributed to various levels of the deflector and sprayed from many nozzles at rates from 1600 GPM to 5000 GPM.

4.1.2.7.3 Facility Changes and/or Additions

Present water deluge facilities and fire fighting equipment are adequate to handle all except the most catastrophic failures. Cost of the neutralizing agents such as soda ash would rule this method out for the larger spills. However, a quantity of soda ash ($Na_2 CO_3$) should be kept on hand for treatment of smaller isolated spills and any toxic by-products found by the water treatment.

4.1.2.8 Neutralization of Combustion Products

4.1.2.8.1 Background Information

Combustion products will be produced at the approximate rate of 30,000 Lb/Sec when the booster engines are ignited, of which better than half will be composed of hydrogen fluoride (HF) and carbon monoxide (CO). The toxicity of both compounds would indicate that some means of exhaust treatment is necessary. A number of methods appear feasible at this time although each has a major disadvantage. The exhaust stream can be deluged with a large quantity of water. While the concentration of HF could be lowered appreciably, the bulk temperature of the cloud would also be lowered thereby slowing the atmospheric dispersion. A second method would be to design a water scrubber to lower the percentage of noxious gases to a safe level. Because of the high velocity of the gases, contact time between liquid and gas becomes a major consideration if any mass transfer is to take place. A longer contact time permits more efficient absorption but requires larger facilities.

Finally, special weather conditions, such as prevailing winds, temperature, and humidity, as well as minimum population density may justify uncontrolled atmospheric diffusion of the exhaust cloud. More detailed study of local conditions at MILA and MTO must be carried out before approval could be given this method.

.1.2.8.2 Present Facilities at Mississippi Test Facility (See Reference 3)

The present equipment at Mississippi Test Facility which could be used for neutralization of the combustion products is the deflector water deluge system. This system supplies 400,000 GPM total to many nozzles located on different positions on the deflector. The individual nozzles spray from 1600 GPM to 5000 GPM. The individual nozzles are actually holes drilled in the surface of the flame deflector. The holes are arranged to supply the maximum flow rates to the area of maximum flame impingement. The percent of the hydrogen fluoride in the exhaust which is absorbed into the water and the percent hydrofluoric acid in the deluge water after the test are difficult to product because of the free nature of the reaction. A parametric attempt has been made in the section on materials and processes.

.1.2.8.3 Facility Changes and/or Additions

Determination of a safe atmospheric concentration for hydrogen fluoride and carbon monoxide must be investigated. A further study of weather conditions which would permit uncontrolled dispersion, i.e., a launch envelope, of the gas cloud should also be investigated The determination of firm ground rules in these areas will dictate the final solution on designing special equipment for treatment.

4.1.2.9 Off-Loading and Disposal of Residual FLOX

4.1.2.9.1 Background Information

Off-loading, which is removal from the S-IC oxidizer tank of FLOX, presents two major problems. The FLOX should be contained because of its toxic nature and released only under controlled conditions if release is absolutely necessary. The FLOX should be contained because of its cost. Both of these problems can be solved by off-loading the FLOX back to storage through the propellant loading lines. Pressurized transfer can be used to accomplish this transfer process since pump seals and FLOX are generally not compatible. Line size should be made compatible with the tank pressure available and the off-loading time required.

4.1.2.9.2 Present Facilities at Mississippi Test Facility (See Reference 3)

Off-loading is presently accomplished for the S-IC at MTF by opening the LOX fill and drain valves and allowing LOX to flow out of the tank through the fill lines with the aid of the ullage pressure supplied by the GSE. At the static test stand emergency draining of the LOX is provided through a 17 inch emergency drain line attached to the lower bulkhead of the LOX tank. The LOX is then drained into the LOX Dump Pond where it evaporates. This emergency drain is only used in the case of a fire near the LOX tank and would be considered as an uncontrolled release because of the infrequency of its occurrence.

4.1.2.9.3 Facility Changes and/or Additions

The normal off-loading procedure can be accomplished with FLOX without changing the existing equipment. The emergency dump will not be a cold spill with FLOX since the FLOX will be hypergolic with the LOX Dump Pond.

4.1.3 Problems at Merritt Island Launch Area

4.1.3.1 Central Storage of Liquid Fluorine or FLOX

4.1.3.1.1 Background Information

The Background Information will be the same as 4.1.2.1.1.

4.1.3.1.2 Present Facilities at Merritt Island Launch Area (See Reference 4)

Present Liquid Oxygen Storage at Merritt Island Launch Area

The liquid oxygen storage tank at MILA will be a 900,000 gallon double-walled insulated sphere. The inner tank will be stainless steel and will have a diameter of 62 feet 9 inches. The insulation space will be filled with perlite and nitrogen at a slight positive pressure. The outer tank will be carbon steel or equivalent and will have a diameter of 68 feet 9 inches. An internal pressure of 10 PSIG will be maintained during fill and standby operations by gaseous oxygen from an air/LOX vaporizer. The tank will withstand an external blast pressure of 6 PSIG. The tank weighs 1,600,000 pounds and will store 8,600,000 pounds of fluid. The tank is supported above ground with 16 36-inch-diameter legs. The tank has a boiloff rate of 0.18 percent per day maximum. The tank is located 1450 feet away from the pad.

Present Liquid Hydrogen Storage at Merritt Island Launch Area

The liquid hydrogen storage tank at MILA will be a 850,000 gallon double walled insulated sphere. The inner tank will be stainless steel and will have a diameter of 56 feet 6 inches. The insulation space will be filled with perlite and maintained near a vacuum. The outer tank will be carbon steel or equivalent and will have a diameter of 62 feet 6 inches. An internal pressure of 25 PSIG will be maintained by vaporizing coils. The tank will withstand an external blast pressure of 6 PSIG. The tank weighs 1,600,000 pounds and will store 385,000 pounds of fluid. The tank is supported above ground by 10 30-inch-diameter legs. The tank has a boiloff rate of 0.10 percent per day minimum. The tank is located 1450 feet from the pad. Daily loss is vented to the atmosphere. Rapid vent will be through the hydrogen burn pond.

Present Liquid Nitrogen Storage at Merritt Island Launch Area

The liquid nitrogen storage at MILA will be a 500,000 gallon double walled, indulated sphere. The inner tank will be 300 series stainless steel and will have a diameter of 50 feet. The insulation space will be filled with perlite. The outer tank will be carbon steel and will have a diameter of 60 feet. An internal operating pressure of 25 PSIG will be maintained with a vaporizer. The tank will have a boiloff rate of 0.2 percent per day.

4.1.3.1.3 Facility Changes and/or Additions

At Merritt Island Launch Area it will be necessary to build an entirely new facility to store liquid fluorine or FLOX since the LOX will be needed for the upper stages. However, since about 72 percent of the LOX is required for the S-IC stage, the present LOX storage facility may be converted to FLOX storage and a new smaller LOX storage tank constructed.

Again the problem will need only an economic analysis to determine the solution. The technical problems can be solved.

4.1.3.2 Transfer of Liquid Fluorine or FLOX to the Launcher

4.1.3.2.1 Background Information

The background information is the same as 4.1.2.2.1.

4.1.3.2.2 Present Facilities at Merritt Island Launch Area (See Reference 4)

Present LOX Transfer at Merritt Island Launch Area

The LOX transfer at MILA is accomplished by 14-inch uninsulated line for main fill and by 6-inch vacuum jacketed lines for replenishing. Pumping will be accomplished by two main transfer pumps and two replenish pumps. Each two will be paralleled so that one is available as a back-up. Each main pump shall be a 10,000 gallon per minute centrifugal pump with a discharge pressure of 320 PSI. The pump motor will be a fan-cooled, 2500 HP, 1800 RPM, 4,160 volts, 3 phase induction type, totally enclosed. Each replenish pump will be a 1000 gallon per minute centrifugal pump with a discharge pressure of 260 PSI. The pump motor will be a 275 HP, 440 volt motor.

Present Liquid Hydrogen Transfer at Merritt Island Launch Area

The liquid hydrogen transfer is accomplished using only the 75 PSIG pressure in the storage tank to force the transfer. The transfer line to the LUT will be vacuum jacketed, 10-inch-diameter, invar pipe. The outer jacket shall be stainless steel.

4.1.3.2.3 Facility Changes and/or Additions

Since the storage facility will be on the order of 1400-1500 feet from the launcher, it will be necessary to design a low heat leak transfer system in order to minimize the boiloff and temperature rise during the transfer process.

The present liquid hydrogen transfer system is designed for low heat leak and a similar system could be used for the FLOX transfer. Again the technical problems will be easily solved when economics dictates to method.

4.1.3.3 Passivation of All In-Line Components

4.1.3.3.1 Background Information

The Background Information is the same as 4.1.2.3.1.

4.1.3.3.2 Present Facilities at Merritt Island Launch Area

The present cleaning specifications are per MSFC-SPEC-164 and there is no passivation equipment at MILA as at MTO.

4.1.3.3.3 Facility Changes and/or Additions

Since passivation equipment is necessary at both MILA and MTO and economics do not play a major role in the passivation area, the solution at MILA will be the same as that at MTO outlined in 4.1.2.3.3.

4.1.3.4 Mixing of Liquid Fluorine and LOX

4.1.3.4.1 Background Information

The Background Information is the same as 4.1.2.4.1.

4.1.3.4.2 Present Facilities at Merritt Island Launch Area

There are no special mixing facilities for mixing liquid fluorine and liquid oxygen at MILA since the mixture is not used.

4.1.3.4.3 Facility Changes and/or Additions

The facility changes and/or additions will be the same as those outlined in 4.1.2.4.3.

4.1.3.5 Disposal of Passivation Gas

4.1.3.5.1 Background Information

The background information is the same as 4.1.2.5.1.

4.1.3.5.2 Present Facilities at Merritt Island Launch Area

There are no present facilities at MILA to dispose of passivation gas because there is no passivation with fluorine.

4.1.3.5.3 Facility Changes and/or Additions

Since equipment to dispose of passivation gas is required at both MILA and MTO and the economic effect is the same at both locations, the facility changes and/or additions are the same as 4.1.2.5.3.

4.1.3.6 Disposal of Boiloff Gas

4.1.3.6.1 Background Information

The Background Information is the same as 4.1.2.6.1.

4.1.3.6.2 Present Facilities at Merritt Island Launch Area

There are no facilities at MILA presently capable of handling the boiloff gas since GOX boiloff is non-toxic and is merely vented to the atmosphere.

4.1.3.6.3 Facility Changes and/or Additions

Economics play an important part in the choice of a method of disposing of the boiloff gases. The methods of 4.1.2.6.1 should be analyzed as outlined in 4.1.2.6.3.

4.1.3.7 Neutralization of Spills

4.1.3.7.1 Background Information

The Background Information is the same as 4.1.2.7.1.

4.1.3.7.2 Present Facilities at Merritt Island Launch Area (See Reference 5)

The present facilities at MILA which could be used for neutralization of spills are the water deluge systems. These deluge systems are planned for the flame deflector, the LUT deck, and the storage areas. There is 20,000 GPM available as the flame deflector quench. There is 50,000 GPM available for the LUT deck quench. The exact rates and locations of the sprays in the storage areas have not been determined but it is assumed that they will be similar to those at Mississippi Test Facility discussed in 4.1.2.7.2.

4.1.3.7.3 Facility Changes and/or Additions

The facility changes and/or additions will be the same as those outlined in 4.1.2.7.3.

4.1.3.8 Neutralization of Combustion Products

4.1.3.8.1 Background Information

The Background Information is the same as 4.1.2.8.1.

4.1.3.8.2 Present Facilities at Merritt Island Launch Area (See Reference 5)

The present facilities at MILA which could be used to neutralize a portion of the combustion products are the water deluge systems. The flame deflector quench of 20,000 GPM starts at T + 2 and lasts till T + 32 seconds. The LUT deck quench of 50,000 GPM exists for the same period of time. These water quenches are apt to be of little significance since only about 2 percent of the burning will take place in a position where the quenching would be the least bit effective.

4.1.3.8.3 Facility Changes and/or Additions

No facility changes or additions will be recommended for the purpose of neutralizing the combustion products at MILA. This is one situation in which the toxic cloud resulting from the use of fluorine as part of the oxidizer in the S-IC will have to be tolerated in order to take advantage of the payload gain from using fluorine.

4.1.3.9 Off-Loading and Disposal of Residual FLOX

4.1.3.9.1 Background Information

The Background Information is the same as 4.1.2.9.1.

4.1.3.9.2 Present Facilities at Merritt Island Launch Area

Off-loading is presently accomplished for the S-IC at MILA by opening the LOX fill and drain valves and allowing the LOX to flow out of the tank through the fill lines with the aid of the ullage pressure supplied by the GSE.

4.1.3.9.3 Facility Changes and/or Additions

The present off-loading procedure could be used without change.

4.2 TOXIC EXHAUST PRODUCTS EFFECTS

4.2.1 Introduction

As was seen in Section 2, the performance gains which can be realized by the use of FLOX on the S-IC are of very significant magnitude. Unfortunately, however, there are certain problems which are created. The most outstanding being that of the effect of the toxic exhaust products. Studies have been conducted to determine the composition of the F-1 engine exhaust products and to estimate the diffusion effects of the toxic exhaust cloud. The following paragraphs discuss the results of these findings.

4.2.2 Prediction of FLOX/RP-1 Exhaust Cloud Composition

Digital calculations have been made to determine the composition of an exhaust gas cloud at standard atmospheric pressure, formed by the combustion of fluorine-oxygen and RP-1 propellants. Gas compositions were plotted over a range of temperatures for several selected mixture ratios and fluorine concentrations. These plots are shown in Figures 4-11 through Figure 4-18.

The following products were considered in the calculations and were assumed to be in thermodynamic equilibrium at the specified temperatures and pressure.

CO CO_2 F H H_2 HCO HF H_2O O O_2

OH C C_2 C_3 CF CF_2 CF_3 CF_4 CH CH_2

CH_3 CH_4 C_2H_2 C_2H_4 COF_2 F_2 Carbon

No attempt was made to account for mixing of the exhaust products with the atmosphere, or for the effect of test stand flame deflector cooling water entrainment. Mixing will both dilute and cool the exhaust gases. Any water vapor condensation in the exhaust cloud will dissolve HF and form hydrofluoric acid.

4.2.3 Air Polution

Methods for controlling and/or predicting air pollution resulting from booster rocket engine exhaust need to be developed. A survey of current literature failed to turn up a single paper that adequately covered this subject. Because of the numerous variables associated with atmospheric diffusion and the exhaust cloud, a clean, clear-cut solution to the air pollution problem cannot be obtained.

Another undefined area is the level of tolerance for fluorine and hydrogen fluoride (HF). It is imperative that this be established in the near future. The tolerance level should be based on the ability of the human body to detoxify itself from a high level, short term exposure to fluorine or hydrogen fluoride. It appears that there is varied thinking among the "experts" on this subject.

The following paragraphs outline the toxic cloud analysis that was done in conjunction with TAO-22. It should be pointed out that a certain amount of conservatism is included in the analysis.

4.2.3.1 Toxic Cloud Analysis

Most of the data used in this study were extracted from Reference (9). The reason for choosing this particular study was the extensive amount of field testing that was done to correlate the dosage equations. The equations developed in Reference (10) were also considered, but ORG 17 (Reference (9)) yielded more conservative numbers. It should be pointed out that none of the studies to date have developed an analysis technique that can be used with a high degree of confidence.

The analysis technique used for the "Normal Launch" condition, considered the HF release from engine start to 2000 feet altitude (ref. Figure 4-19 and 4-20) to be a point source at ground level.

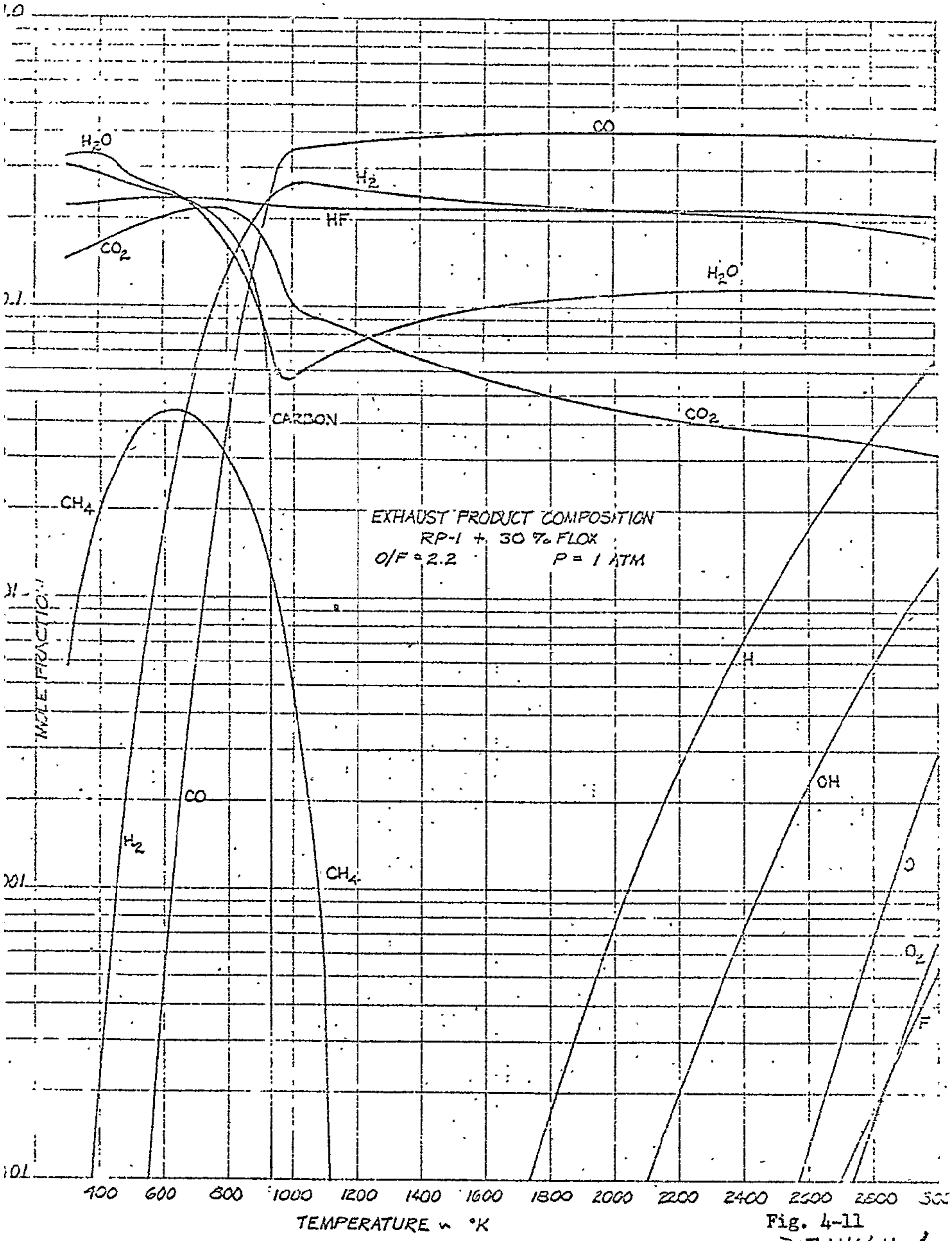

EXHAUST PRODUCT COMPOSITION
RP-1 + 30 % FLOX
O/F = 2.2
P = 1 ATM
MOLE FRACTION
TEMPERATURE ~ °K
.0
.1
.01
.001
.0001
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
30
CO
H2O
H2
HF
CO2
CARBON
CH4
H
OH
O
O2
F

Fig. 4-11

Sec 4

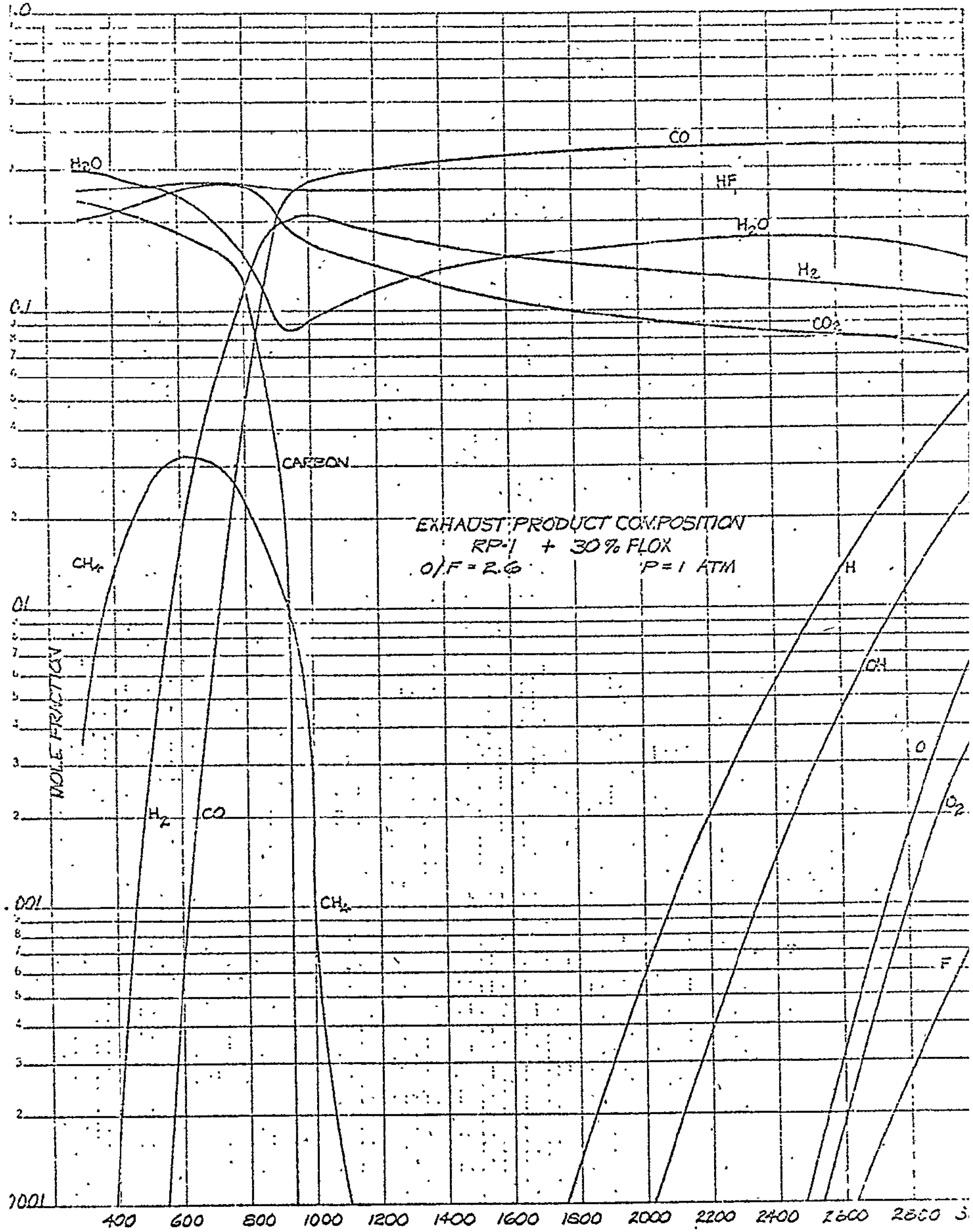
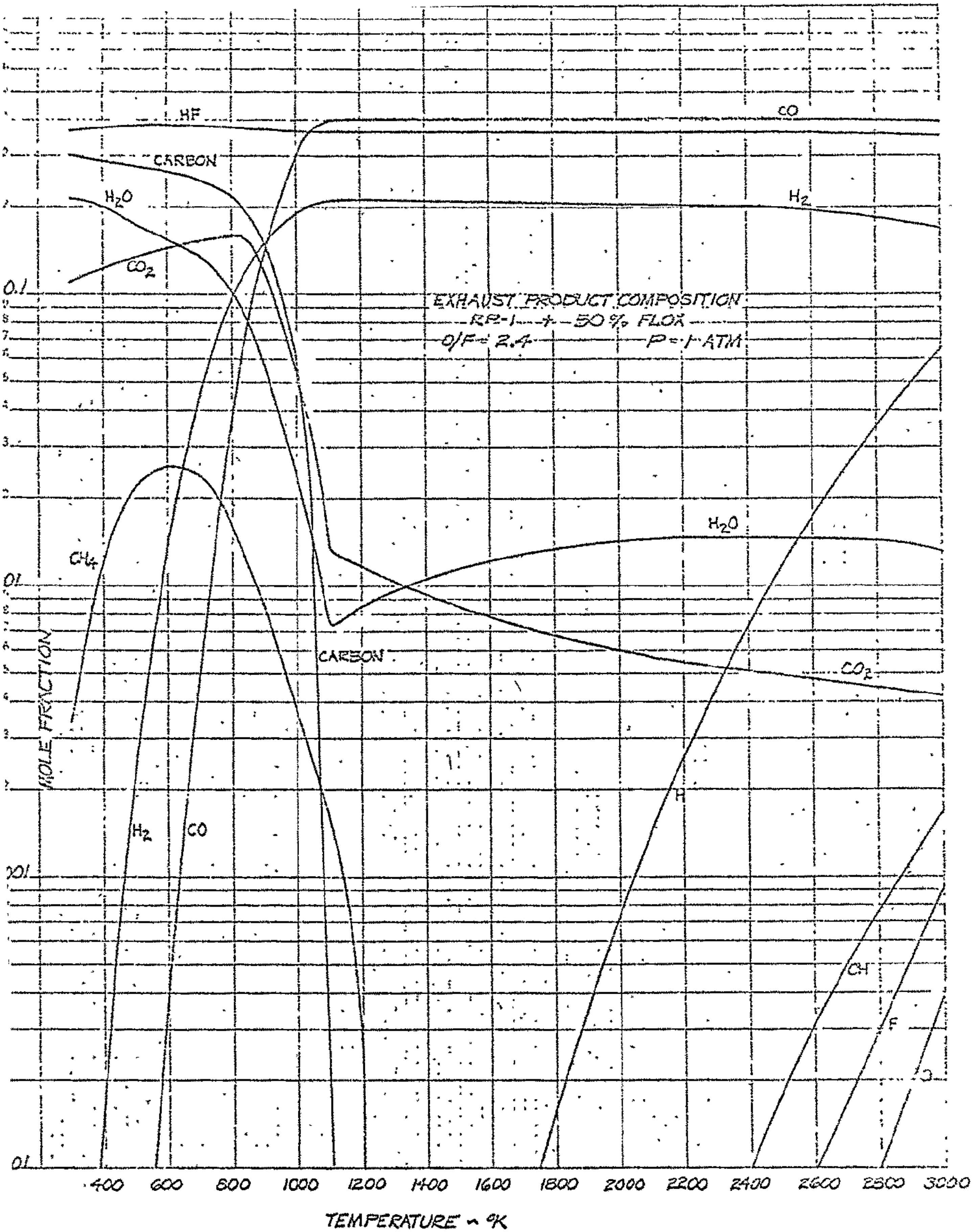

EXHAUST PRODUCT COMPOSITION
RP-1 + 30% FLOX
O/F = 2.6
P = 1 ATM
MOLE FRACTION
TEMPERATURE ~ °K
1.0
0.1
.01
.001
.0001
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
CO
HF
H_2O
H_2
CO_2
CARBON
CH_4
H_2
CO
CH_4
H
OH
O
O_2
F

Fig. 4-12


EXHAUST PRODUCT COMPOSITION
RP-1 + 50% FLOX
O/F = 2.4 P = 1 ATM

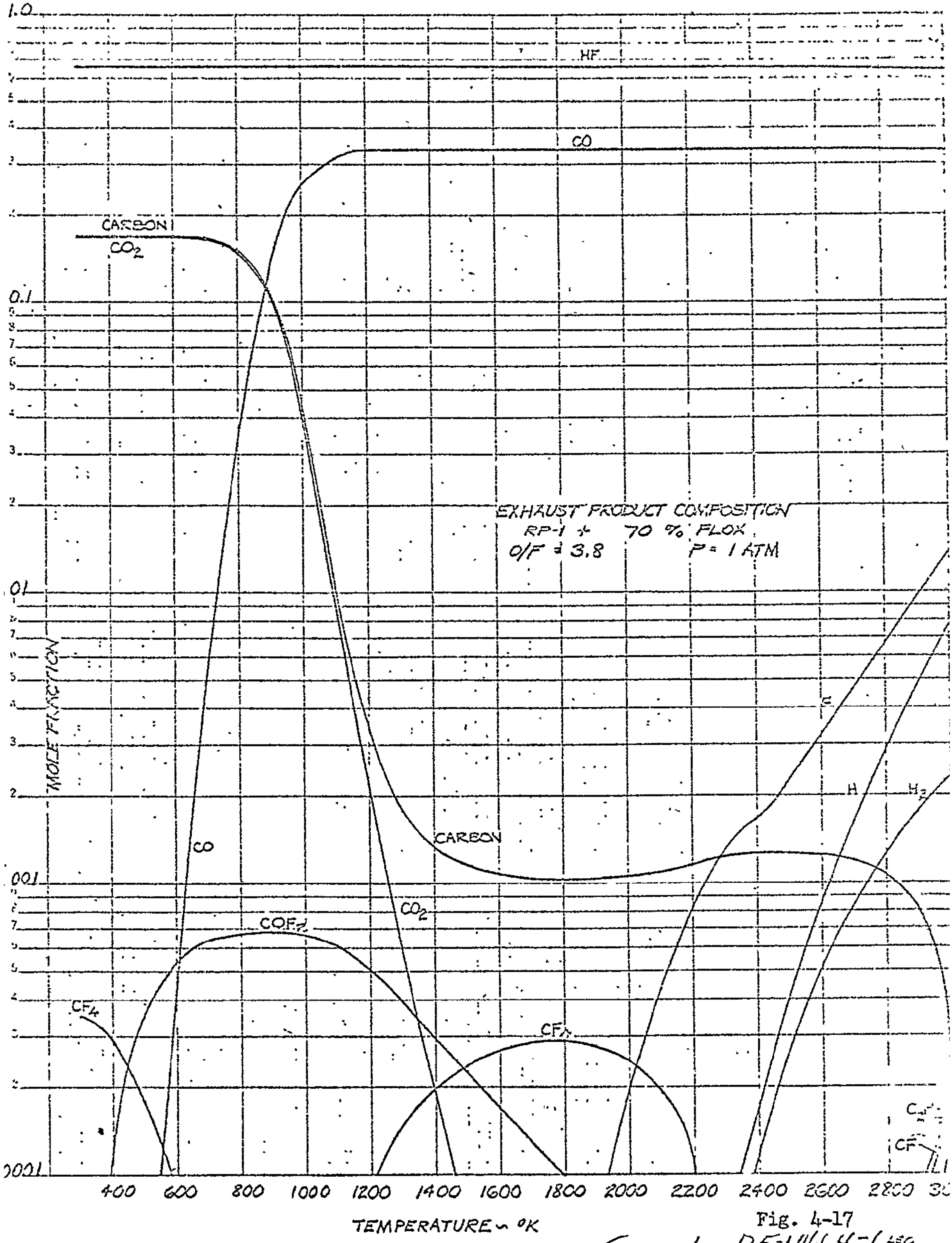

1.0
HF
CO
CARBON
CO₂
0.1
.01
.001
.0001
MOLE FRACTION
EXHAUST PRODUCT COMPOSITION
RP-1 + 70 % FLOX
O/F = 3.8 P = 1 ATM
CO
CARBON
CO₂
COF₂
CF₄
CF₂
F
H
H₂
C₂F₂
CF
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE ~ °K

Fig. 4-17

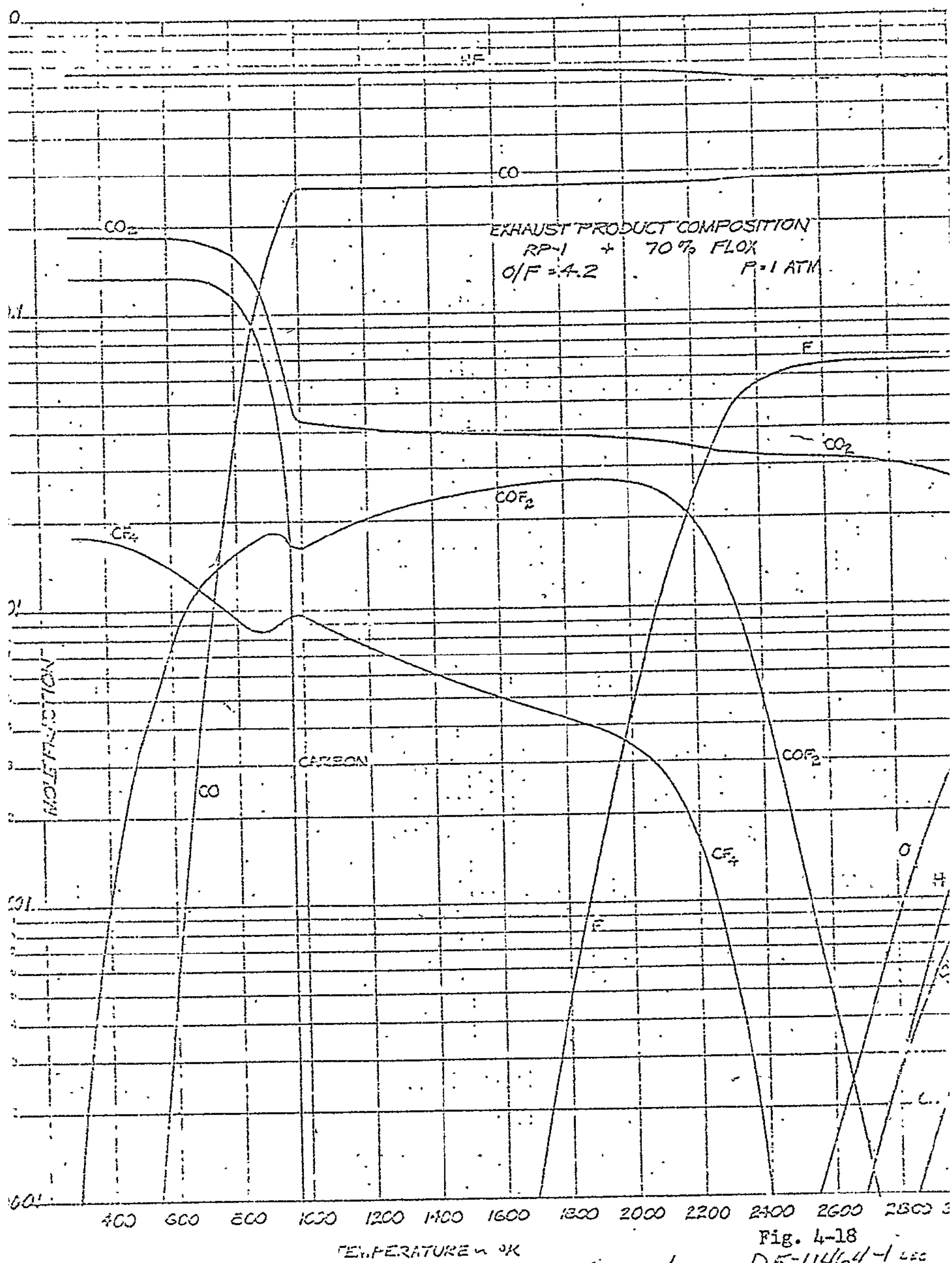
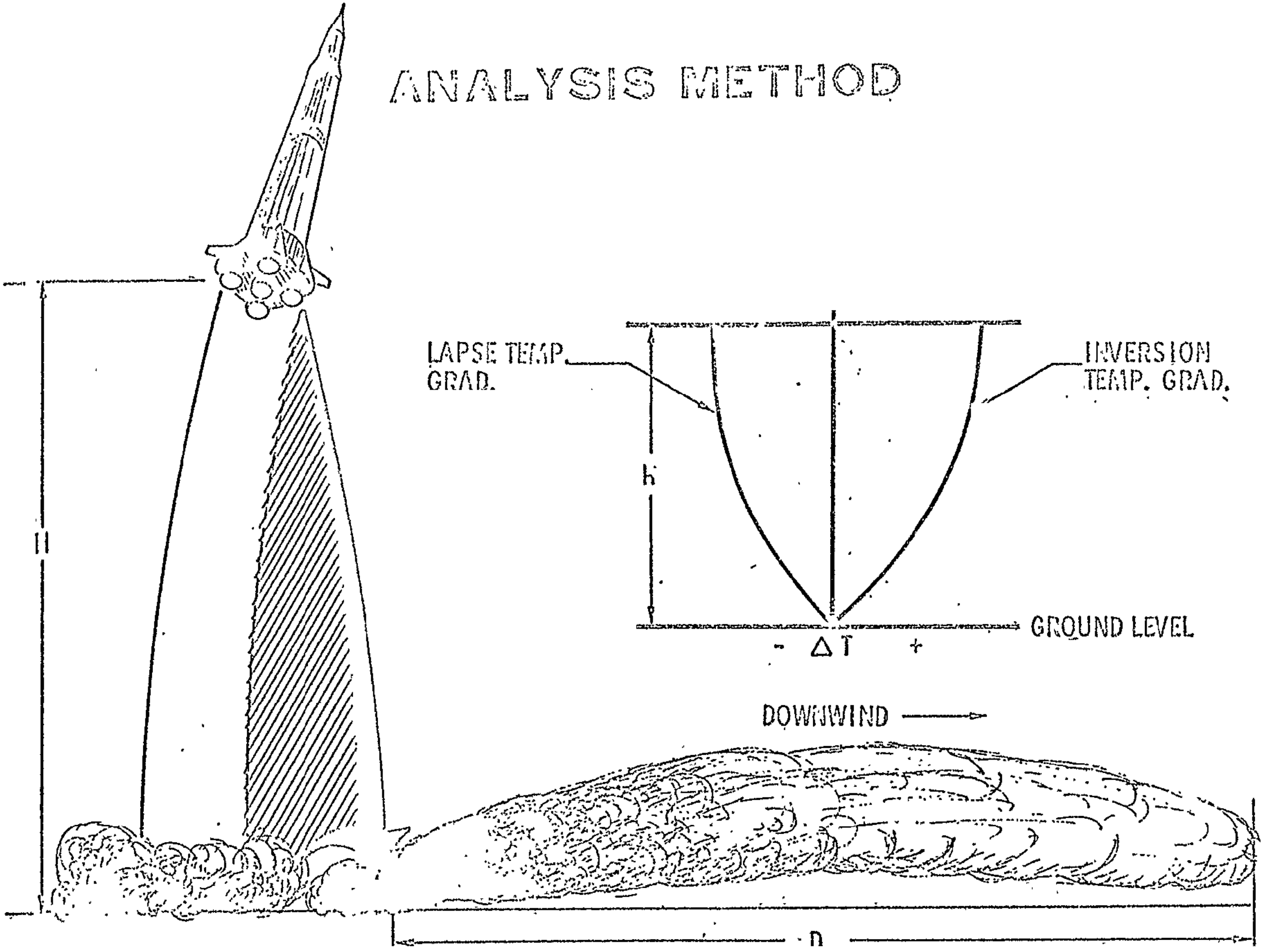
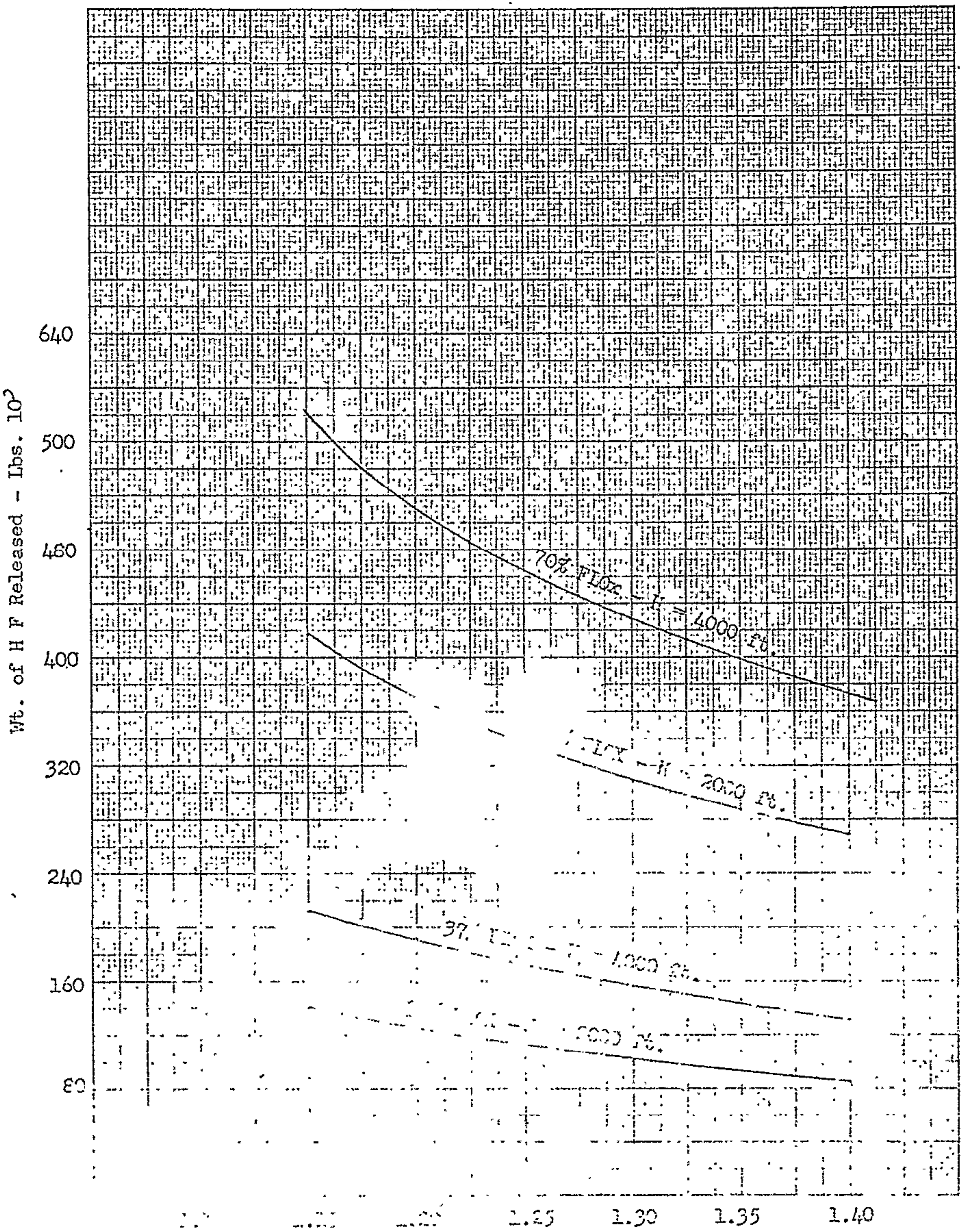

EXHAUST PRODUCT COMPOSITION
RP-1 + 70% FLOX
O/F = 4.2
P = 1 ATM
HF
CO
CO_2
F
COF_2
CF_4
CARBON
O
H
MOLE FRACTION
.1
.01
.001
.0001
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE ~ °K

Fig. 4-18

ANALYSIS METHOD



NORMAL LAUNCH - H F RELEASED



It was assumed that any HF released above 2000 ft. would not add to the ground level air pollution problem. It was also assumed that all the fluorine released, reacted to form HF. Figure 4-21 and 4-22 illustrate the marked effect of atmospheric conditions on its ability to diffuse the toxic cloud. From these curves, it is evident that if the temperature gradient is greater than -1°F, a launch would not be feasible. Figure 4-23 is a summary chart that shows the effects of % FLOX, vehicle T/W and dosage range for the noted atmospheric condition.

The definitions of terms used in this analysis are as follows:

- Temperature Gradient - The difference between the temperature at 0.5 and 5.0 meters -°F.
- Wind Speed - The average wind velocity - miles/hour
- Thrust/Weight - Booster Thrust/Gross Weight of the Vehicle
- W_p - Total S-IC propellant loading - lbs.
- $\dot{W}_p$ - Propellant flow rate

The conditions considered are as follows:

- Normal launch - 37% & 50% FLOX
- Fall-Back Failure - 30% & 37% FLOX
- Line Rupture - Pure Fluorine & 50% FLOX.

The "Fall-Back Failure" condition, considered $W_p = 4.8 \times 10^6$ pounds. From this, the correspondong amount of HF was assumed to be released as a point source. Figures 4-24 and 4-25 show the dosage range as a function of wind speed and temperature gradient, for 30 and 37 percent FLOX respectively. It is again evident that atmospheric conditions will determine when sufficient diffusion of the toxic cloud can be accomplished.

Figures 4-26 and 4-27 show the effect of a line rupture with the conditions as noted. In addition, it is assumed that all of the fluorine is reacted to yield hydrogen fluoride. This figure indicates that certain atmospheric conditions will be more favorable for transferring fluorine.

4.2.3.2 Conclusions & Recommendations

The primary conclusion that can be drawn from this analysis is that the air pollution problem will not prevent the implementation of FLOX on the S-IC. However, it should be pointed out that the times for aunch will be more restrictive by use of FLOX.

t is recommended that a more detailed analysis be accomplished, elative to the air pollution problem at the launch area and some ield testing be done for verification. It is believed that a more detailed study would indicate less restriction, because of the conservatism used in this analysis.

4.3 FLUORINE AVAILABILITY

The use of FLOX on the S-IC would require the use of large amounts of fluorine. Assume that one Saturn FLOXed vehicle is static tested and

TOXIC CLOUD ANALYSIS - NORMAL LAUNCH (37% FLOX)

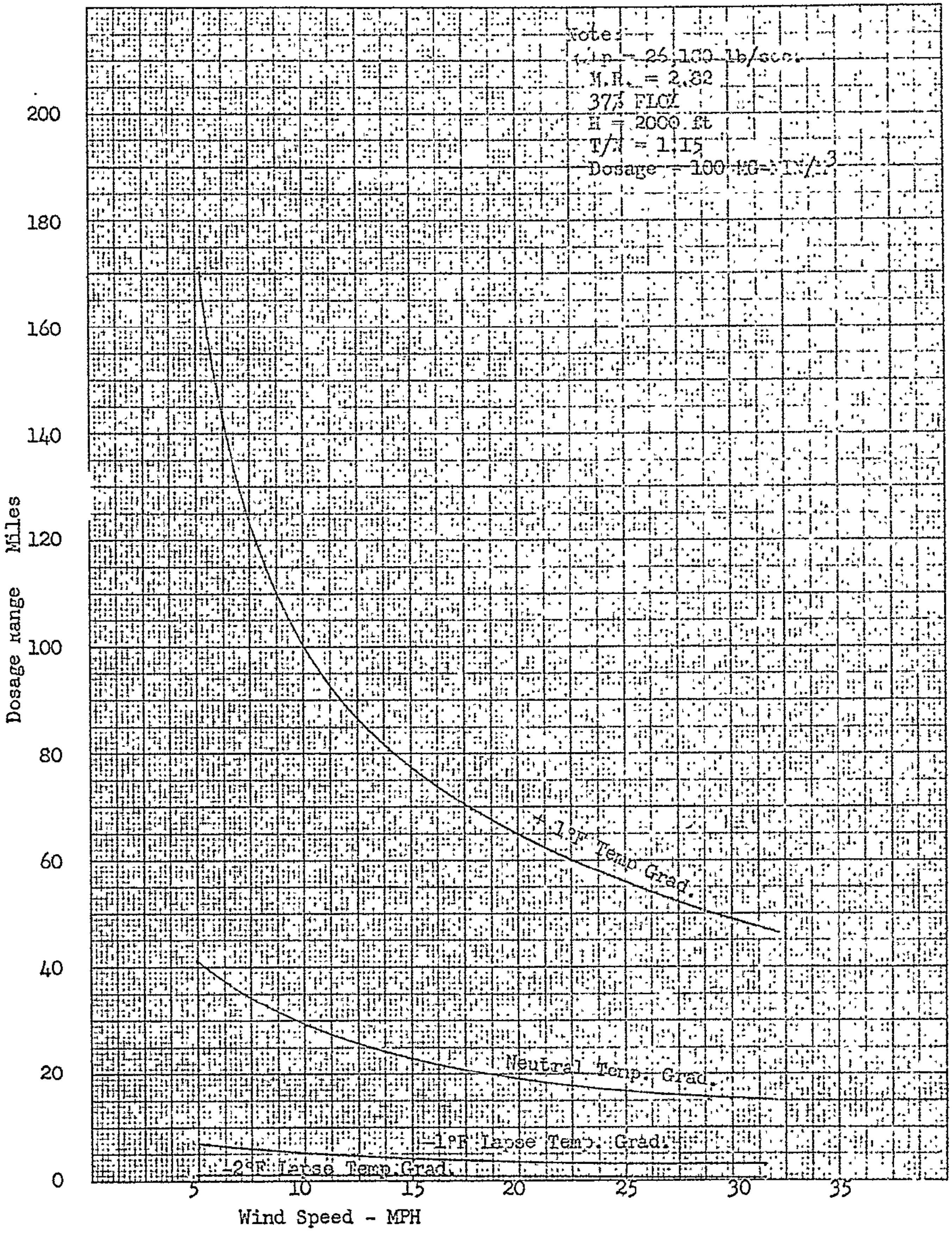
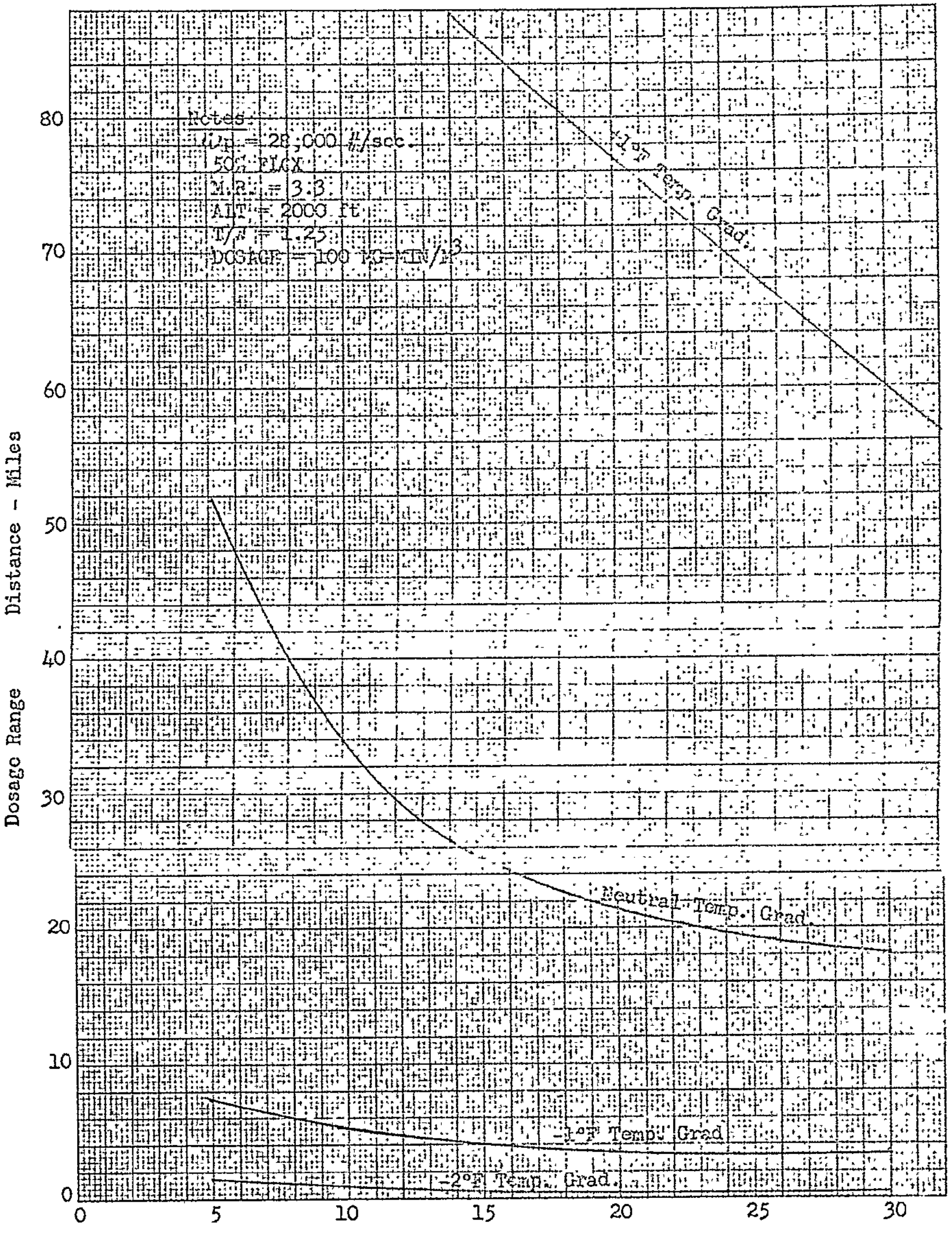


Figure 4-21

TOXIC CLOUD ANALYSIS - NORMAL LAUNCH (50% FLOX)



TOXIC CLOUD ANALYSIS - NORMAL LAUNCH(SUMMARY)

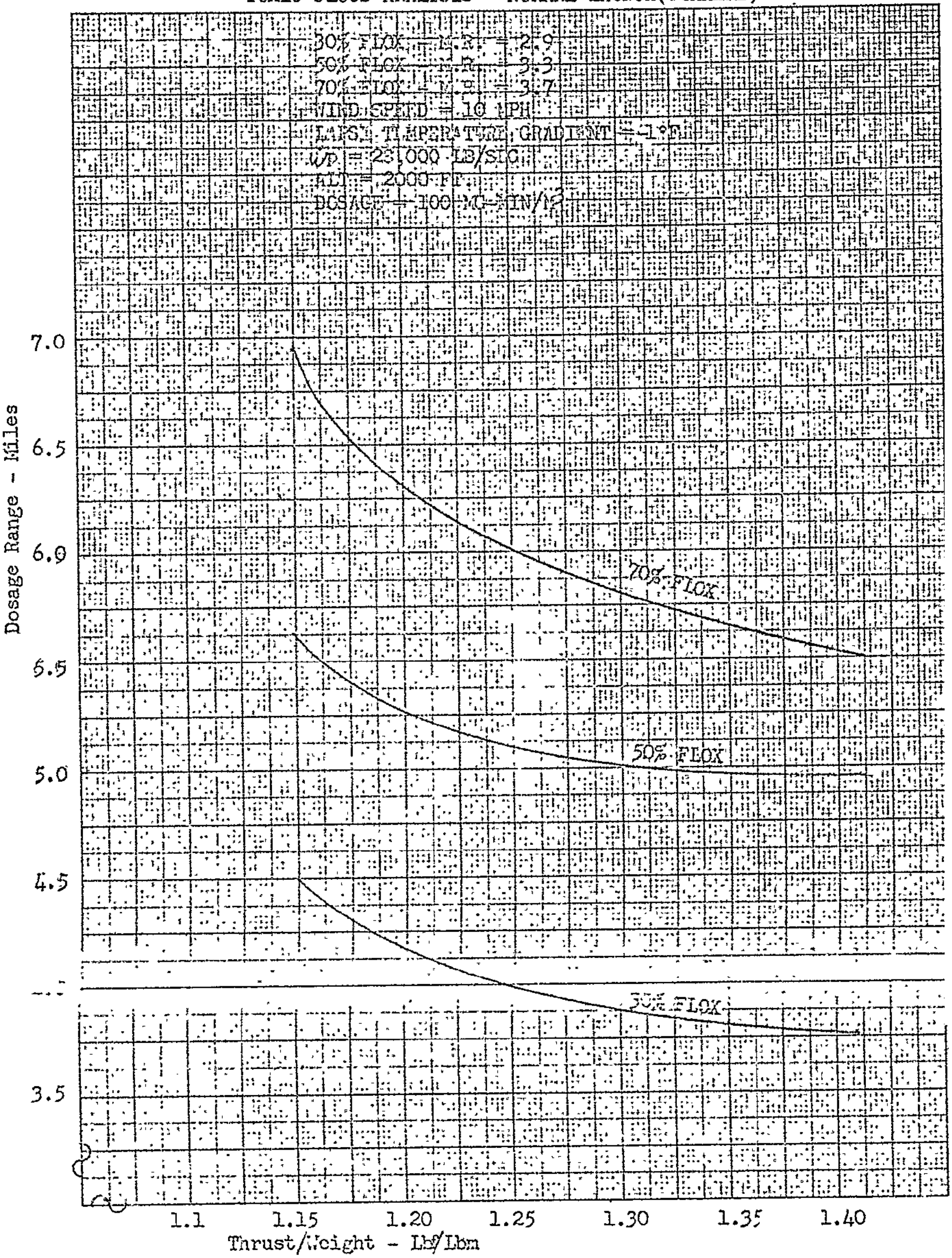


Figure 4-23

TOXIC CLOUD ANALYSIS - "FALL BACK" (30% FLOX)

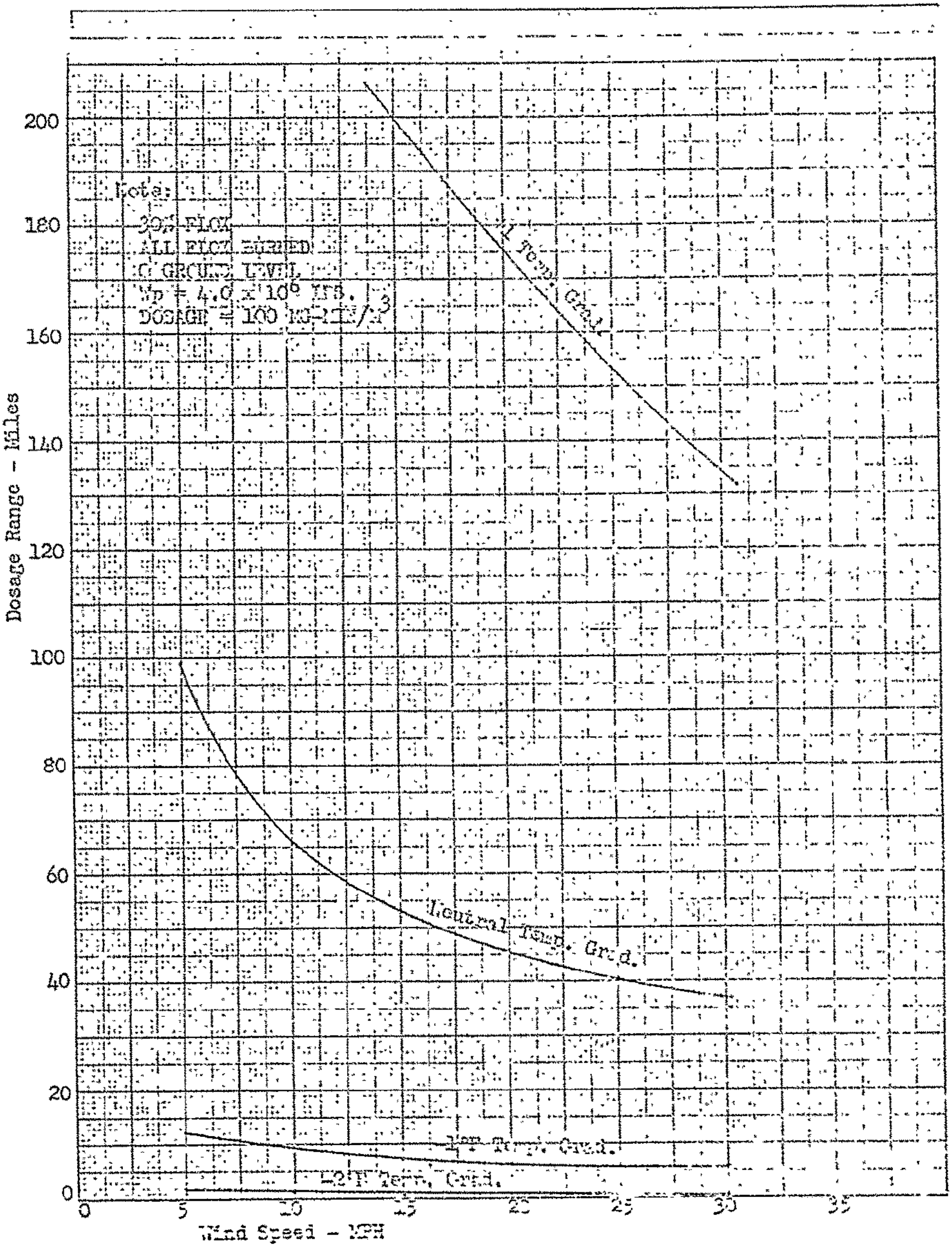


Figure 4-24

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SEC. 4

TOXIC CLOUD ANALYSIS - "FALL BACK" (37% FLOX)

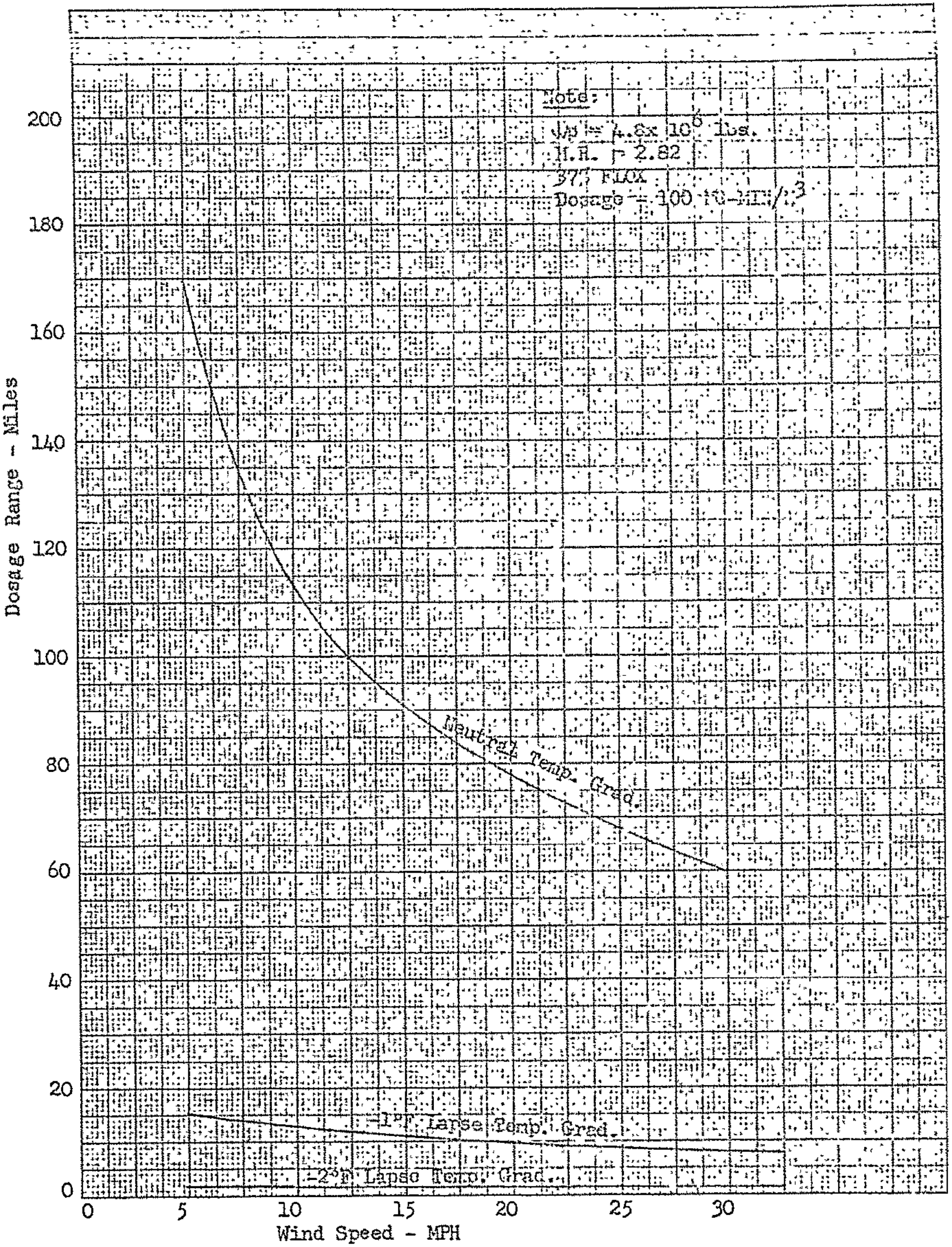

Figure 4-25

TOXIC CLOUD ANALYSIS - TRANSFER LINE RUPTURE

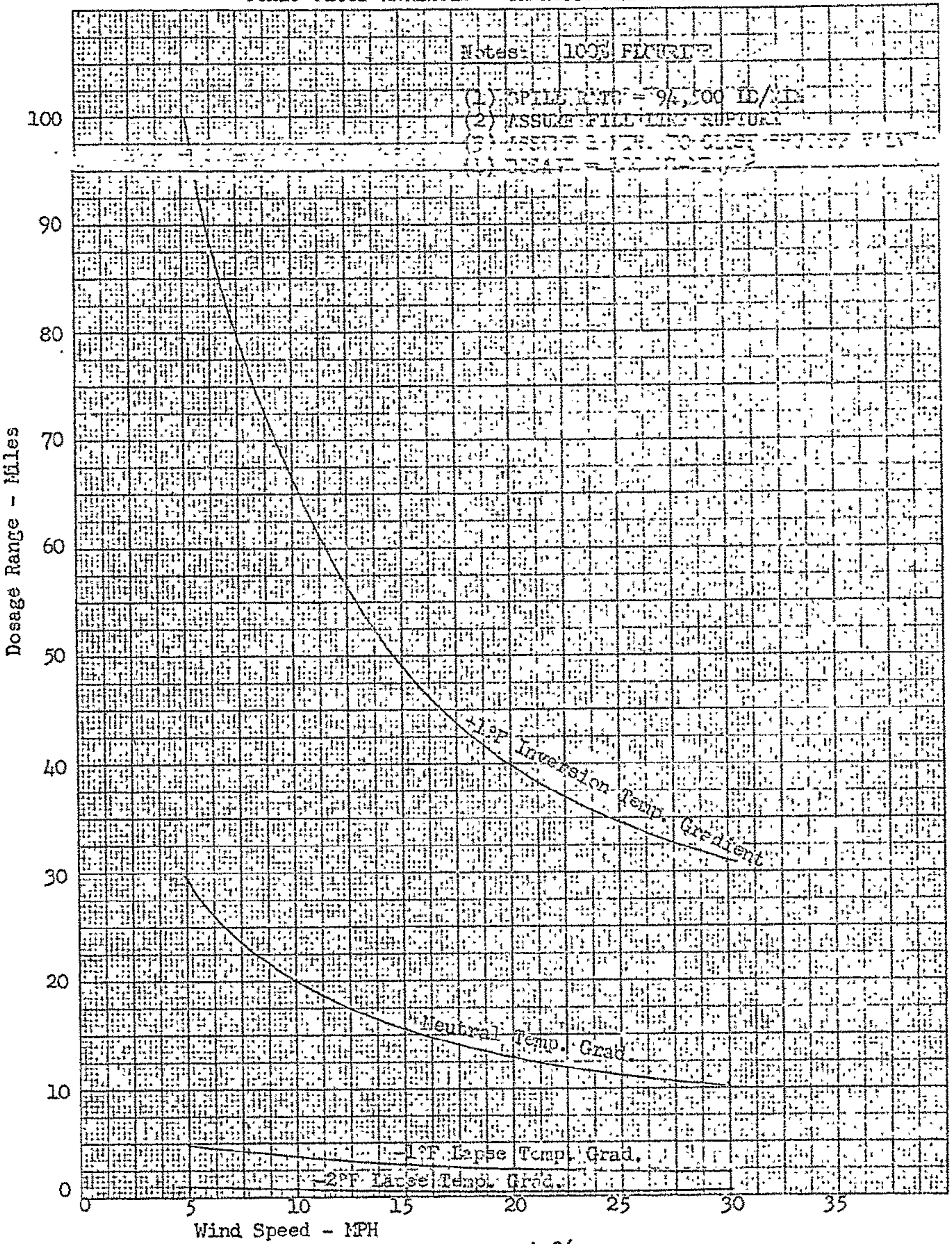

Figure 4-26

DS-11461

SEC. 4

TOXIC CLOUD ANALYSIS - TRANSFER LINE RUPTURE

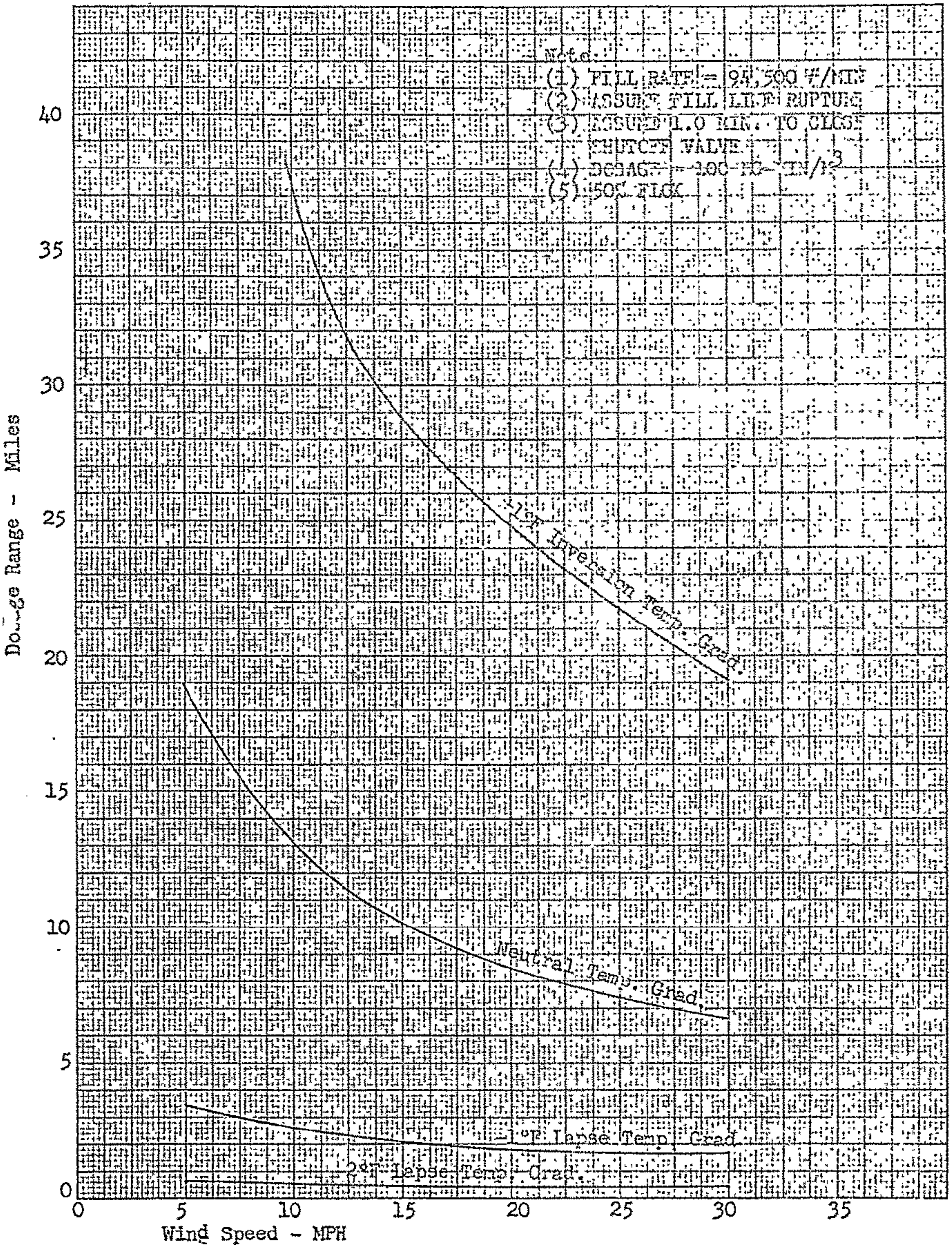

Figure 4-27

launched each month. From Figure 28, it can be seen that for a 70% FLOXed vehicle this would require approximately 5.5 million pounds of fluorine per month. In case it is determined that the vehicles may be static tested with LOX approximately 2.6 million pounds of fluorine would be required per month to launch a 70% FLOXed vehicle. This immediately raises the question relative to the total fluorine production in this country.

The largest producer of fluorine in this country is Allied Chemical. In a recent telephone conversation to Allied Chemical Company, Dr. Neumark stated that their present capacity is 1,500,000 #/year of liquid and 3,000,000 #/year of gaseous fluorine. In approximately 6 months, all of their production could be converted to liquid production. It would take 12 - 18 months for them to gear up for production of 4,000,000 #/month.

Their previous studies have indicated that fluorine production can be increased faster than the vehicle program requirements develop. On this basis, it appears that the supplying of fluorine for a FLOXed Saturn program would not be a significant problem.

FLUORINE QUANTITY REQUIREMENTS

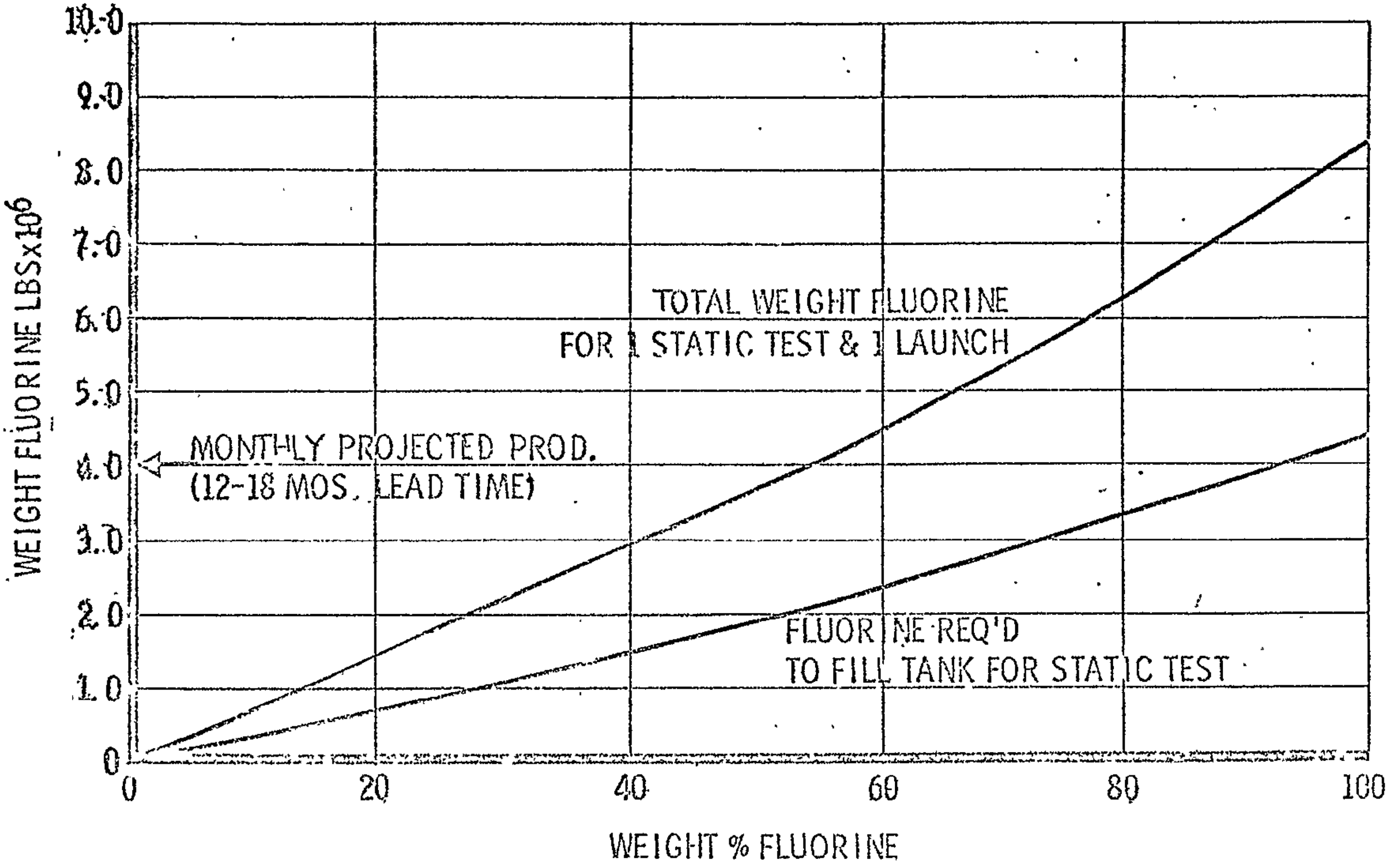

Fig. 4-28

SEC. 4

4.4 REFERENCES

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3. S-IC Technical Systems Criteria; Sverdrup and Parcel and Associates, Inc.; Volume II-C.

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6. Design Handbook for Liquid Fluorine Ground Handling Equipment; Wadd Technical Report 60-159; Aerojet-General Corporation; December 1960.

7. Handbook of Analytical Chemistry, Meites, Louis, 1963.

8. The Determination of Fluorine in FLOX Mixtures; ERR-HN-64-484; General Dynamics/Astronautics; January 1964.

9. Ocean Breeze and Dry Gulch Diffusion Programs, AFCRL-64-791, Vol. I and II; dtd Nov. 1963

10. Atmospheric Diffusion and Generalized Munitions Expenditures, T.O. 11C-1-6; The Chemical Corps Operations Research Group Study NR 17.

SECTION 5

COST ANALYSIS

5.0 COST ANALYSIS

A preliminary investigation was conducted to obtain a general trend of cost effectiveness of a FLOX vehicle program compared to the present Saturn V program. Since several arbitrary assumptions were made, the results presented here are trends. More accurate data would require a detailed analysis.

For purposes of investigation, 60% FLOX in the S-IC was used. Two separate programs were chosen, namely, an all FLOX vehicle program and a 2:1 FLOX program. A 2:1 program is defined as one which launches two LOX vehicles for each 60% FLOX vehicle.

In the investigation, the research, development and testing (RD&T) cost increase over the existing program was assumed to be 200 million dollars. The FLOX production engine costs were assumed to be 1.25 x LOX F-1 engine costs. The stage production costs were assumed to be 3% more than LOX stage costs.

Following is the basic data and sample calculations used in the investigation of the 60% FLOX vehicle.

5.1 COST EFFECTIVENESS OF THE 60% FLOX VEHICLE

5.1.1 Data:

Payload to Escape 135,000 lbs. per vehicle
Propellant Loading 5 million lbs. per vehicle
Oxidizer to Fuel Ratio 3:1
Engine Costs ------------------------- $ 125 million
Stage & GSE Costs ------------------- 75
Total Additional RD&T Costs ---------- 200
Engine Prod. Costs = 1.25 x F-1 engine costs
Stage Prod. Costs = 1.03 x Sat V stage costs

Propellant Costs:		
	Fluorine	$0.50 per lb.
	LOX	0.02
	RP-1	0.02

Eng. Prod. Cost is 15.8% of the total
Stage Prod. Cost is 84.2% of the total.

5.1.2 All FLOX Program

The first ten research vehicle intended for LOX tests have been modified for FLOX.

5.1.3 2:1 LOX-FLOX Program

Flight program uses two LOX vehicles for every FLOX vehicle. Ten additional FLOX research vehicles are required.

5.1.4 Calculations

Cost of propellants using 60% Fluorine-40% LOX oxidizer with RP-1
cost of fluorine = 0.6 x 0.50 = $ 0.30/lb
cost of LOX = 0.4 x 0.02 = 0.008/lb
cost of oxidizer = ---------- 0.308/lb
cost of RP-1 = ------------ 0.020

oxidizer to fuel ratio 3:1
cost of propellant = (3/4 x .308) + (¼ x .02) = 0.236/lb
propellant loading = 5 million lbs/vehicle
propellant cost per vehicle = $1.18 million

Ratio of FLOX Vehicle Cost to Sat V Vehicle Cost

Engine ———————— .158 x 1.25 = .1975
Stage ———————— .842 x 1.03 = .8673
Cost Ratio FLOX/Sat V ———— 1.065

TOTAL FLOX VEHICLE COSTS

Sat V RD&T Cost Plus $200 million
plus Sat V Vehicle cost x 1.065 (include spares)
plus Sat V Operating cost less Sat V propellant costs
plus FLOX propellant cost

5.1.5 Sample Calculation for One FLOX Production Vehicle

RD&T plus GSE assumed total cost		$ 2852 million
Vehicle	66.5 x 1.065 N	70.8
Operating	21.55 - .27 + 1.18 N	22.5
Cost of one FLOX prod. vehicle (N=1)		$ 2945.3
Cost of one SAT V prod. vehicle		2739.2

Total Payload to Escape (millions of pounds)

FLOX Vehicle = .135 NR = .135 x Number x Reliability
Sat V Vehicle = .09 NR = .09 x Number x Reliability

5.2 2:1 LOX-FLOX PROGRAM WITH 60% FLUORINE

CALCULATIONS

Cost of Propellants: 1 FLOX vehicle ———————— $ 1.18 million
2 Sat V's ———————— .539
Total for 3 Vehicles ———— 1.719

Average cost per Vehicle for the program ———— 0.573

Cost 2 Sat V and 1 FLOX vehicle = (2 + 1.0648) = 3.0648 Sat V's
Average cost of vehicles for program = 1.0216 x Sat V costs

Research and development cost of the program plus additional FLOX Research vehicles ———————————— $ 3540. million

FLIGHT NUMBER	R	VEHICLE COST	PROPELLANT COST	TOTAL COST OPERATIONS	TOTAL COST PROGRAM
20	.954	.793	001146	.9747	4.515
90	.964	3.116	0516	3.809	7.349
190	.970	5.973	1100	7.308	10.848
390	.974	11.064	2235	13.510	17.050
590	.977	15.730	3381	19.537	23.077
990	.979	24.359	5673	30.158	33.698

FLIGHT NUMBER	TOTAL PAYLOAD	SPECIFIC COST
20	2.00	2257
90	9.10	808
190	19.34	561
390	39.85	428
590	60.5	381
990	101.8	331

5.3 DISCUSSION

Figure 5-1 shows the total cost vs. the payload to escape for the LOX Sat V vehicle, the "all FLOX" vehicle and the 2:1 LOX-FLOX vehicle programs. From the curves, it can be seen that for a total accumulative payload greater than 1.5 million pounds the 60% "all FLOX" vehicle program is cheapest.

Figure 5-2 compares the specific costs of the three programs. As in the previous figure, for a total accumulative payload greater than 1.5 million pounds, the 60% "all FLOX" program is cheapest.

Figure 5-3 compares the specific costs of the three programs on a number of missions basis. This shows that the 60% "all FLOX" vehicle program is cheapest for any number of missions. This can be accounted for by the greater payload capability of the FLOX vehicle. For sixty missions or more, the 2:1 FLOX program has a lower specifi cost than the Sat V program.

Table 5-1

COST EFFECTIVENESS OF THE 60% FLOX VEHICLE

N	R	VEHICLE COSTS SAT V	VEHICLE COSTS FLOX	PROPELLANT COST SAT V	PROPELLANT COST FLOX	TOTAL OPERATIONS SAT V	TOTAL OPERATIONS FLOX
1	.920	.0665	.0708	.00027	.00118	.0881	.0933
10	.945	.5089	.5420	.00269	.0118	.6459	.6881
30	.954	1.294	1.378	.00808	.0354	1.612	1.723
100	.964	3.559	3.790	.0269	.1180	4.361	4.683
200	.970	6.356	6.769	.0539	.2360	7.770	8.365
400	.974	11.340	12.077	.1078	.4720	13.805	14.906
600	.977	15.907	16.947	.1617	.7080	19.672	21.258
1000	.979	24.356	25.938	.2695	1.180	29.992	32.484

TOTAL COST = RD&T COSTS PLUS TOTAL OPERATIONS COSTS

N	TOTAL COST SAT V	TOTAL COST FLOX	TOTAL PAYLOAD SAT V	TOTAL PAYLOAD FLOX	SPECIFIC COST SAT V	SPECIFIC COST FLOX
1	2.739	2.945	.0828	.1242	33,100	23,700
10	3.297	3.540	.850	1.275	3,880	2,780
30	4.263	4.575	2.575	3.865	1,656	1,185
100	7.012	7.535	8.67	13.0	808	580
200	10.421	11.217	17.46	26.2	597	428
400	16.456	17.758	35.1	52.6	470	338
600	22.323	24.110	52.8	79.1	423	305
1000	32.643	35.336	88.1	132.2	371	267.5

COSTS IN BILLIONS OF DOLLARS
PAYLOAD IN MILLIONS OF POUNDS TO ESCAPE
SPECIFIC COST IN $/LB

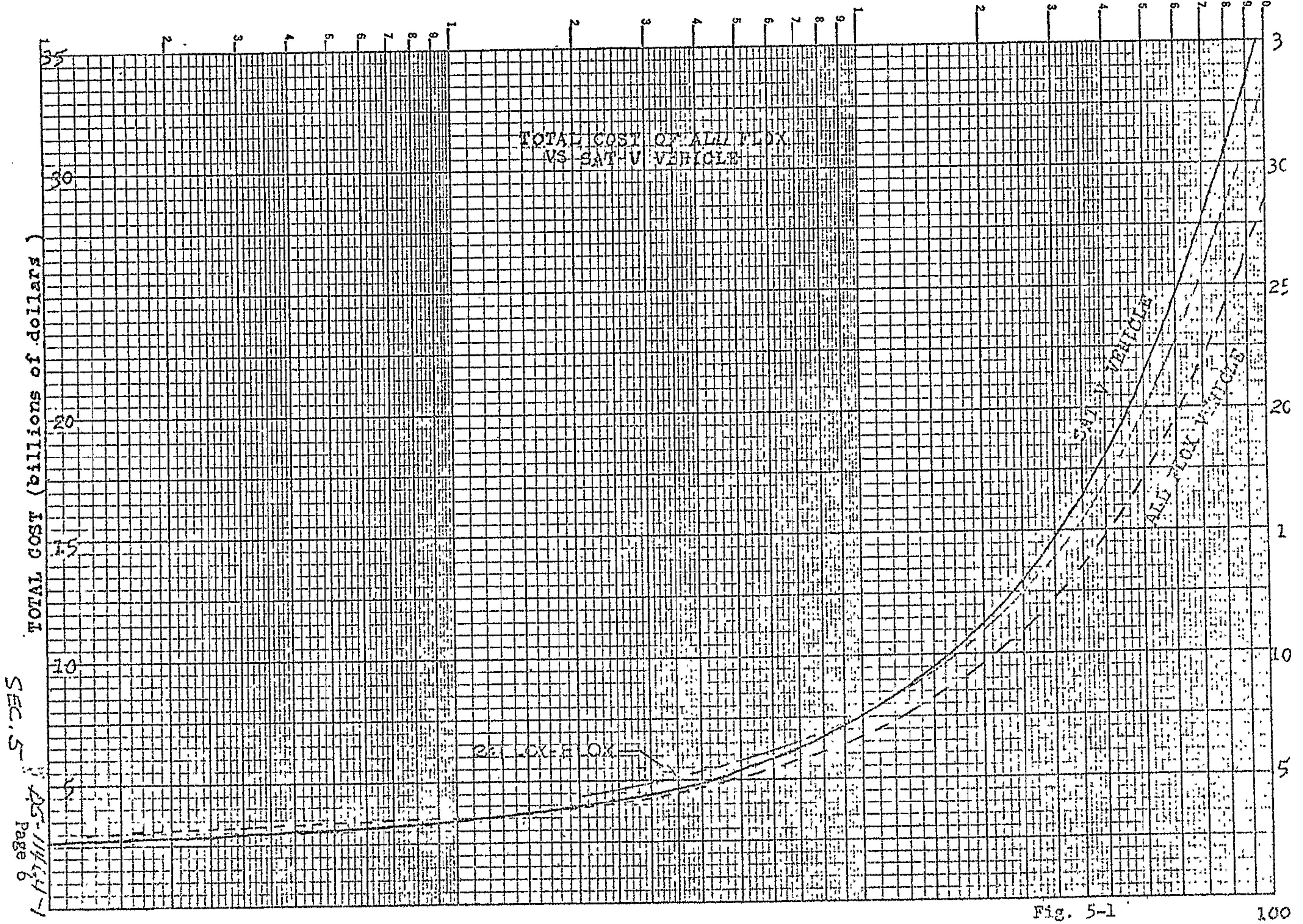

Fig. 5-1

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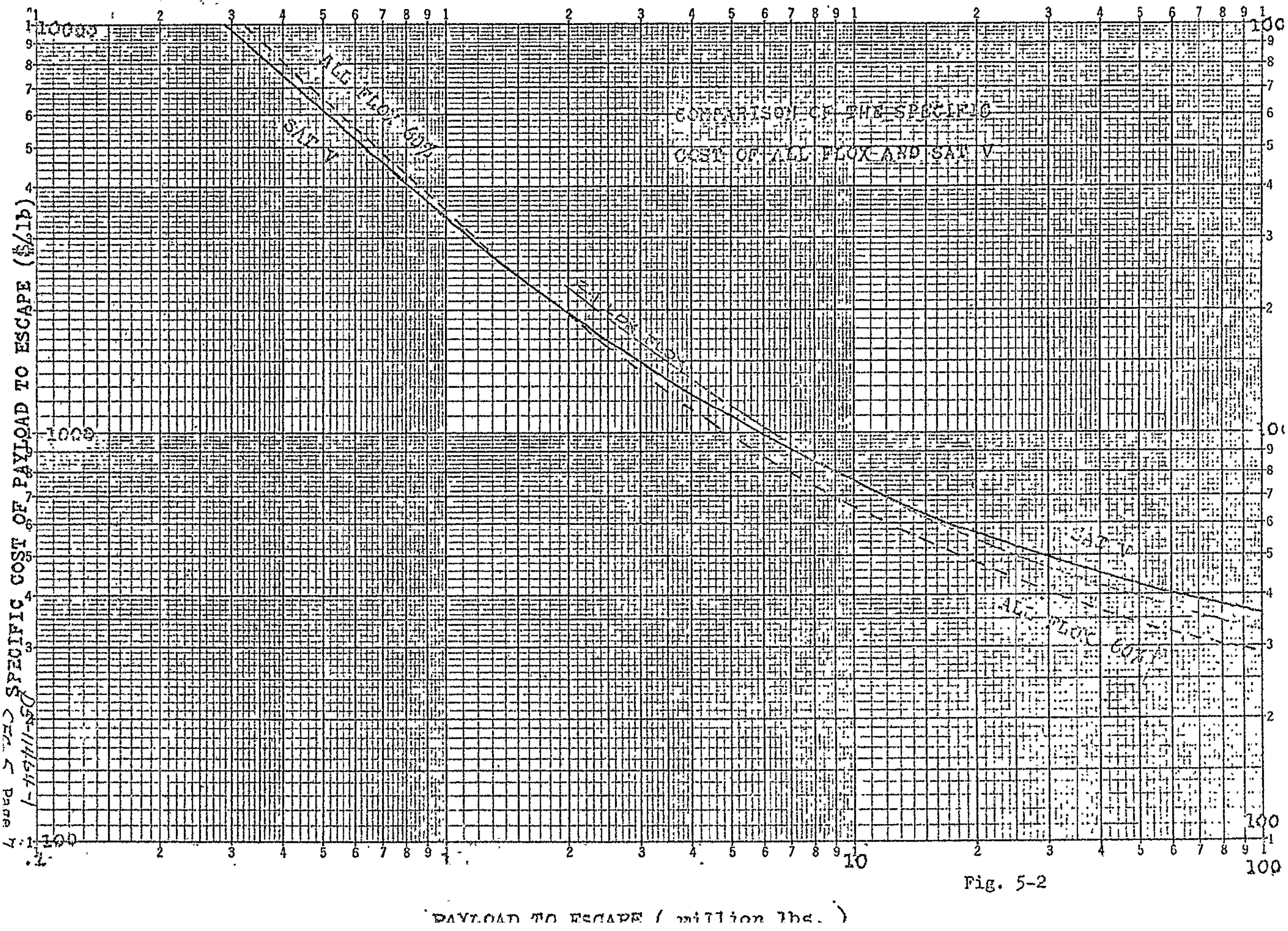

COMPARISON OF THE SPECIFIC
COST OF ALL FLOX AND SAT V
SPECIFIC COST OF PAYLOAD TO ESCAPE ($/lb)
PAYLOAD TO ESCAPE (million lbs.)
10000
1000
100
.1
1
10
100
ALL FLOX CON
SAT V
ALL FLOX
SAT V
ALL FLOX CON

Fig. 5-2

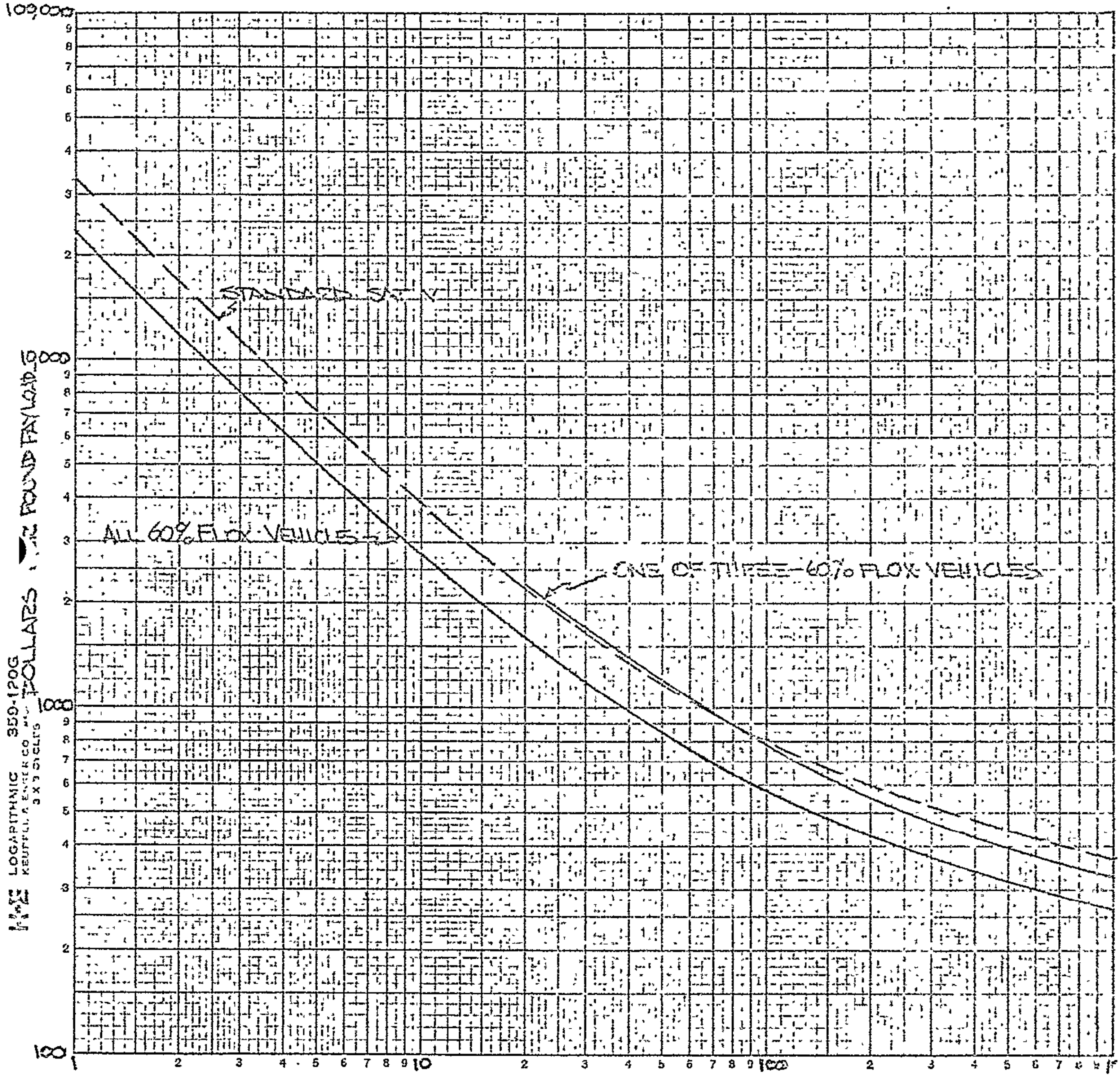

100,000
10,000
1000
100
DOLLARS [illegible] POUND PAYLOAD
NUMBER OF MISSIONS
1
10
100
1000
STANDARD SAT V
ALL 60% FLOX VEHICLES
ONE OF THREE 60% FLOX VEHICLES
LOGARITHMIC 359-120G
KEUFFEL & ESSER CO.
3 X 3 CYCLES

Fig. 5-3

SECTION 6

CONCLUSIONS & RECOMMENDATIONS

6.0 CONCLUSIONS & RECOMMENDATIONS

Because of the large performance potential from FLOX, follow-on studies are recommended and outlined below. A suggested general work statement is included in the appendix.

6.1 PERFORMANCE

As discussed in Section 2, fluorine is a very potent oxidizer and offers tremendous payload advantages when utilized in the S-IC. D5-11464-2 compared FLOX with other methods of uprating such as strap-on solids, larger propellant tanks, and higher thrust LOX/RP-1 engines. FLOX looks especially competitive since it offers the high payload increases without changing current stage geometry. The payload capability may be varied from the present value to the maximum available with FLOX merely by adjusting the FLOX concentration.

It is recommended that F-1 sub-scale chamber tests be conducted to confirm the performance and define the engine carbon build-up rate. Further work should be done to determine more closely the stage design of specific optimized vehicles. The use of FLOX in upper stages should be included in future studies.

6.2 STAGE DESIGN

6.2.1 Materials Compatibility

Only minor design and materials compatibility problems are apparent on the S-IC. The area of major question is in the LOX tank pressurization system which routes high temperature GOX (or FLOX) through numerous fittings and joints which may have contaminate traps. Contaminant reactivity with FLOX has been shown to be extremely great at elevated temperatures, and relatively non-existant at cryogenic temperatures. This makes it appear desirable to use a different oxidizer tank pressurization system. Some S-IC components may need modification to eliminate contamination traps. The LOX tank, engine system and pressurization system should be passivated to react any contaminants before full strength FLOX is allowed to contact the surfaces.

It is recommended that all non-metals be eliminated from the entire FLOX system. If this is not possible, a minimum surface area of non-metals should be exposed to flow.

It is recommended that tests be conducted on specific critical materials to verify compatibility with FLOX before proceeding into any sizable program.

6.2.2 Pressurization and Vent Systems

The pressurization requirements for the FLOX tank will not exceed the present LOX system. The present vent system is capable of passing a higher flow rate of FLOX than GOX and should meet the FLOX vent system requirements. Modifications to the existing heat exchanger, if used, may be required to permit passage of less than 20 #/sec of pressurant without overheating the piping system.

6.2.3 Effect of Engine Ignition System Removal

It has been concluded that 340 pounds of weight saving would result from elimination of the present ignition system and taking advantage of the hypergolic reaction of FLOX and RP-1 for ignition.

6.2.4 Thermal Environment

Aerodynamic heating rates due to FLOX application are believed negligible. An increase in convective and radiant heating in the base area may be realized, however, and should be studied.

6.3 OPERATIONAL FEASIBILITY ANALYSIS

6.3.1 FLOX Effect on Ground Support Equipment

It has been concluded that changes in existing facilities will be straightforward design and cost evaluation problems. The major equipment additions will be a chemical reactor to neutralize fluorine or hydrogen fluoride gases and a condenser to liquify boil-off gases from the booster storage tank. Water deluge facilities at the firing sites may be adequate for treatment of fluorine spills but study is required. Transfer and handling of FLOX apparently can be accomplished with present type equipment, however, confirmation of material compatibility is required.

6.3.2 Toxic Exhaust Products Effects

Methods for controlling and/or predicting air pollution resulting from booster rocket engine exhaust need to be developed. Because of the numerous variables associated with atmospheric diffusion and the exhaust cloud behavior, a clear-cut solution to the air pollution problem was not obtained in the study.

Another area which is not clearly defined is the tolerance level for fluorine and hydrogen fluoride and further coordination is required.

6.3.3 Fluorine Availability

It has been concluded that the large quantities of fluorine required in the application of FLOX to the S-IC would not present a significan problem. Allied Chemical has conducted studies which indicate that their fluorine production could be increased at a faster rate than the vehicle program requirements develop.

APPENDIX A

SPECIAL PERFORMANCE CONSIDERATIONS

APPENDICES

A.0 SPECIAL PERFORMANCE CONSIDERATIONS

B.0 TOXIC EXHAUST AND BOIL-OFF GAS CONSIDERATIONS

C.0 FLOX THERMODYNAMIC PROPERTIES

D.0 BACKGROUND OF FLUORINE-FLOX STUDIES

E.0 TAO-22 STATEMENT OF WORK - USE OF FLUORINE (FLOX) FOR PERFORMANCE IMPROVEMENT ON THE S-IC

REFERENCES

A.0 SPECIAL PERFORMANCE CONSIDERATIONS

A.1 DESCRIPTION OF DIGITAL PROGRAM USED TO CALCULATE FLOX/RP-1 THEORETICAL PERFORMANCE

A large amount of theoretical FLOX/RP-1 performance data has been generated, and applied. This appendix section briefly describes the capabilities and limitations of the digital program used to accomplish the performance predictions.

The program was developed at NASA Lewis Research Center (Reference 1) and evolved over a period of years from a series of less sophisticated programs requiring computers smaller than the 7090. The program has the following capabilities:

1. Theoretical rocket performance calculation for both shifting and frozen equilibrium expansions from an assigned initial propellant enthalpy and combustion chamber pressure to either a series of assigned exit pressures or expansion ratios.

2. Theoretical rocket performance calculation for both shifting and frozen equilibrium expansions from an assigned temperature and pressure in the combustion chamber to either a series of assigned exit pressures or expansion ratios.

   Equilibrium composition for an assigned pressure at a series of assigned temperatures.

   Equilibrium composition for an assigned temperature at a series of assigned pressures.

   Equilibrium composition for an assigned propellant enthalpy at a series of assigned pressures.

6. Chapman-Jouguet detonation properties for an assigned temperature and pressure precdding the detonation wave

The program requires simple input, needs no initial estimates to assure convergence, and handles up to 30 different propellant constituents (1 - 15 fuels and 1 - 15 oxidizers). As many as 90 exhaust products can be accounted for in a single reaction. The master thermodynamic data tape presently contains data for over 200 species. For each species is stored 14 "curve-fit" coefficients for specific heat, enthalpy, and entropy as a function of the temperature. These "curve-fit" data given in Reference 2 determine the accuracy of the predicted combustion products and performance. JANAF thermochemical data are universally accepted as a standard source and are, therefore, considered to be as accurate as possible. These tables are continually kept up to date by the Dow Chemical Company and periodically are incorporated into the computer program data tape. The calculations in the program are based on the following usual assumptions.

a) perfect gas law
b) adiabatic combustion at constant pressure

c) negligible combustion chamber velocity
d) expansion at constant entropy
e) inviscid flow
f) homogeneous mixing
g) one-dimensional flow

The combustion products of FLOX/RP-1 are assumed to be any or all of the following species:

C	C_2	C_3	CF	CF_2	CF_3	CF_4
CH	CH_2	CH_3	CH_4	C_2H_2	C_2H_4	CO
CO_2	COF_2	F	F_2	H	H_2	HCO
HF	H_2O	O	O_2	OH	Graphite	

The graphite, or solid phase of carbon, is assumed to be finely dispersed and in temperature and velocity equilibrium with the expanding gases.

Over the past year of use within Boeing, the program has proved to be an extremely valuable and reliable tool, requiring a minimum expenditure of effort for the user. There is presently no reason to suspect that the data generated by the program for FLOX/RP-1 propellants are anything other than reliable, and therefore, directly applicable to expected F-1 engine performance when the appropriate efficiencies and assumptions are used.

A.2 THEORETICAL PERFORMANCE OF THE FLUORINE + OXYGEN/RP-1 PROPELLANT SYSTEM

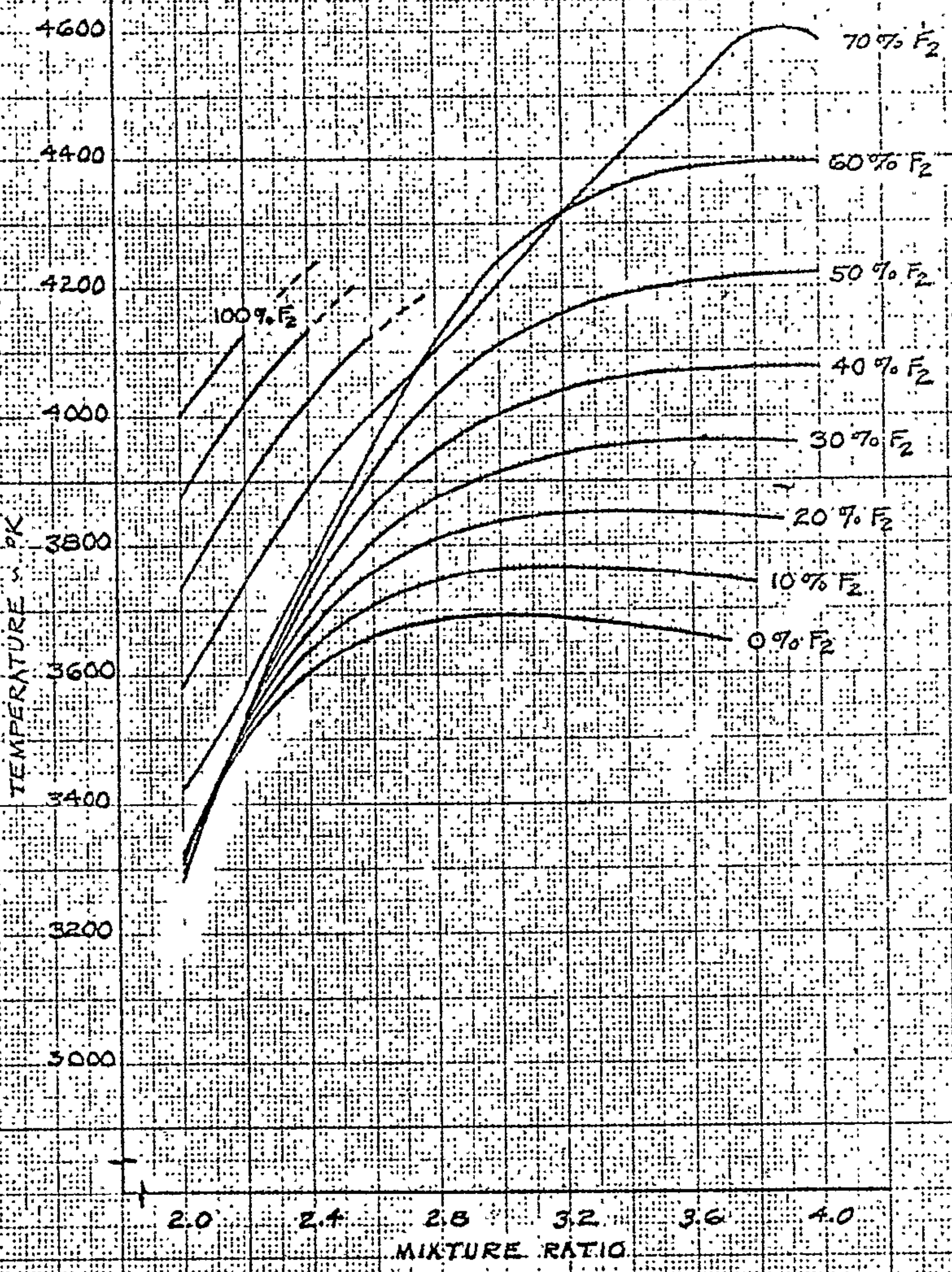
Theoretical performance for both frozen and shifting equilibrium composition during expansion was calculated for RP-1 fuel with several fluorine-ozygen mixtures for a range of oxidant to fuel ratios. The expansion area ratio and chamber pressure were held constant at the F-1 engine nominal operating conditions. The parameters included were temperature, molecular weight, specific impulse, characteristic velocity, thrust coefficient, and exist pressure ratio. The flame temperatures and molecular weight relationships with mixture ratio are given in Figures A-1 and A-2. Figures A-3 through A-7 are for shifting equilibrium conditions. The frozen equilibrium relationships are given in Figures A-8 through A-12.

The data were generated using the combustion equilibrium computer program described in Section A.1

Propellant properties used as input to the computer program are as follows:

<u>Fuel</u> RP-1

Composition: $C_{12.501} H_{24.414}$
Heat of formation: -80449.7 cal/mole



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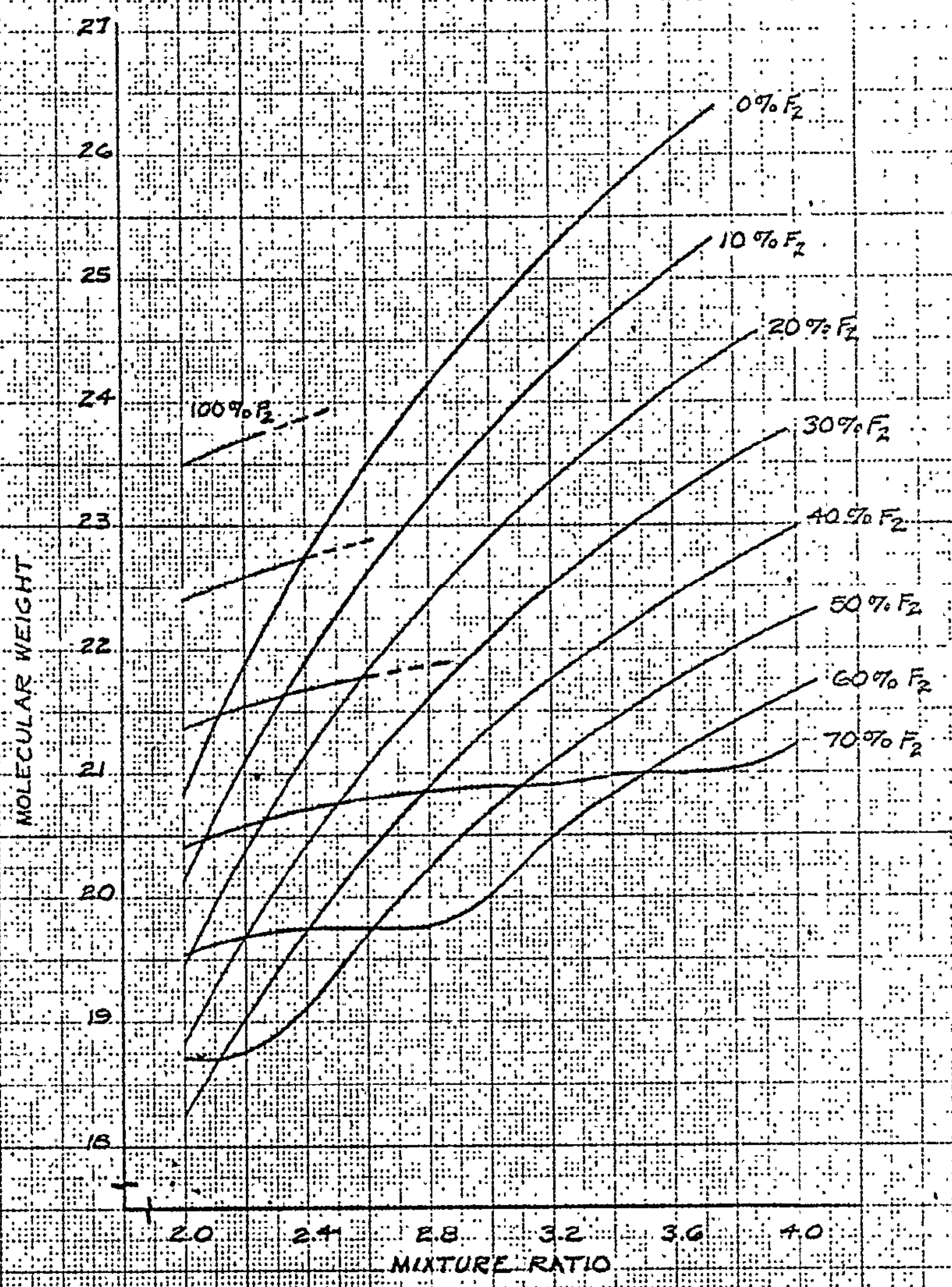
THEORETICAL FLAME TEMPERATURE
CHAMBER PRESSURE = 960 PSIA
RP-1 + O_2 & F_2
COMBUSTION CHAMBER CONDITIONS

THE BOEING COMPANY

App. A

D5-11464

A-1



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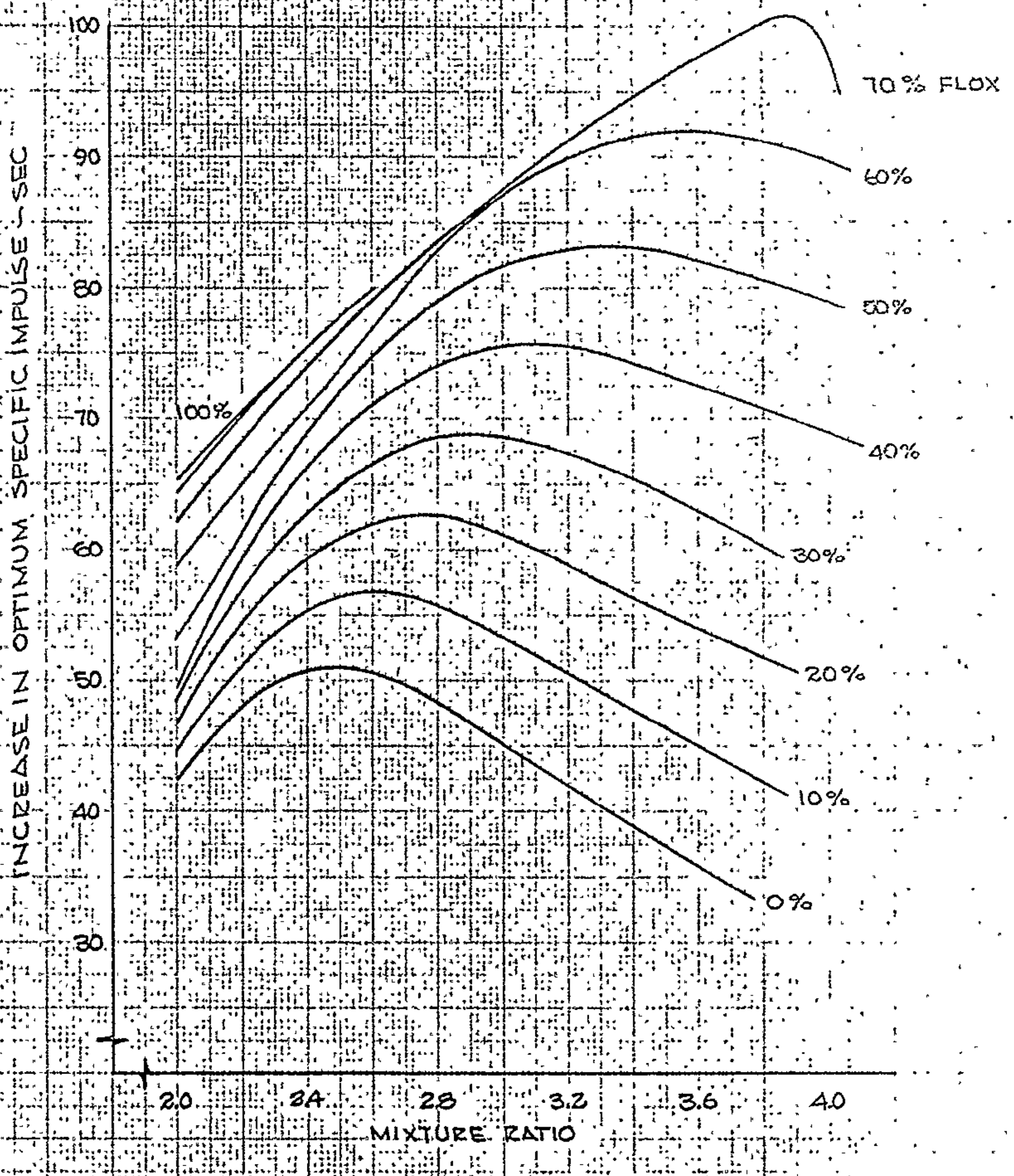
THEORETICAL MOLECULAR WEIGHT
CHAMBER PRESSURE = 960 PSIA
RP-1 + O_2 & F_2
COMBUSTION CHAMBER CONDITIONS

D5-11
A-2

THE BOEING COMPANY SEC. A.



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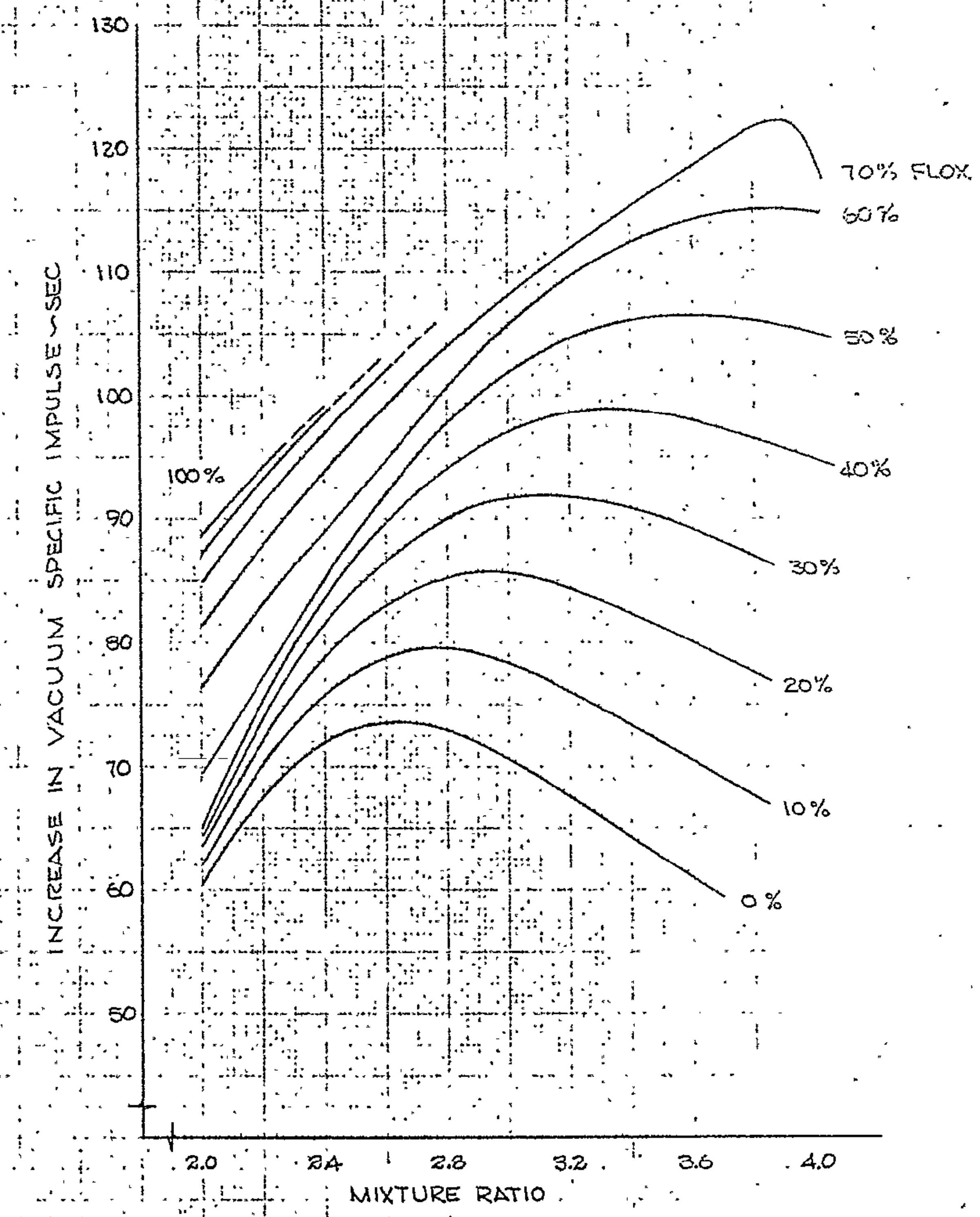
THEORETICAL PERFORMANCE
P_c = 900 PSIA ε = 16:1
RP-1 + O_2 & F_2
SHIFTING EQUILIBRIUM

D5-11664
1-3

THE BOEING COMPANY Sec. A



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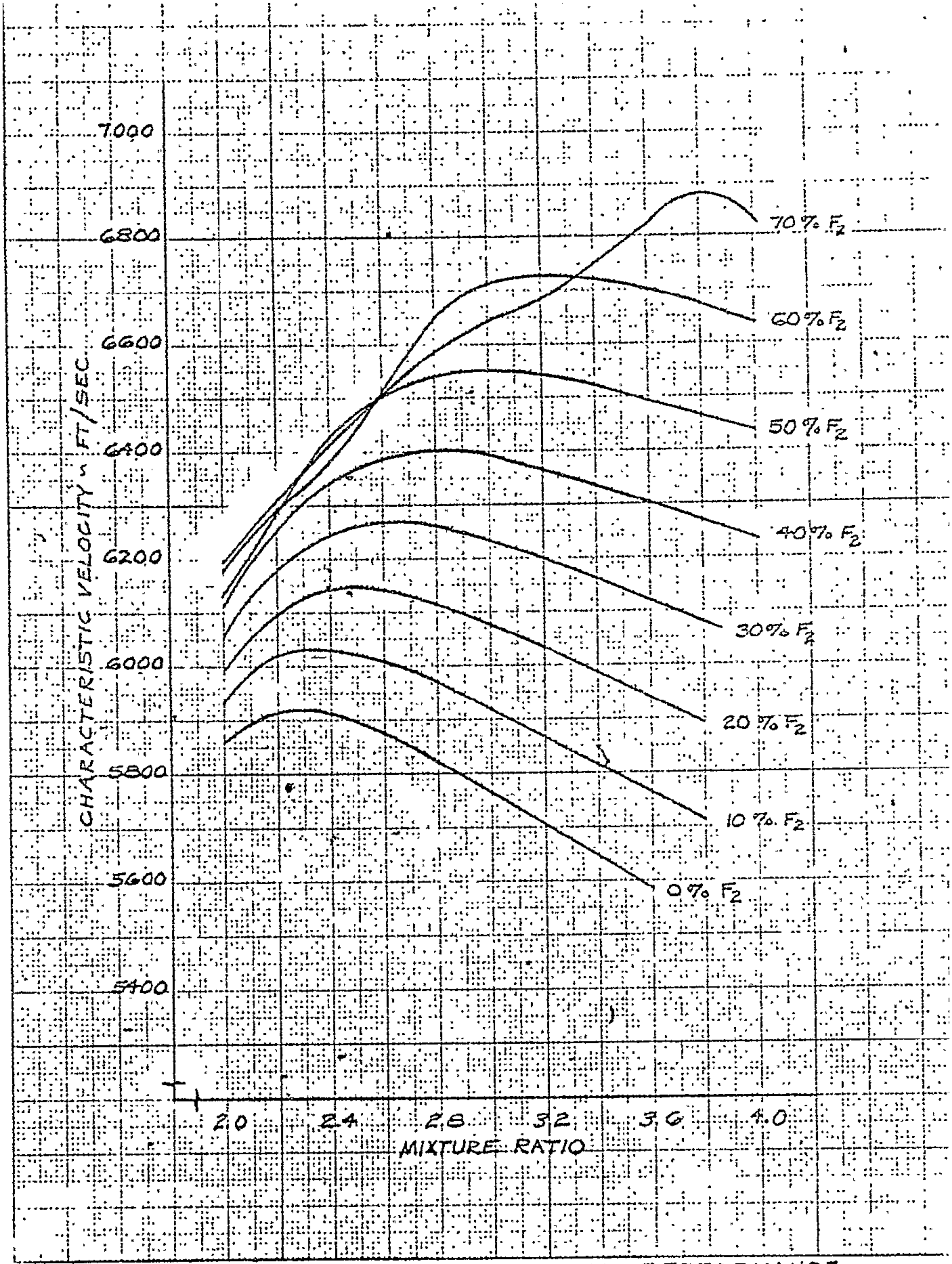
THEORETICAL PERFORMANCE
P_c = 960 PSIA ϵ = 16:1
RP-1 + O_2 & F_2
SHIFTING EQUILIBRIUM

D5-11461
A-1

THE BOEING COMPANY SEC. A



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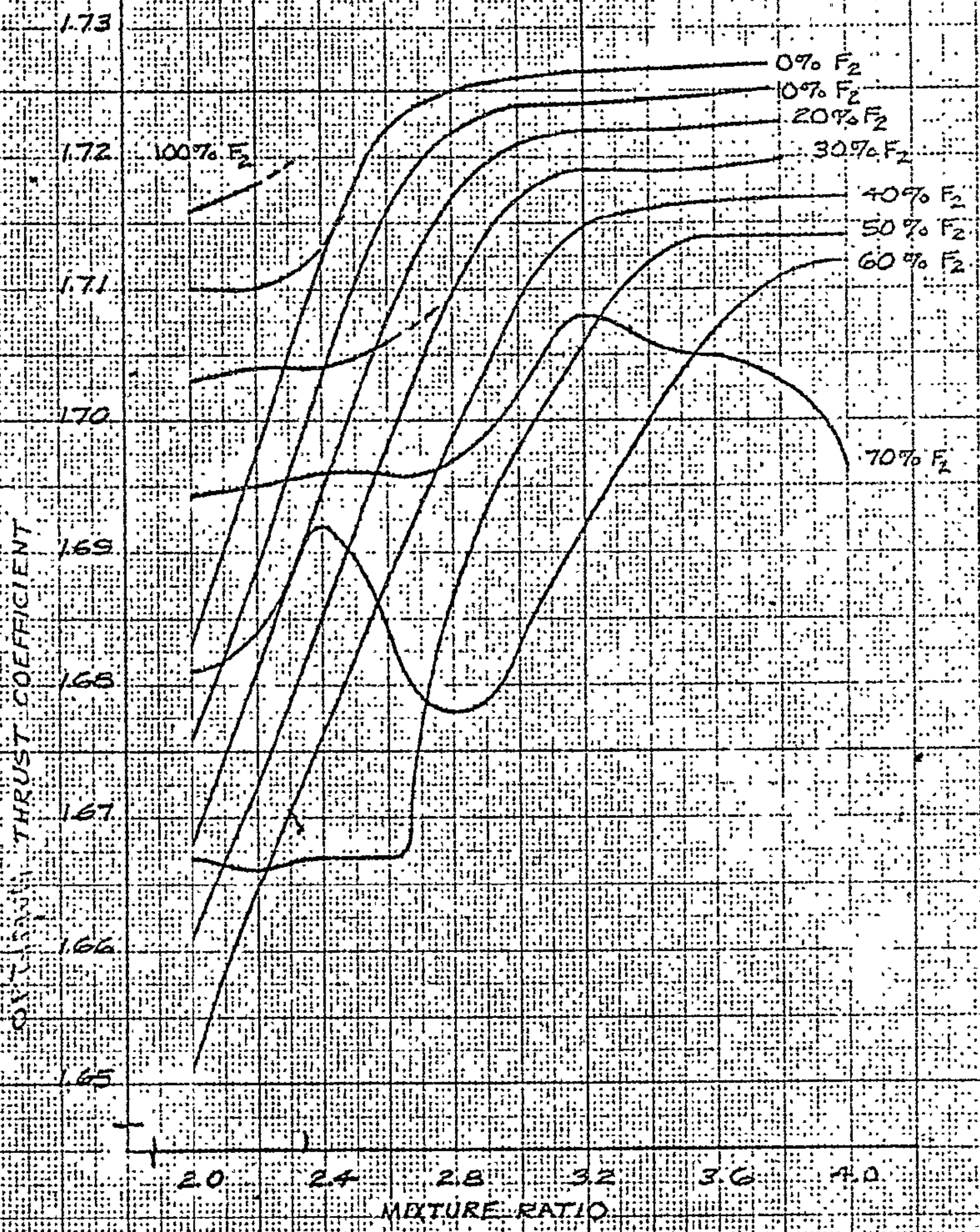
THEORETICAL PERFORMANCE
P_c = 960 PSIA ϵ = 16:1
RP-1 + O_2 & F_2
SHIFTING EQUILIBRIUM



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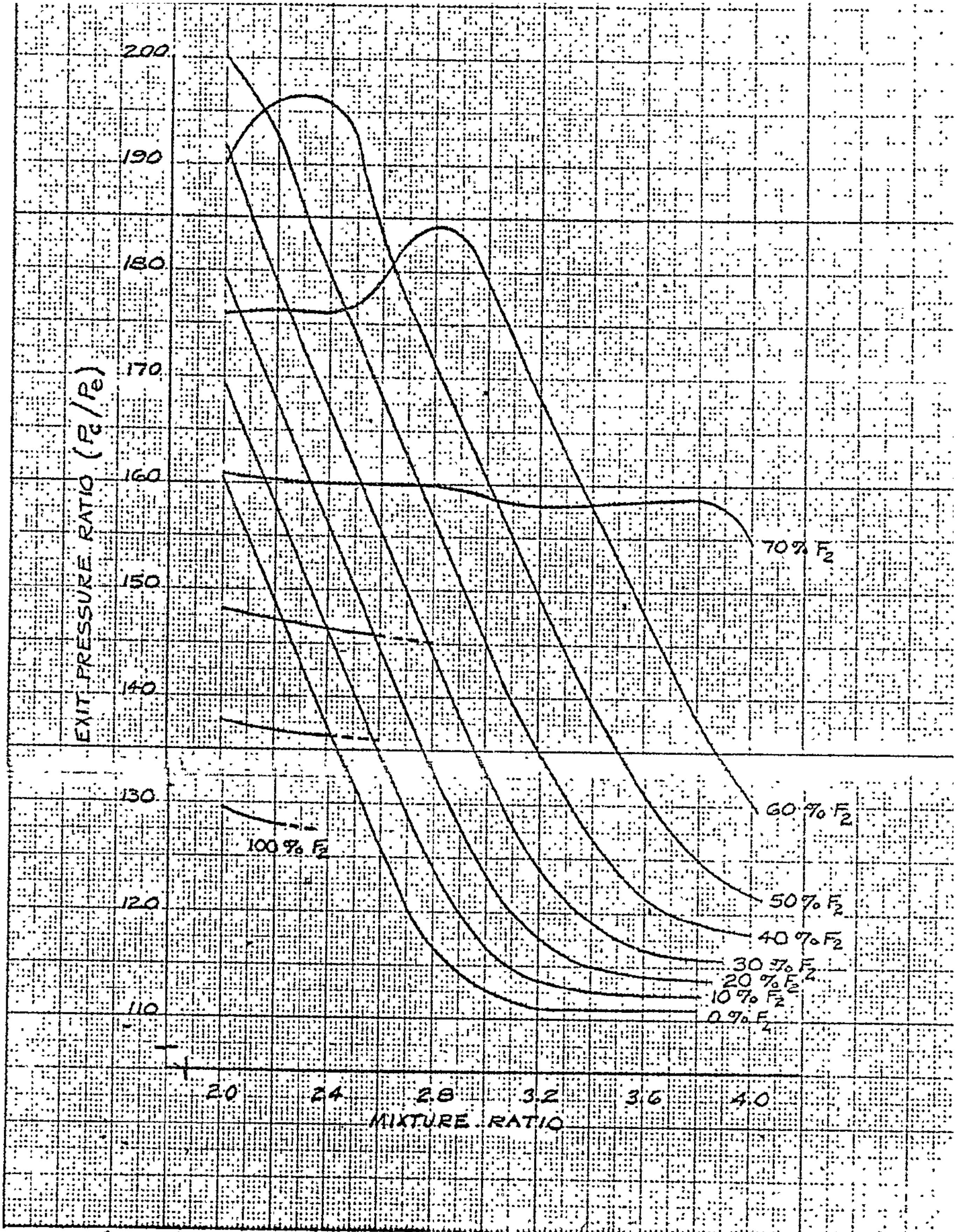
THEORETICAL PERFORMANCE
P_c = 960 PSIA ε = 16:1
RP-1 + O_2 & F_2
SHIFTING EQUILIBRIUM

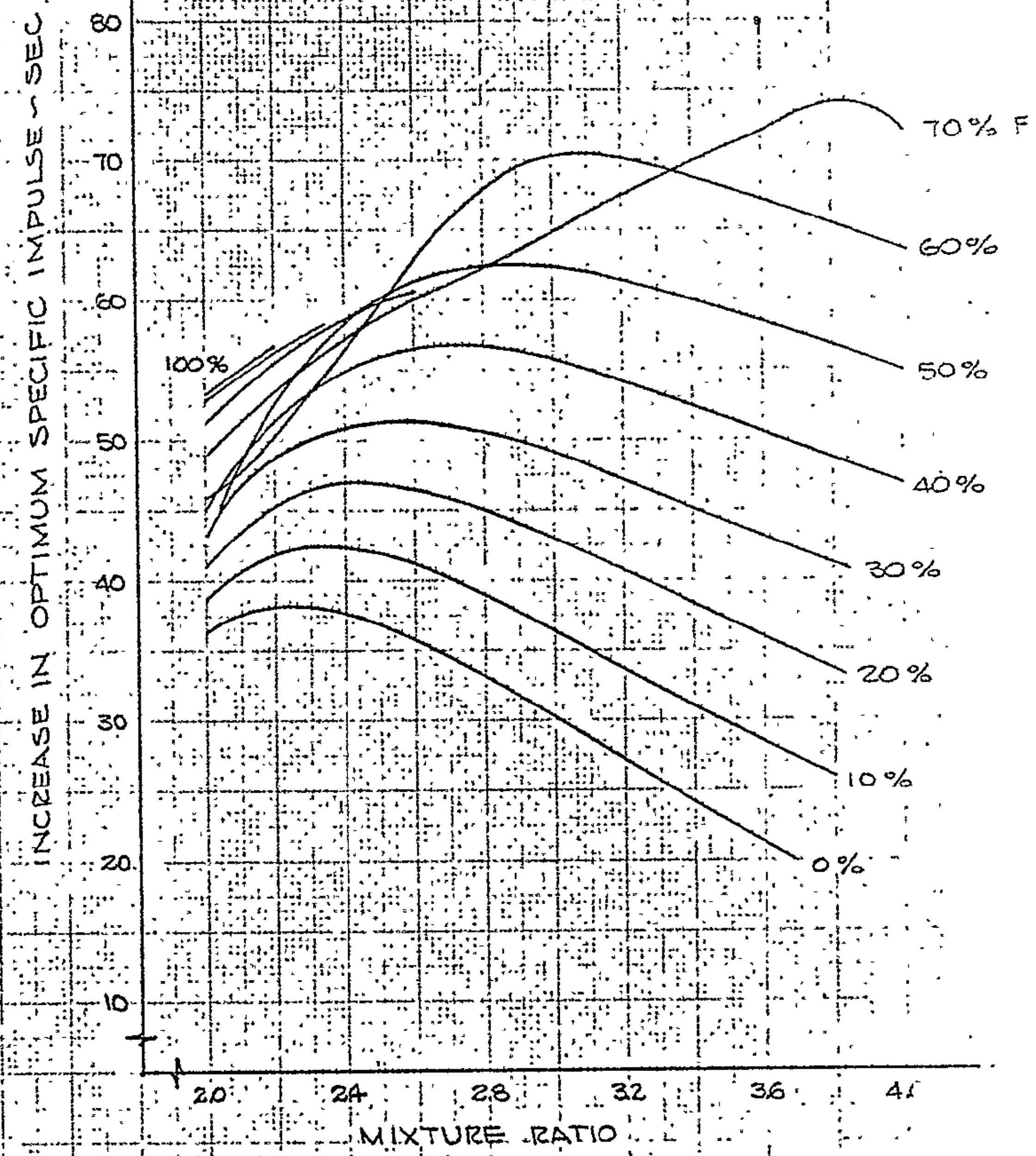
A-6

THE BOEING COMPANY SEC. A



L.E.C. 11-7-63

THEORETICAL PERFORMANCE
P_c = 960 PSIA ϵ = 16:1
RP-1 + O_2 & F_2
SHIFTING EQUILIBRIUM



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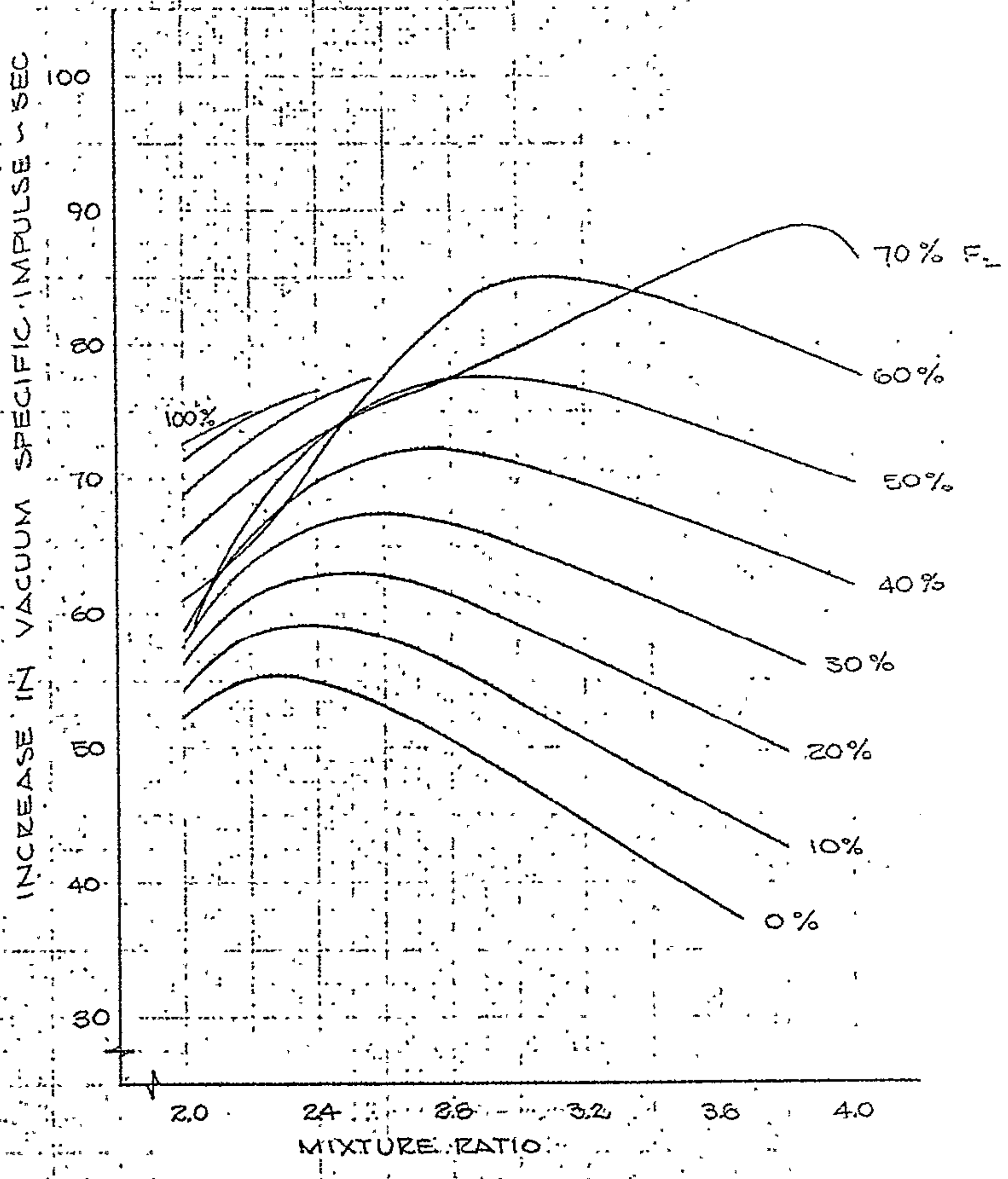
THEORETICAL PERFORMANCE
P_c = 960 PSIA ε = 16:1
RP-1 + O_2 & F_2
FROZEN EQUILIBRIUM

A-8

SEC. A

THE BOEING COMPANY D5-11464



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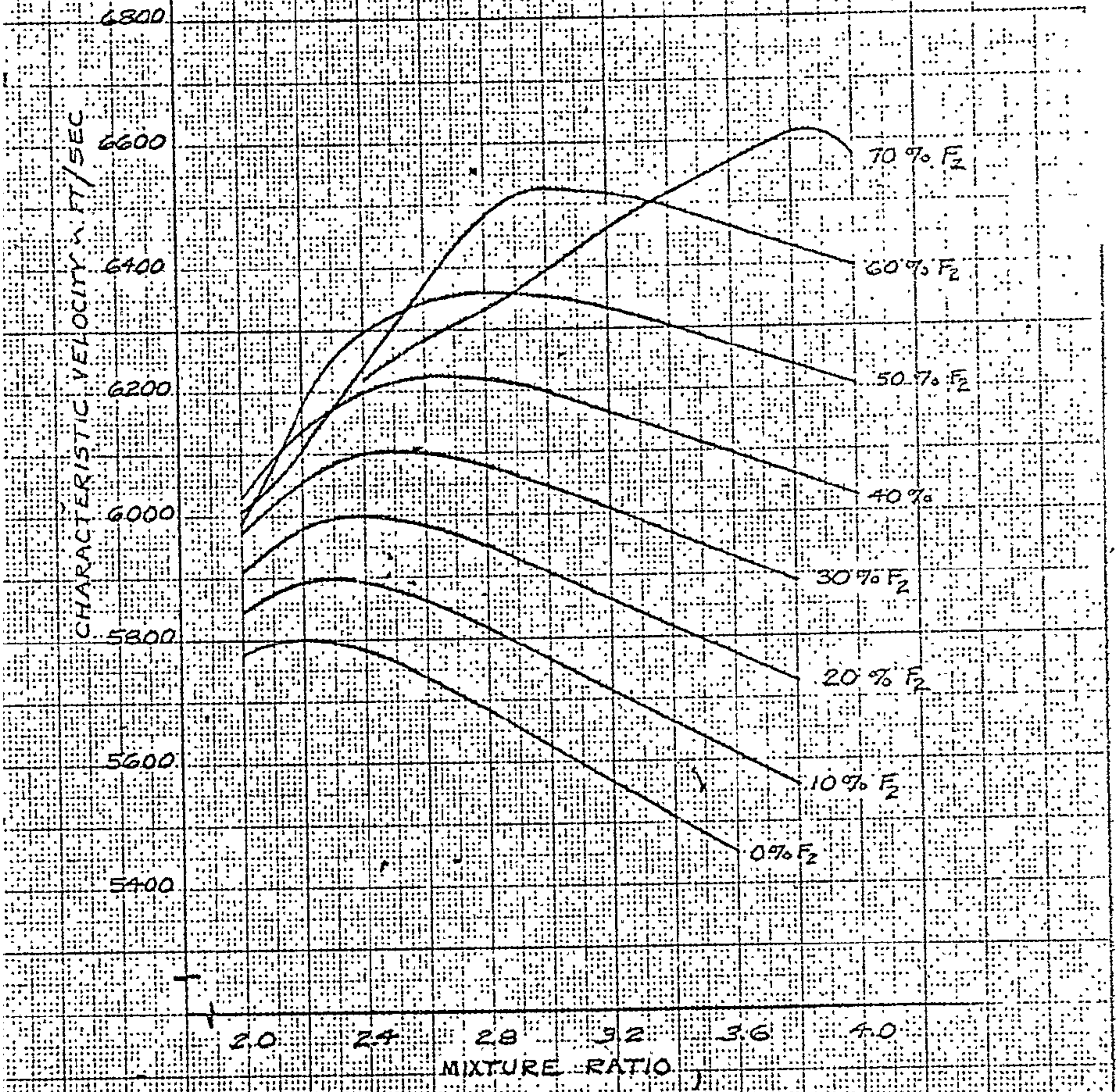
THEORETICAL PERFORMANCE
P_c = 960 PSIA ϵ = 16:1
RP-1 + O_2 & F_2
— FROZEN ··· EQUILIBRIUM

THE BOEING COMPANY D5-11421-1

SEC. A

A-9



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THEORETICAL PERFORMANCE

P_c = 960 PSIA ϵ = 16:1

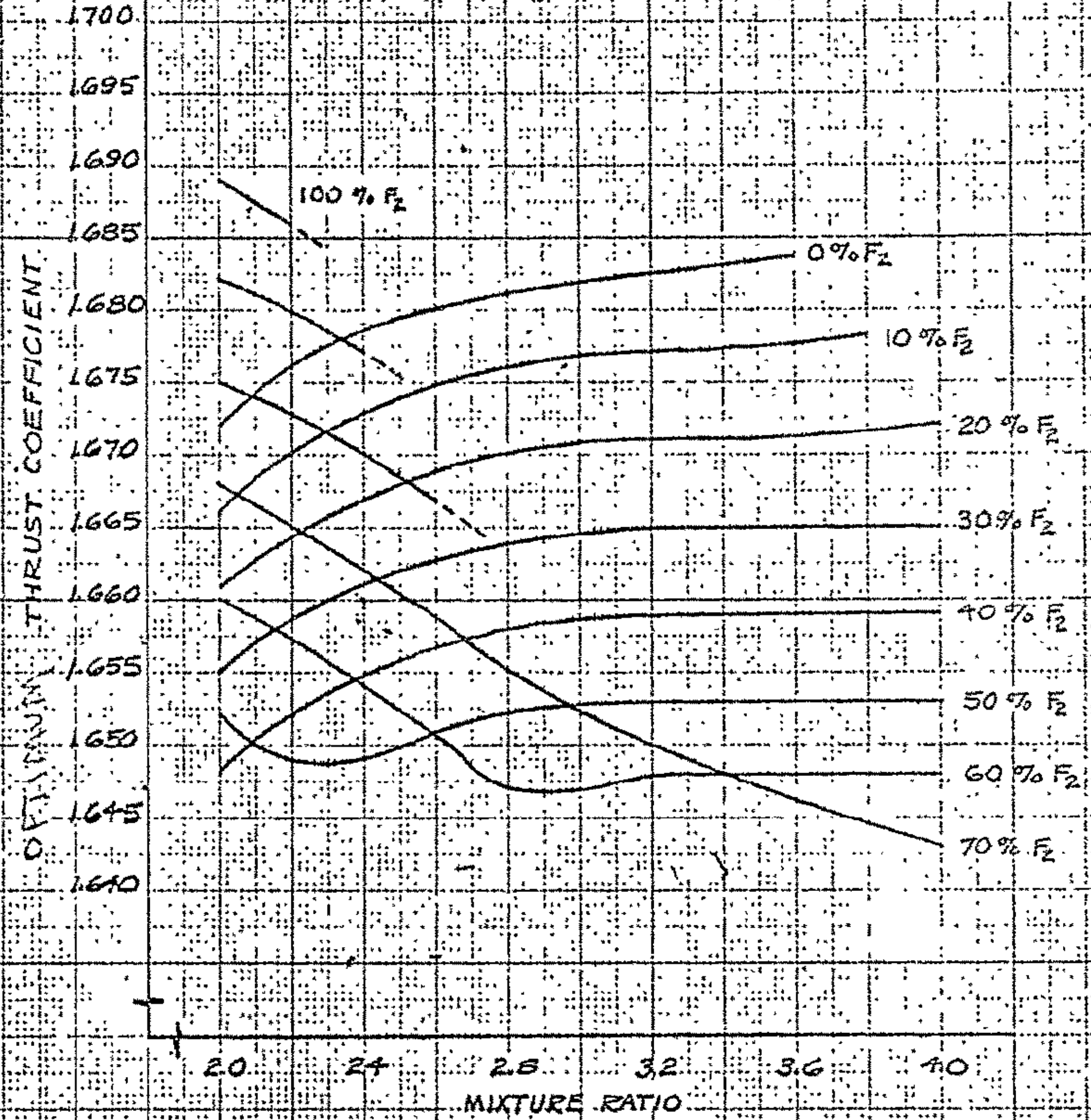
RP-1 + O_2 & F_2

FROZEN EQUILIBRIUM

SEC. A

A-10

THE BOEING COMPANY



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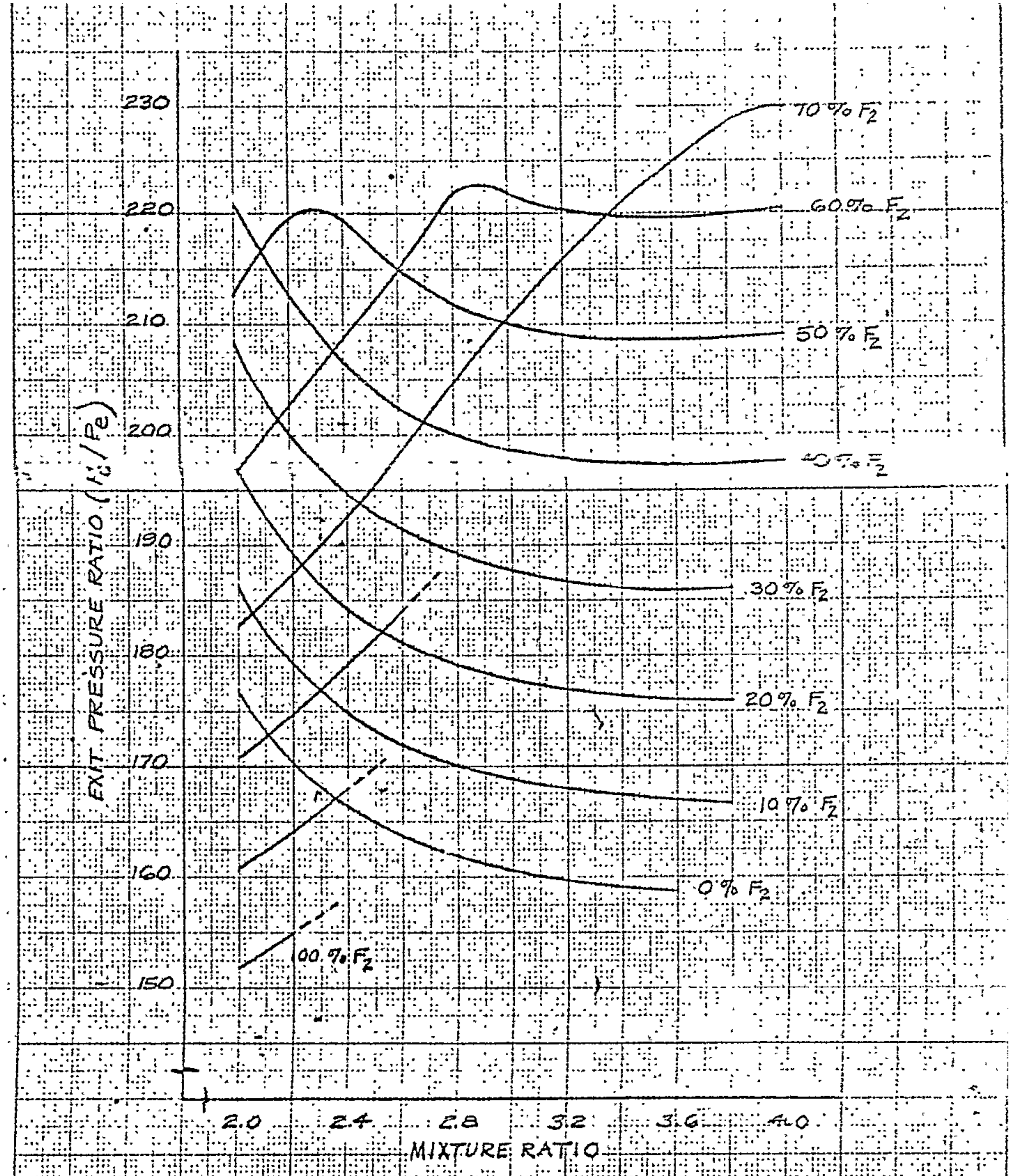
THEORETICAL PERFORMANCE
P_c = 960 PSIA ϵ = 16:1
RP-1 + O_2 / F_2
FROZEN EQUILIBRIUM

A-11



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THEORETICAL PERFORMANCE
P_c = 960 PSIA ϵ = 16:1
RP-1 + O_2 & F_2
FROZEN EQUILIBRIUM

A-12

APPENDIX B

TOXIC EXHAUST AND BOIL-OFF GAS CONSIDERATIONS

Oxidizer	Liquid fluorine (F_2) and Liquid oxygen (O_2)
Heat of formation of liquid F_2:	-3030 cal/mole
Heat of formation of liquid O_2:	-3081 cal/mole

B.0 TOXIC EXHAUST AND BOIL-OFF GAS CONSIDERATIONS

B.1 GENERAL

During the course of investigation of TAO-22, numerous references relative to toxic cloud behavior and tolerance levels were reviewed. The following observations summarize some of the undefined aspects and present one equation series for determination of distance dosage relationship.

B.1.1 Air Pollution & Toxic Limits

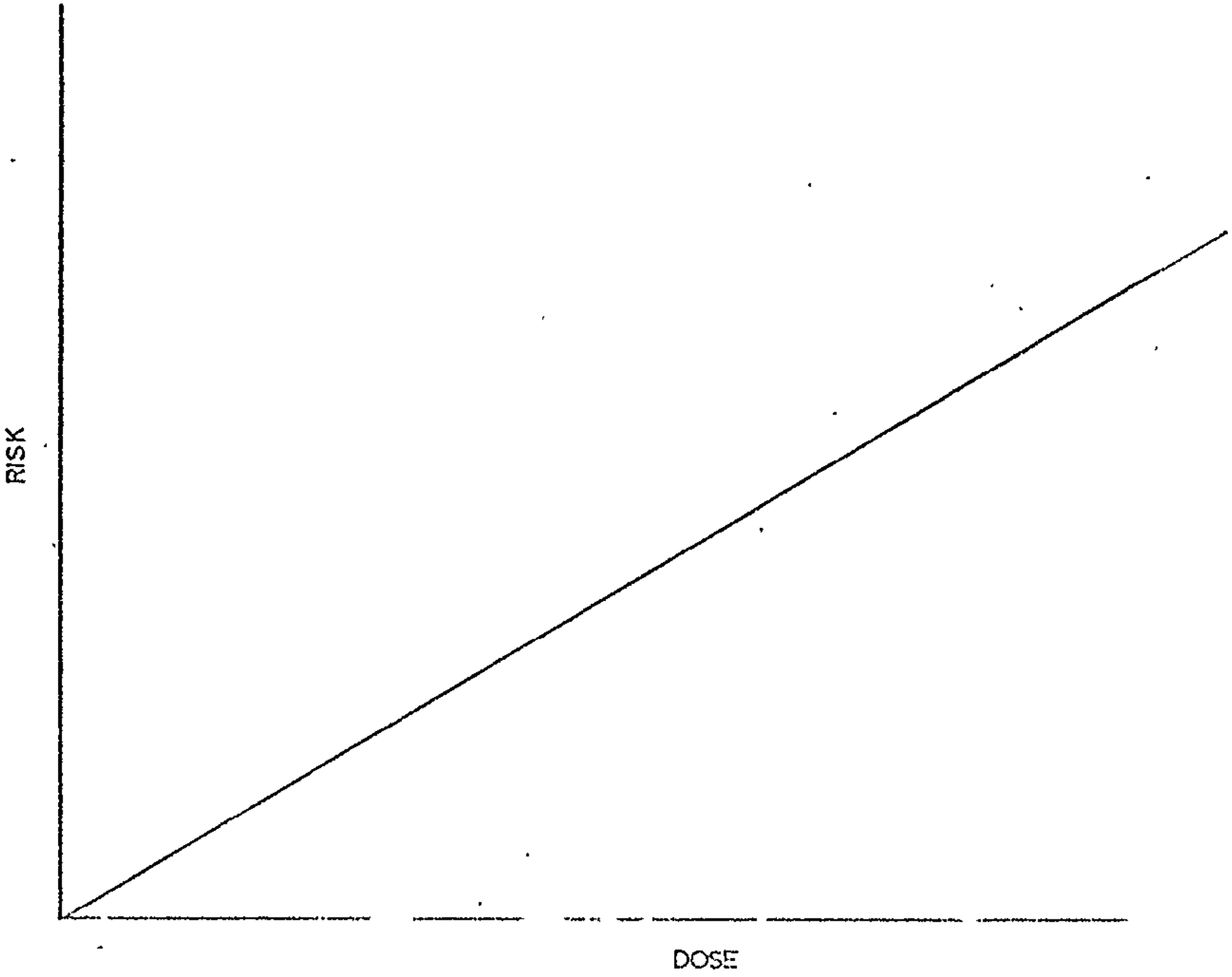
Methods for preventing and controlling air pollution from rocket engines or more specifically from multi-engine booster rockets need to be developed. A survey of current literature on this subject failed to turn up a single paper which adequately covered the problem. Weather Bureau climatology reports suggest that the area east of the Mississippi River has poor diffusion characteristics except during those periods when strong fronts from the Northwest sweep the pollution easterly out over the Atlantic. The natural control of air pollution requires dilution, which in turn depends entirely on air movement; particularly vertical air motion. Air movement carries the pollutant aloft, away from communities, into the upper atmospheric turbulence and diffuses airborne debris over a wide area.

The use of fluorine on the S-IC to improve performance generates hazards which require the development of additional disciplined skills for their control. The level of tolerance for fluorine and HF must be established for atmospheric pollution. This quantity should be based on the ability of the human body to detoxify itself from a high level, short term exposure. Dose-time relationships for either fluorine or HF is somewhat controversial. Local industrial hygiene thinking is that the risk is linear with dose similar to Figure B-1. Generally, most toxics perform more like Figure B-2. Below some threshold dose, risk is negligible. As the dose increases, the probability of injury increases. Figure B-3 is a graphical presentation differentiating total dose, effective dose and detoxicated dose.

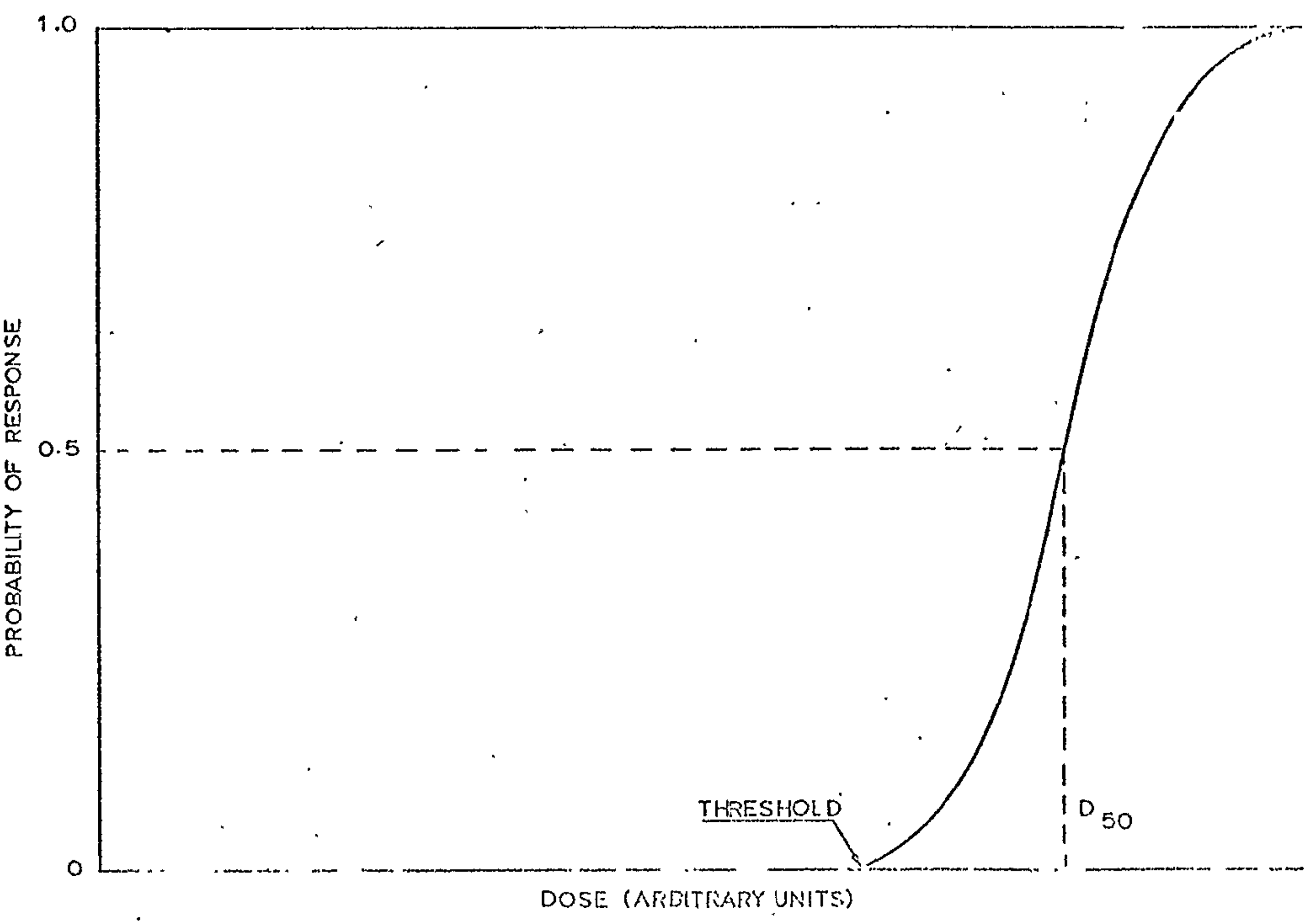
A generalized standard of dosage or hygienic standard follows:

a) Plus or Minus: The maximal time weighted average concentration which produces only minor injury, and that in a very small proportion of exposed workmen.

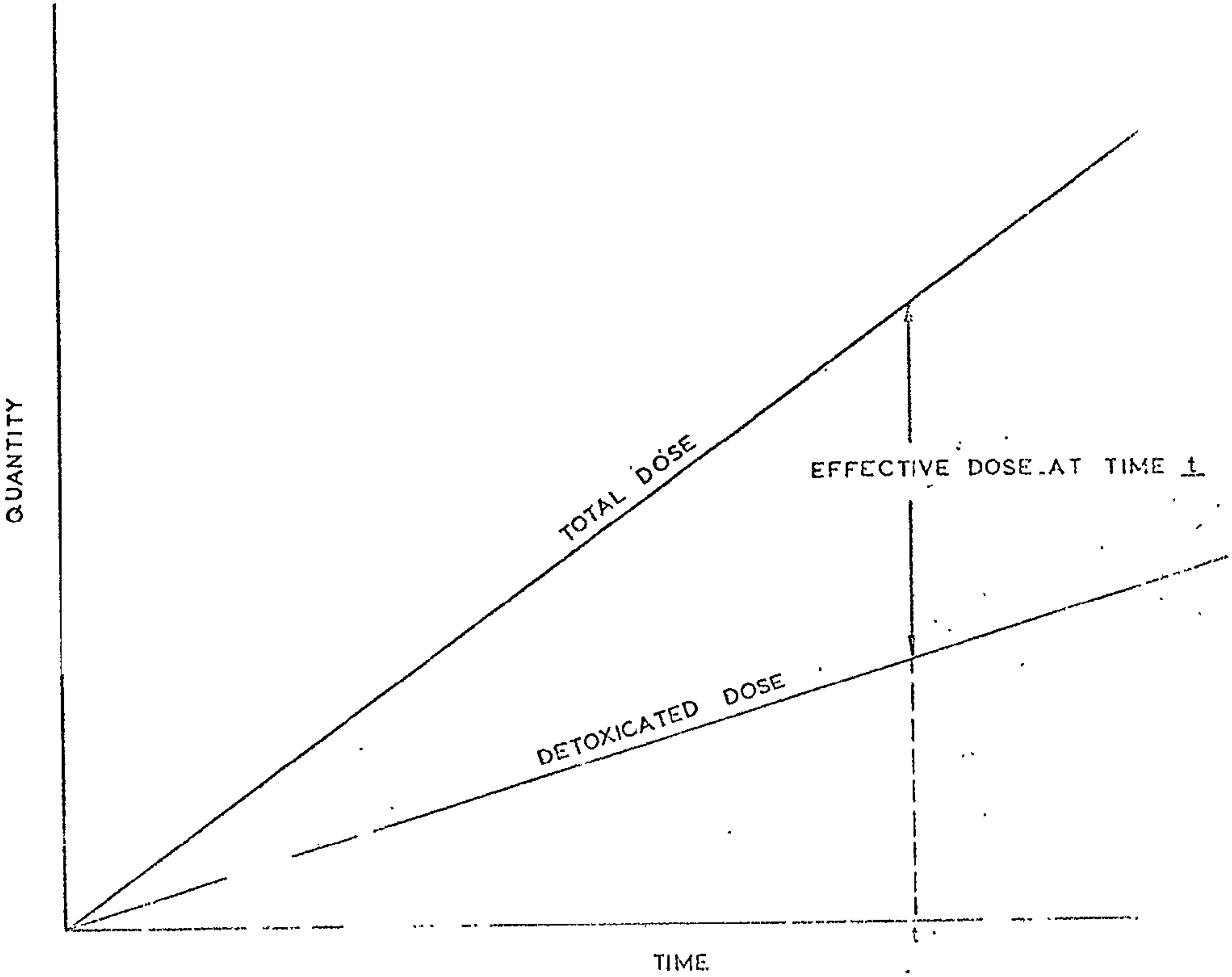
b) The "maximal time weighted average concentration" which sound evidence leads one to believe will cause no demonstrable illness or other symptoms of toxic effect in any workman during a lifetime of industrial exposure.



Linear Dose-Risk Relationship



Typical Non-Linear Dose-Response Relationship



Decrease in Effective Dose by Concurrent Detoxi

c) Bench Mark: A concentration based on the belief that any unnecessary exposure is undesirable - a concentration lower than that of a or b, one as low as is consistent with practical engineering control.

d) Comfort: A concentration lower than a or b, representing the maximum which in a short time is not objectionable to 9 out of 10 of a group of persons not accustomed to inhalation of fluorine.

B.1.2 Rocket Operation with Toxics

A measuring program should be designed to provide micrometeorological data. This would allow a qualitative and quantitative estimate of air diffusion. These data could be sorted into categories typical of various pollution conditions and then by considering actual operating factors pollution concentrations could be predicted. The "Diffusion Index" in Section B.1.3 is intended as a controlling tool for this operation.

The gross pollution characteristics of a rocket firing requires continuing effort to devise adequate methods for predicting pollution. Transport and removal properties of the atmosphere for meteorological control is currently the only feasible method.

The basic mathematical analysis for air pollution stems from the Sutton diffusion equations. The typical atmospheric release situation is a long term continuous low level point source such as smoke stacks. The U.S. Weather Bureau adapted these diffusion equations for AEC use for their instantaneous, high level volume source type nuclear weapons testing. Consideration was also given to the inadvertent rupture of a power re-actor. This is the instantaneous release of a large quantity of high temperature particles.

Combustion of missile propellants, however, involves a release situation somewhere in between the two extremes: that is, a short term continuous intermediate volume source. The temperature of the exhaust product varies over a wide range, from near ambient in the case of a test stand with a water cooled flame deflector to about 3000°K when the booster is launched.

The Chemical Corps Operations Research Group Study NR 17 titled "Atmospheric Diffusion and Generalized Munitions Expenditures" contains considerable information which can be reoriented and applied to this problem. Considerable field testing proved the dosage equations.

B.1.3 Diffusion Index Determination

1. Determine Stability Index $\text{S.I.} = \dfrac{T1 - T_2 \times 10^5}{\bar{u}^2}$

T_1 degrees centigrade upper level (32 meters)
T_2 degrees centigrade lower level (2 meters)
$\bar{V}$ · mean wind speed in cm. per sec.

2. These then define a stability nomogram with selected values tabulated below:

S.I. Value		Stability Category	Cx	Cy	Cz	n
above	-3.0	A	.44	.44	.44	.085
-3.0	-2.0	B	.35	.37	.33	.135
-2.0	-1.0	C	.25	.27	.22	.185
-1.0	-0	D	.17	.20	.14	.26
0	+1.0	E	.13	.16	.09	.39
1.0	+2.0	F.	.09	.14	.05	.58
2.0	3.0	G	.06	.12	.02	.67

3. The values of Cx Cy Cz and n are put into the Sutton equation

$$C_{(\text{at } x,\ y,\ z\ \&\ t)} = \frac{2\,Q}{\pi^{3/2}\,Cx\,Cy\,Cz\,(\bar{u}t)^{3/2\,(2-n)}}$$

$$\exp\left[-(\bar{u}t)^{\bar{n}-2}\ \frac{x^2}{Cx^2} + \frac{y^2}{Cy^2} + \frac{z^2}{Cz^2}\right] \quad \text{Ignore Exp for ℄}$$

In actual use the $(\bar{u}t)$ term is the down-wind distance of interest.
The term (2-n) becomes unity for center line by maximum concentrations.
Q is in milligrams = pounds x 453, 592
$(\bar{u}t)$ is distance in meters = miles x 1609
the result is directly in Mg/meter^3

Integration gives dosage as seen by a centerline observation point

$$D_{x,y,z,} = \frac{2Q}{\pi\ Cy\ Cz\ \bar{U}\ X^{2-n}}\ \exp\left[-x^{(\bar{n}-2)}\ \frac{y^2}{Cy^2} + \frac{Z^2}{C_Z^2}\right] \quad \text{Ignore Exp for ℄}$$

Where Q is in milligrams
$\bar{V}$ is in meters/second
x is in meters
C_x & C_y are as stated in the paragraph 2

B.2 TOXIC GAS ABSORPTION BY DEFLECTOR COOLING WATER

As discussed in the previous section, air pollution from the toxic exhaust gases is relative to use of FLOX on the S-IC. In the static firing case, the exhaust gases are impinging on the water cooled exhaust deflector.

A preliminary investigation was conducted to determine how effective the deflector coolant water is in absorbing the toxic hydrogen fluorine gas from the exhaust.

During static firing a total of 40,200 #/sec of water is pumped through approximately 60,000 holes 5/32-inch in diameter to cool the flame deflector. For a 30% FLOX concentration approximately 5800 lb/sec of HF gas is released in the exhaust.

Using this information, some basic calculations were made to show the effectiveness of the existing test stand system in reducing the HF release to the atmosphere. The results of these calculations are given in Figure (B-4). The best estimates of Boeing and MSFC engineers are that approximately 15% of the exhaust gases would mix with the coolant water. From Figure B-4, this would result in reducing the HF released to the atmosphere from 5800 #/sec to 4900 #/sec.

From these data, absorption of toxic gases by the existing deflector coolant system is rather insignificant and cannot be considered a major factor in reducing atmospheric pollution.

B.3 PRELIMINARY DESIGN WORK FOR BOIL-OFF GAS RECONDENSER

B.3.1 Background Information

One of the problems associated with using FLOX on the S-IC is that of disposing of the toxic boil-off gases from the stage oxidizer and storage tank. One method of promise is that of recondensing the gases and putting them back into the supply system or oxidizer tank. This would completely eliminate air pollution resulting from boil-off gases.

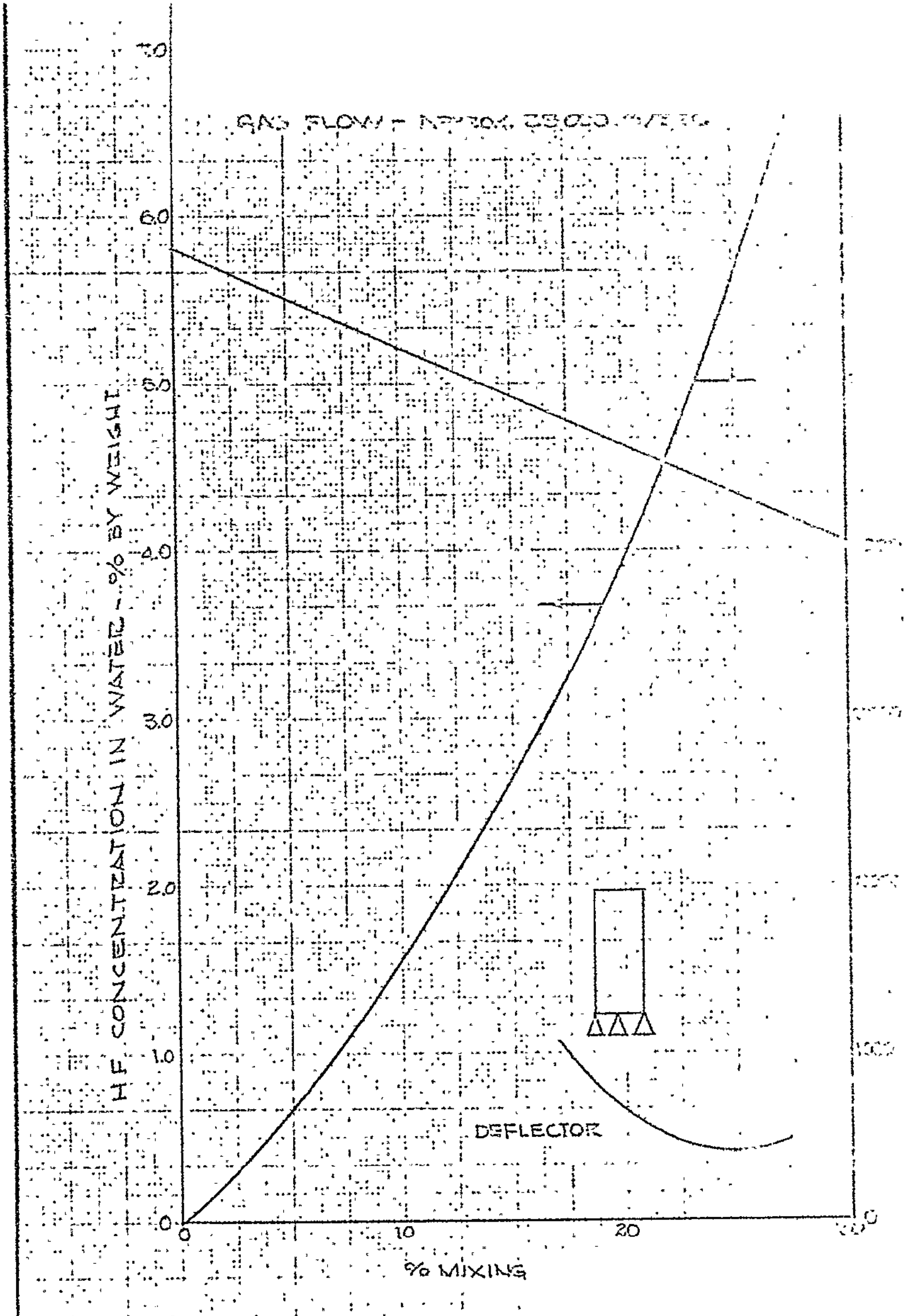
This section presented some preliminary design data pertinent to the development of a recondensing system.

B.3.1.1 FLOX Boiling Temperatures at Different Ullage Pressures - Figure B-5

The FLOX Boiling Temperature Curves were calculated as follows.
Assuming FLOX is a perfect gas, Raoult's Law states that:
For fluorine:

$$\left(\frac{\text{Vapor Pressure } F_2}{\text{Total Ullage Pressure}}\right)(\text{Volume Fraction F in Liquid}) = \text{Volume Fraction } F_2 \text{ in Gas} \quad (1)$$

$$\left(\frac{\text{Vapor Pressure } O_2}{\text{Total Ullage Pressure}}\right)(\text{Volume Fraction O in Liquid}) = \text{Volume Fraction } O_2 \text{ in gas} \quad (2)$$



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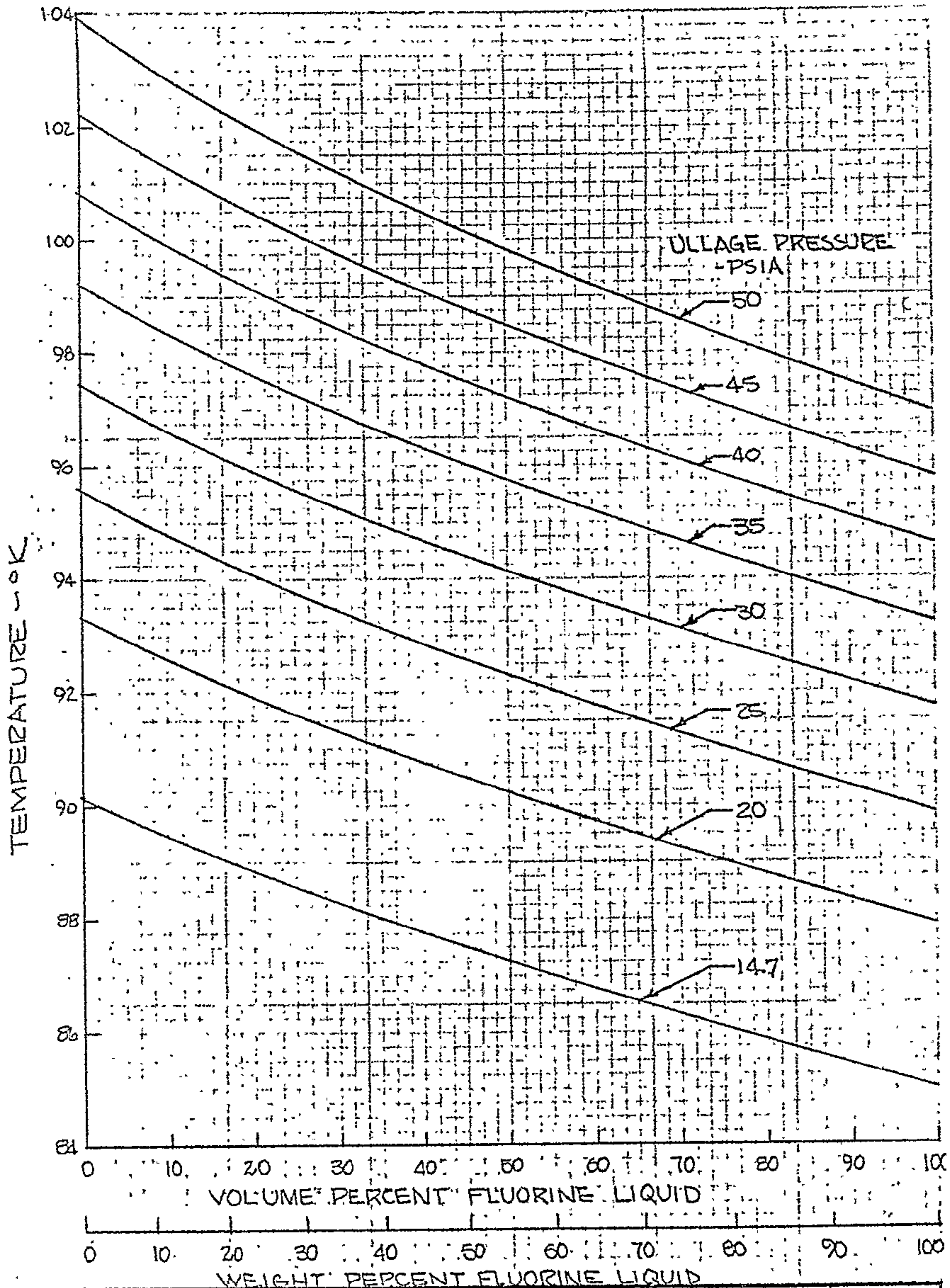

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Adding equations (1) and (2) and multiplying through by the total ullage pressure,

(Vapor pressure F_2) (Volume Fraction F in liquid) +
(Vapor pressure O_2) (Volume Fraction O in liquid) = Total Ullage Pressure

The method is to assume a particular temperature, find the vapor pressures from Figure C-21 and multiply the vapor pressure times its respective volume fraction. The sum of these products must then equal the total ullage pressure.

Sample Calculation

At 70% volume fraction F in liquid and 30% volume fraction O in liquid and total ullage pressure = 25 PSIA
Assume temperature = 91.33°K
(28.73 PSIA) (.7) + (16.3 PSIA) (.3) = 25.00 PSIA
Therefore, the assumption (91.33°K) was correct.

Discussion of Curves

Figure B-5 shows that the value of the boiling temperature increases with percent oxygen which has a higher boiling point than fluorine.

B.3.1.2 Heat Leak into S-IC Oxidizer Tank - Figure B-6

The heat leak was calculated based on the maximum boiloff rate of 72.5 $\frac{\text{lb}}{\text{sec}}$ from Reference 3 . It was assumed that this heat leak occurs at ambient temperature 530°R and pressure 14.7 psia. The heat leak was then calculated by assuming saturated LOX at 14.7 psia has a heat of vaporization of 91 $\frac{\text{BTU}}{\text{lb}}$ at a temperature of 162.3°R. If 72.5 $\frac{\text{lb}}{\text{sec.}}$ boiloff and it takes 91 BTU to boiloff one pound, then the heat leak is 6600 $\frac{\text{BTU}}{\text{sec.}}$ It is assumed that the heat leak into the tank is proportional to the temperature difference or numerically

$$6600 = K(530 - 162.3)$$

solving for K

$$K = 17.95 \ \frac{\text{BTU}}{\text{sec -°R}} \quad \text{assumed to be constant}$$

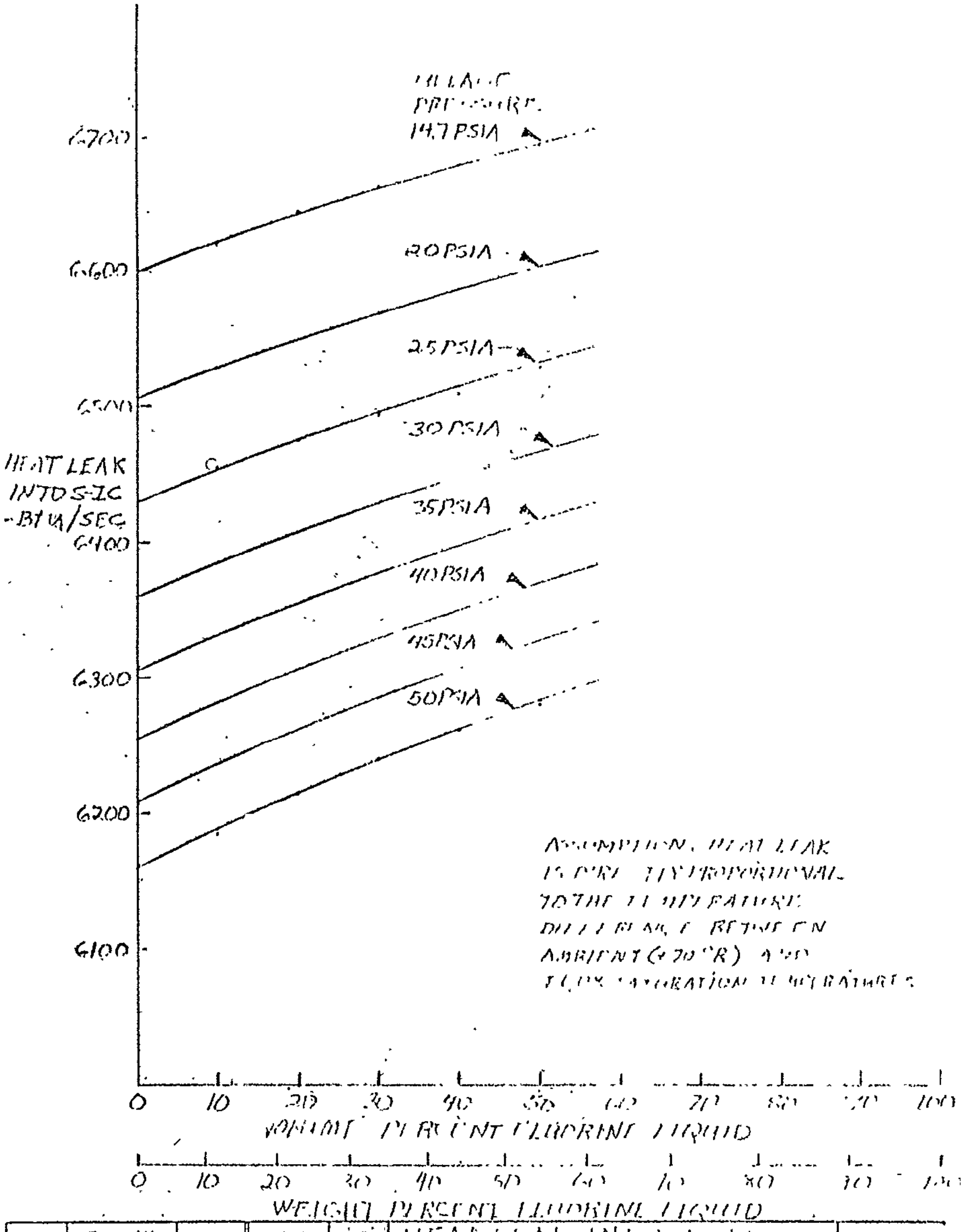
Sample Calculation

At 70% volume fraction F in liquid the saturation temperature at 25 PSIA is 164.5°R from Figure B-5.

$$\text{Heat Leak} = 17.95 \ \frac{\text{BTU}}{\text{sec °R}} \ (530°\text{R} - 164.5°\text{R}) = 6560 \ \frac{\text{BTU}}{\text{sec.}}$$

Discussion of the Curves

With the heat leak proportional to the temperature difference, the heat leak goes up as pressure and saturation temperature go down and also as % fluorine goes up.



ASSUMPTION: HEAT LEAK IS DIRECTLY PROPORTIONAL TO THE TEMPERATURE DIFFERENCE BETWEEN AMBIENT (470°R) AND FLOX SATURATION TEMPERATURES

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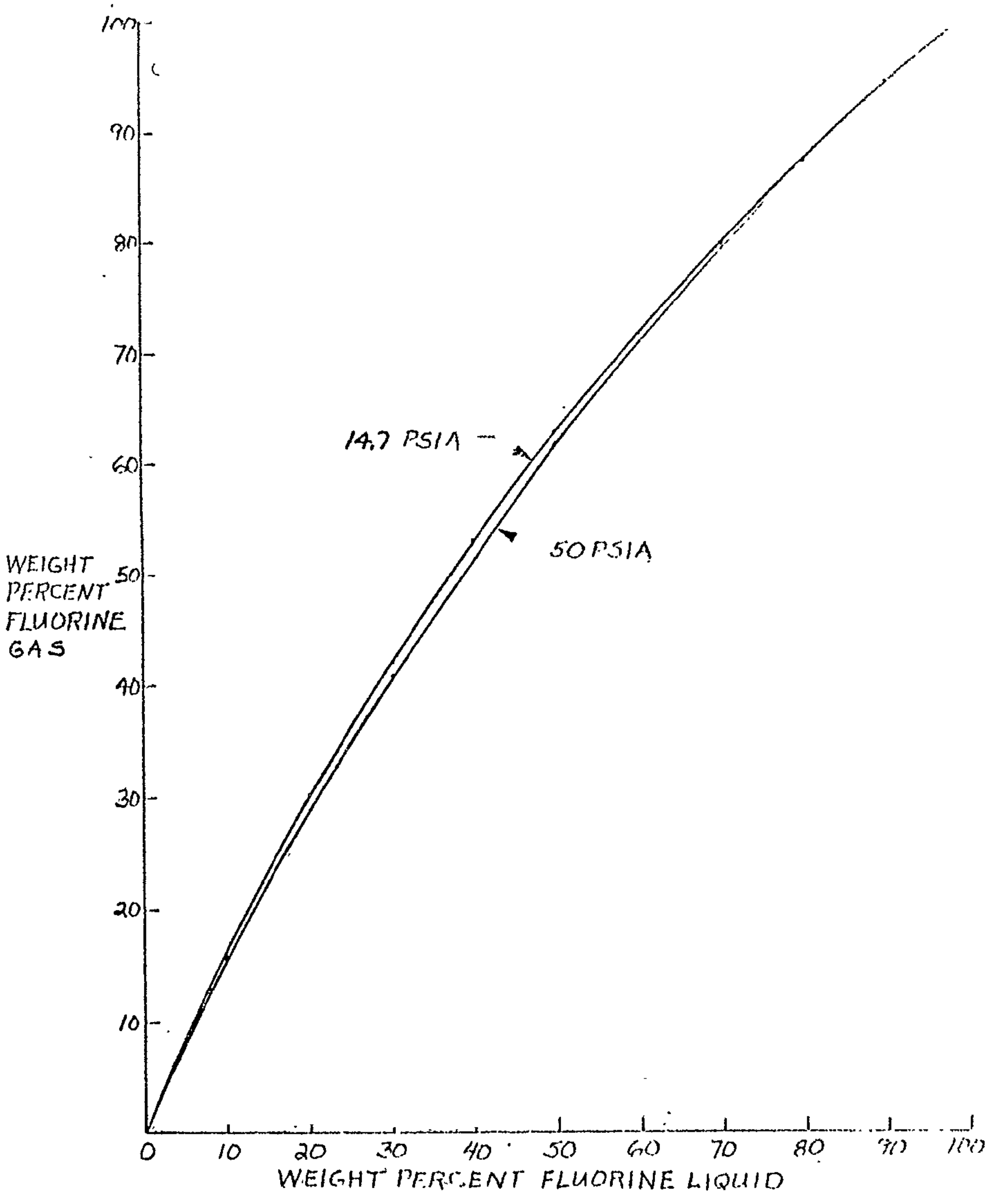

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BOILOFF GAS COMPOSITION
AT DIFFERENT ULLAGE
PRESSURES

THE BOEING COMPANY

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B.3.1.3 Boiloff Gas Composition Different Ullage Pressures - Figure B-7

The boiloff gas composition curves were calculated based on Raoult's Law which states:

$$\frac{\text{Vapor Pressure}}{\text{Total Pressure}} \text{ (Volume Fraction in liquid)} = \text{Volume Fraction in gas}$$

Conversion from weight percent to volume percent is accomplished as follows:

$$\frac{\dfrac{\text{Weight percent F}}{38 \text{ lb/mole}}}{\dfrac{\text{Weight percent F}}{38 \text{ lb/mole}} + \dfrac{100 - \text{weight percent F}}{32 \text{ lb/mole}}} = \text{volume percent F}$$

Conversion from volume percent to weight percent is accomplished as follows:

$$\frac{(\text{Volume percent F})\ 38 \text{ lb/mole F}}{(\text{Volume percent F})(38 \text{ lb/mole F}) + (100\text{-volume percent F})(32 \text{ lb/mole0})} =$$

$$\text{weight percent F}$$

Sample Calculation

At 70 percent weight percent fluorine liquid and 50 psia ullage pressure,

$$\frac{\dfrac{70\%}{38 \text{ lb}}}{\dfrac{70\%}{38 \text{ lb}} + \dfrac{30\%}{32 \text{ lb}}} = 66.3 \text{ volume percent } F_2 \text{ in liquid}$$

$$\text{and } \frac{57.5 \text{ psia}}{50 \text{ psia}} (66.3\%) = 76.25 \text{ volume percent } F_2 \text{ gas}$$

$$\text{and } \frac{(76.25\%)(38 \text{ lb/moleF})}{(76.25\%)(38 \text{ lb/moleF}) + (23.75\%)(32 \text{ lb/mole0})} = 79.2 \text{ weight percent}$$

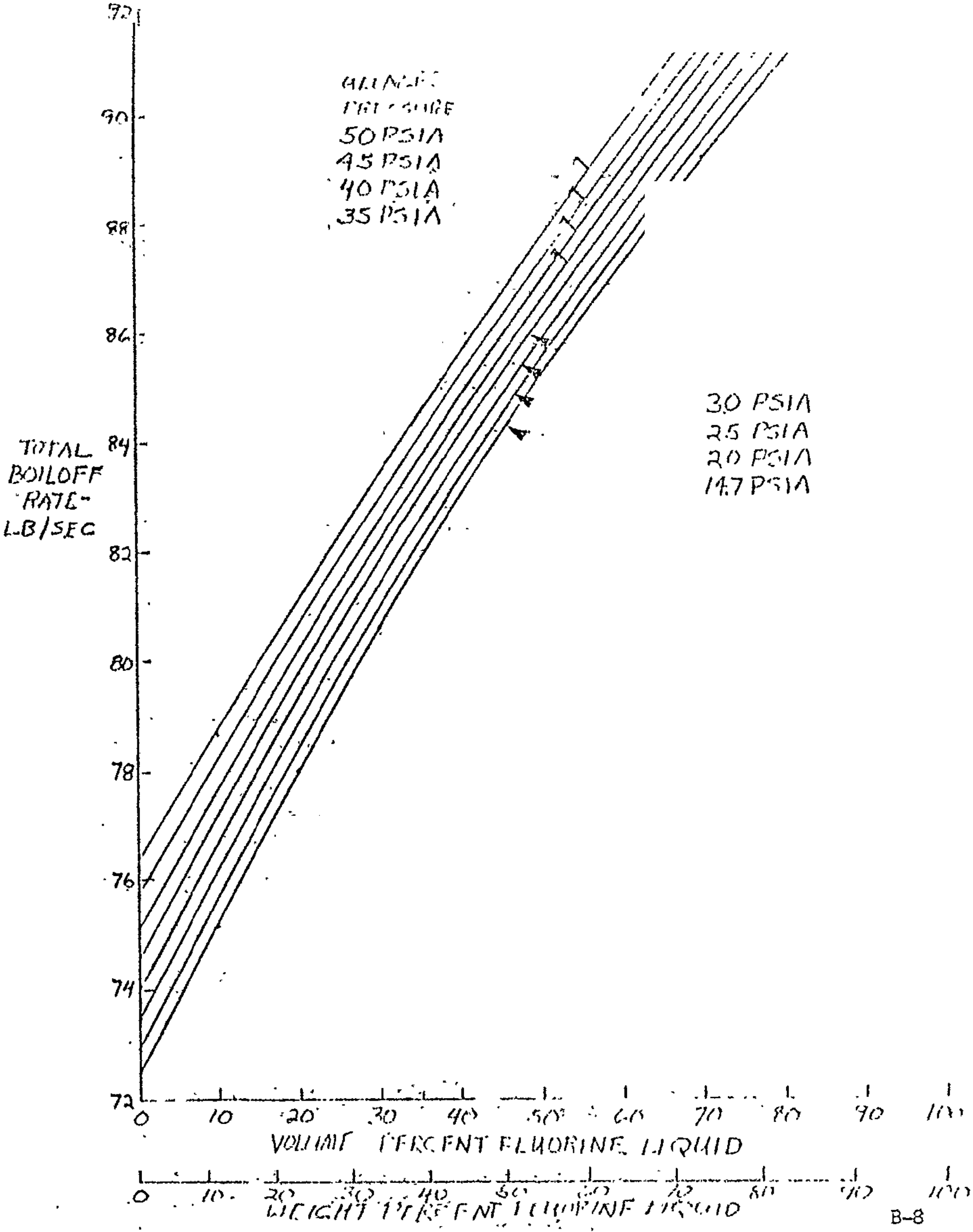
$$+ F_2 \text{ in gas}$$

Discussion of the Curves

The preferential boiloff is less pronounced as the pressure increases since eventually the composition of the boiloff gas must be the same as the liquid as the mixture approaches the critical pressure.

B.3.1.4 Boiloff Rate from S-IC - Figure B-8

The boiloff rate curves were calculated based on the heat leak curves, Figure B-6. The heat of vaporization curves, Figure C-21 and the boiloff gas composition, Figure B-7. The calculation for boiloff rate was performed as follows:



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TOTAL BOILOFF RATE
FROM S-IC

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$$\frac{\text{Total Lb Boiloff}}{\text{sec.}} = \frac{q}{H_F\ (\%\ F2) + H_O\ (\%\ O_2)}$$

Where

q = Heat Leak - BTU/sec

H_F = Heat of Vaporization of Fluorine - BTU/Lb

H_O = Heat of Vaporization of Oxygen - BTU/Lb.

Sample Calculation

At 70 percent weight percent and 50 psig, the heat leak equals 6319 $\frac{\text{BTU}}{\text{sec.}}$,

the weight percent F_2 gas equals 79.4 percent,
the weight percent O_2 equals 20.6 percent,
the heat of vaporization of F equals 64.5 $\frac{\text{BTU}}{\text{lb.}}$
the heat of vaporization of 0 equals 86.6 $\frac{\text{BTU}}{\text{lb}}$

solve for boiloff,

$$\frac{\text{Total lb. Boiloff}}{\text{sec.}} = \frac{6319\ \frac{\text{BTU}}{\text{sec.}}}{(64.5\ \frac{\text{BTU}}{\text{lb}})(.794) + (86.6\ \frac{\text{BTU}}{\text{lb.}})(.206)}$$

$$\frac{\text{Total lb. Boiloff}}{\text{sec.}} = 91.5\ \frac{\text{lb.}}{\text{sec.}}$$

Discussion of Curves

The curves show that total boiloff rate increases with the percent fluorine since it takes fewer BTUs to vaporize a pound of fluorine than it does to vaporize a pound of oxygen. The curves show that total boiloff rate increases with the pressure since the heat of vaporization decrease is much more pronounced than the ΔT decrease between saturation and ambient temperature.

B.3.1.5 Basic Liquefaction Methods

There are three basic liquefaction methods:
(1) Constant Pressure Cooling
(2) Compression and Adiabatic-Reversible Expansion
(3) Compression and Constant Enthalpy Expansion
Since compression of gaseous FLOX is nearly impossible because of the corrosive effects of FLOX on the compresser parts,method (1) will be considered first. A Flow Diagram for a condenser with NO Gas Compression is shown in Figure B-9 and general T-S and P-H Diagrams for a cycle with No Gas Compression are shown in Figure B-10 and B-11.

The total system is divided into processes which can be conveniently diagrammed and mathematically handled. These processes are lettered in Figure B-9 and are briefly discussed below.

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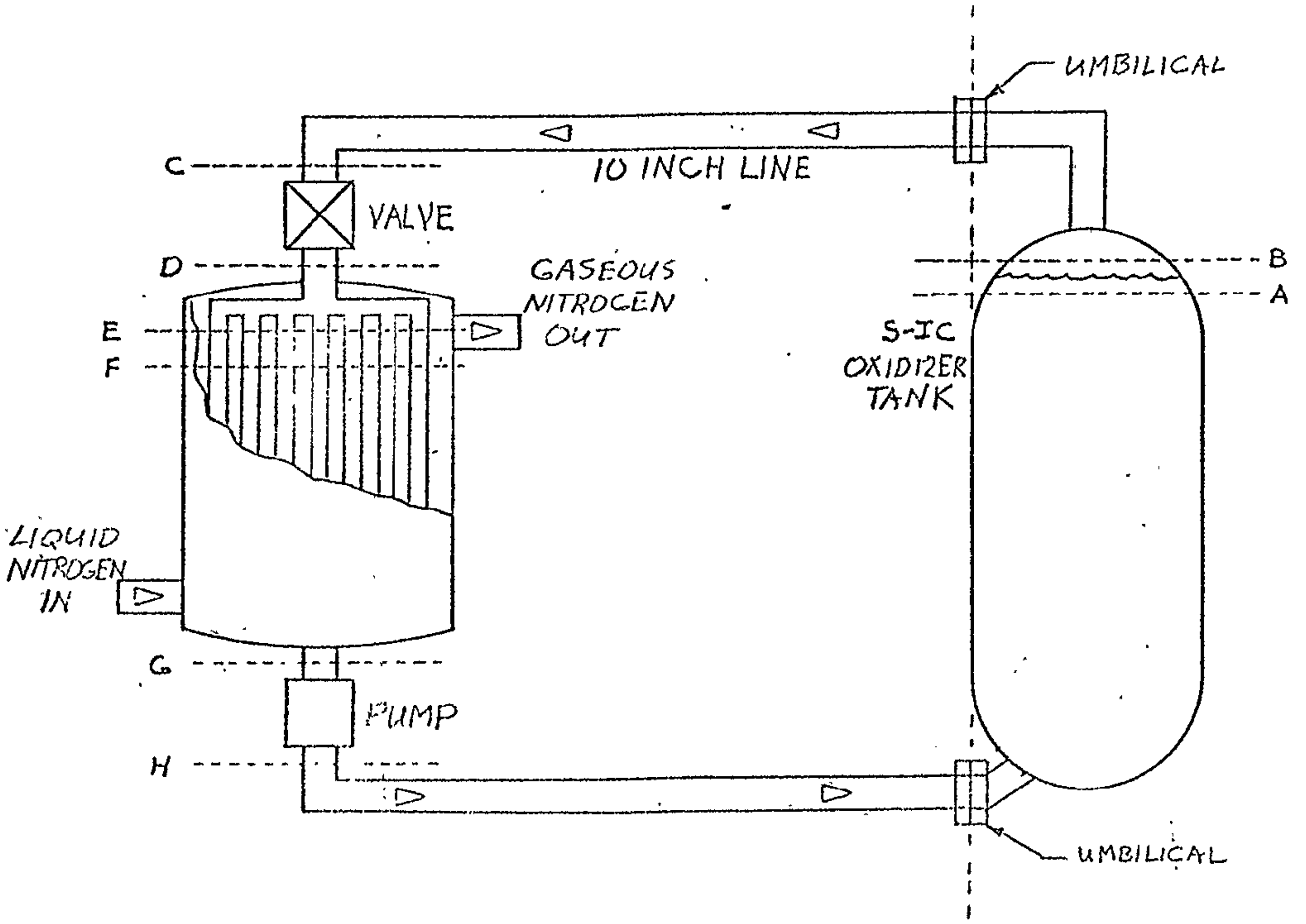
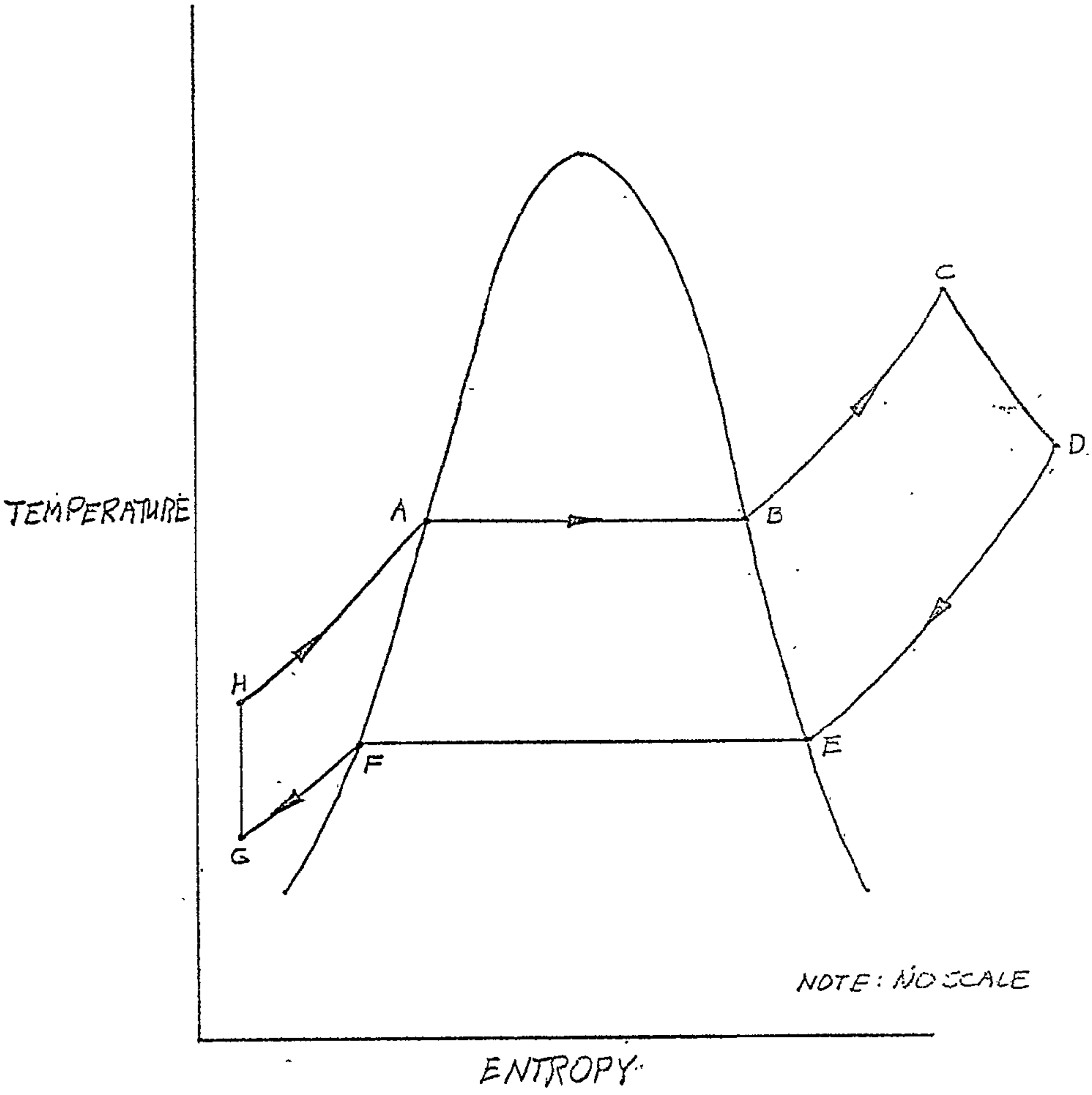


SYSTEM SCHEMATIC



T-S DIAGRAM FOR RECONDENSER

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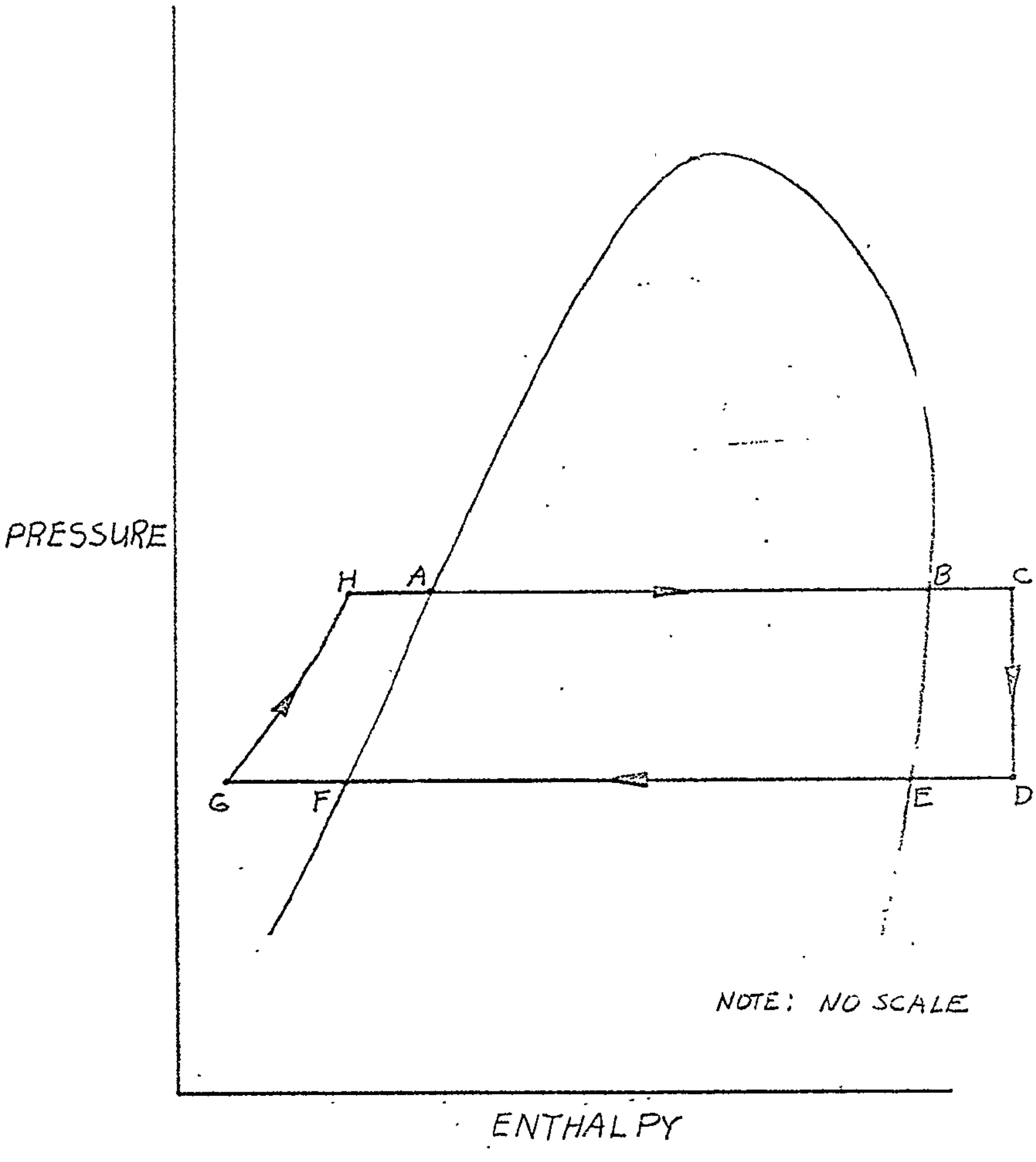


P-H DIAGRAM FOR RECONDENSER

Process A - B

Process A - B is boiling at constant pressure. This process occurs at the liquid surface and along the sides of the S-IC oxidizer tank and occurs at the ullage pressure which will be a constant at steady state boiloff. The required ullage pressures for use with different FLOX mixtures are not known at the present time. Consequently, the calculations have been made at the highest pressure implying the largest recondenser.

Process B - C

Process B - C is heat additon at constant pressure. This process occurs in the transfer lines and the tank between the boiling surface and the valve which is assumed to control the pressure drop.

Process C - D

Process C - D is expansion at constant enthalpy which is a good approximation of expansion through a valve.

Process D - E

Process D - E is cooling at constant pressure and occurs in the recondenser until the gas reaches saturation conditions.

Process E - F

Process E - F is the actual condensation process which occurs in the recondenser. The worst case is condensation at the lowest pressure which results in the lowest temperature and the highest amount of heat to be removed from the FLOX. The lowest temperature results in a minimim ΔT between the FLOX and its coolant fluid. The ΔT is the driving function in heat transfer. This results in less heat transfer per pound of nitrogen used. This area will be expanded in later sections.

Process F - G

Process F - G is subcooling at constant pressure and is necessary only if the Process G - H and H - A Process result in a state where the gas is not in at least a saturated condition. As shown by later calculations this process may be unnecessary depending on the launch pressure - temperature envelope for the oxidizer.

Process G - H

Process G - H is constant enthalpy compression which occurs in the pump which forces the condensed liquid FLOX back to the tank. This process also raises the temperature and increases the pressure to the ullage pressure.

Process H - A

Process H - A is heat addition at constant pressure similar to process B - C.

In addition to these brief cycle descriptions, actual P-H and T-S diagrams should be constructed for the processes. Since there are no data available on FLOX P-H and T-S diagrams, fluorine and oxygen P-H and T-S diagrams must be used. Figure B-12 is a T-S diagram for a compresser with No Gas Compression based on the Oxygen T-S Diagram. Figure B-13 is a P-H Diagram based on the Oxygen P-H Diagram. Figure B-14 is a T-S Diagram based on the Fluorine T-S Diagram. Figure B-15 is a P-H Diagram based on the Fluorine P-H Diagram.

The following pages contain a sample calculation of the recondensing cycle on the fluorine T-S and P-H Diagrams.

As is shown by the two P-H diagrams, about 95% of the work which must be accomplished by the recondenser involves condensing of the boiloff gas. Therefore, in subsequent sections the calculations will be based on the heat of condensation only and the results will be projected to include the remaining small areas.

Sample Calculations (based on Fluorine T-Sand P-H Diagrams
Figures B-14 and B-15)

Process A - B

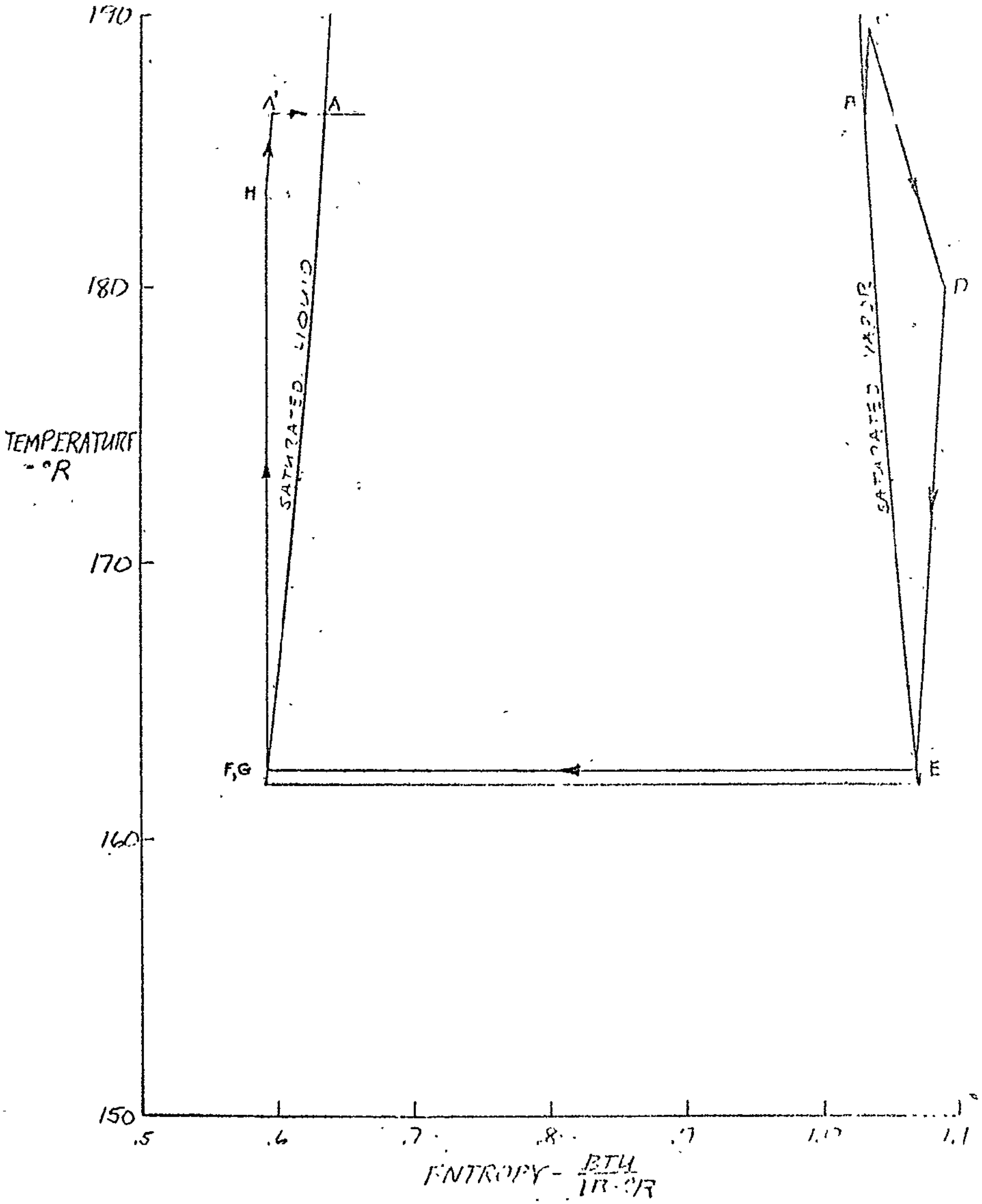
P_A = Ullage Pressure (independent variable)(14.7 - 50 psia)
%F = Weight Percent Fluorine Liquid (independent variable)(0-100%)
T_A = Saturation Temperature at P_A and %F (See FLOX boiling Temperature Figure B-5)
M_A = Mass of Boiloff Gas Per Second (See Boiloff Rate from S-IC Figure B-8)(80 lb/sec)
$\dot{Q}_{A-B}$ = Heat Input at P_A and %F (See Heat Leak into S-IC Oxidizer Tank Figure B-6)

Equation:

$$\Delta H_{A-B} = \frac{\dot{Q}_{A-B}}{M_A} \qquad \Delta H_{A \to B} = \frac{\text{Heat of Vaporization}}{\text{Lb}}$$

Process B - C

$P_B = P_A$ (50 psia)
$T_B = T_A$ (174.7°R)
$M_B = M_A$ (80 lb/sec) saturated vapor
$\dot{Q}_{B-C}$ = Heat Input to Transfer Line, for 10" line
10 BTU/Hr-Ft for vacuum jacketed *
100 BTU/Hr-Ft for insulated *
1000 BTU/Hr-Ft for uninsulated *
* Reference (4).
Line Length 50 ft. if on LUT
200 ft. if on Pad



B-12

CALC	T.E. OTAHAN	9-14-64	REVISED	DATE	TS DIAGRAM FOR CONDENSER WITH NO GAS COMPRESSION BASED ON OXYGEN TS DIAGRAM (REF. 5)
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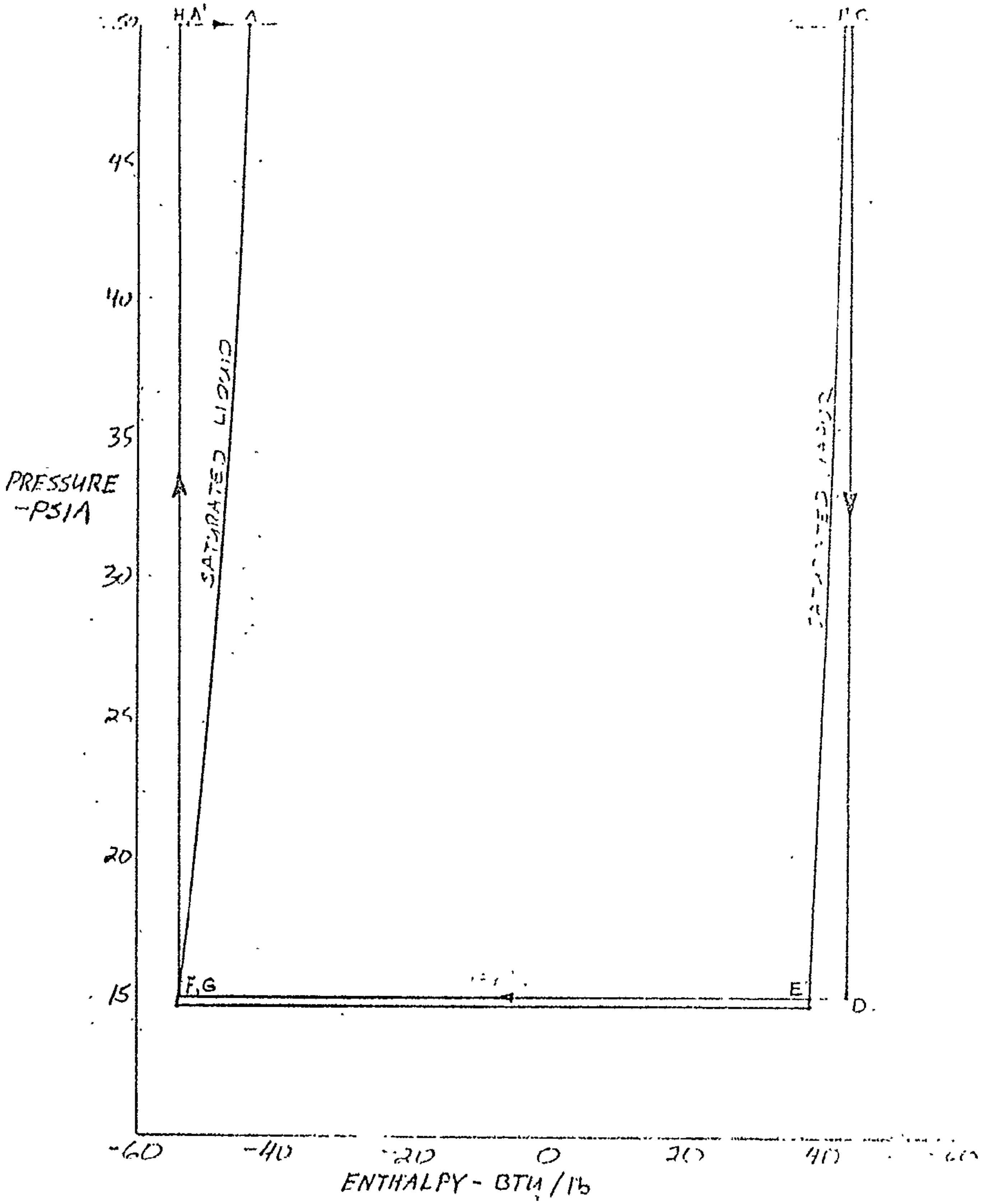

B-13

CALC	T.F. O'FALLON	7-22-64	REVISED	DATE	P-H DIAGRAM FOR CONDENSER WITH NO GAS COMPRESSION BASED ON [illegible] P-H DIAGRAM (REF.5)
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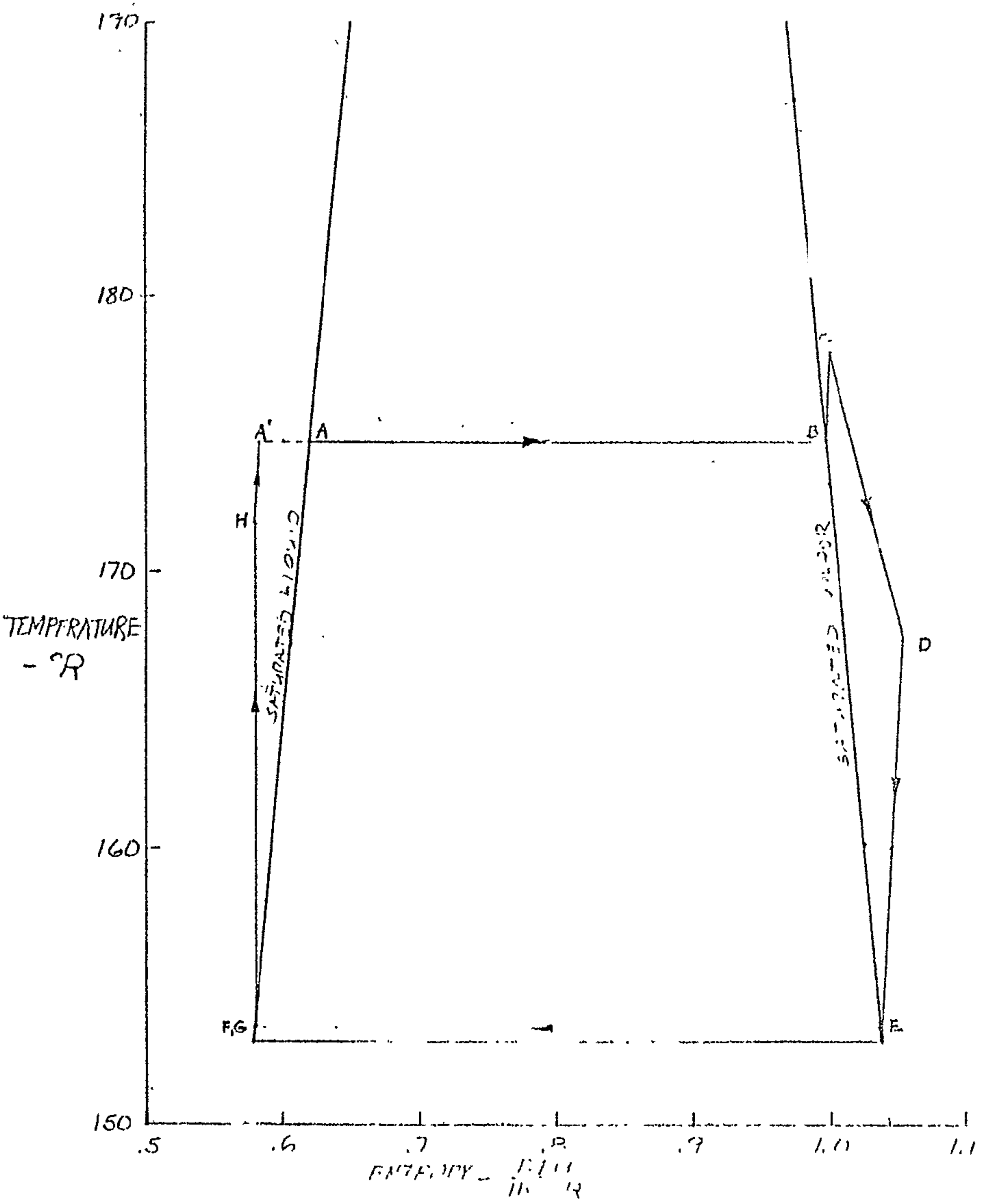

B-14

CALC	T.E. O'TALLON	7-19-64	REVISED	DATE
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T-S DIAGRAM FOR CONDENSER
WITH NO GAS COMPRESSION
BASED ON FLUORINE [illegible] DEGREES)
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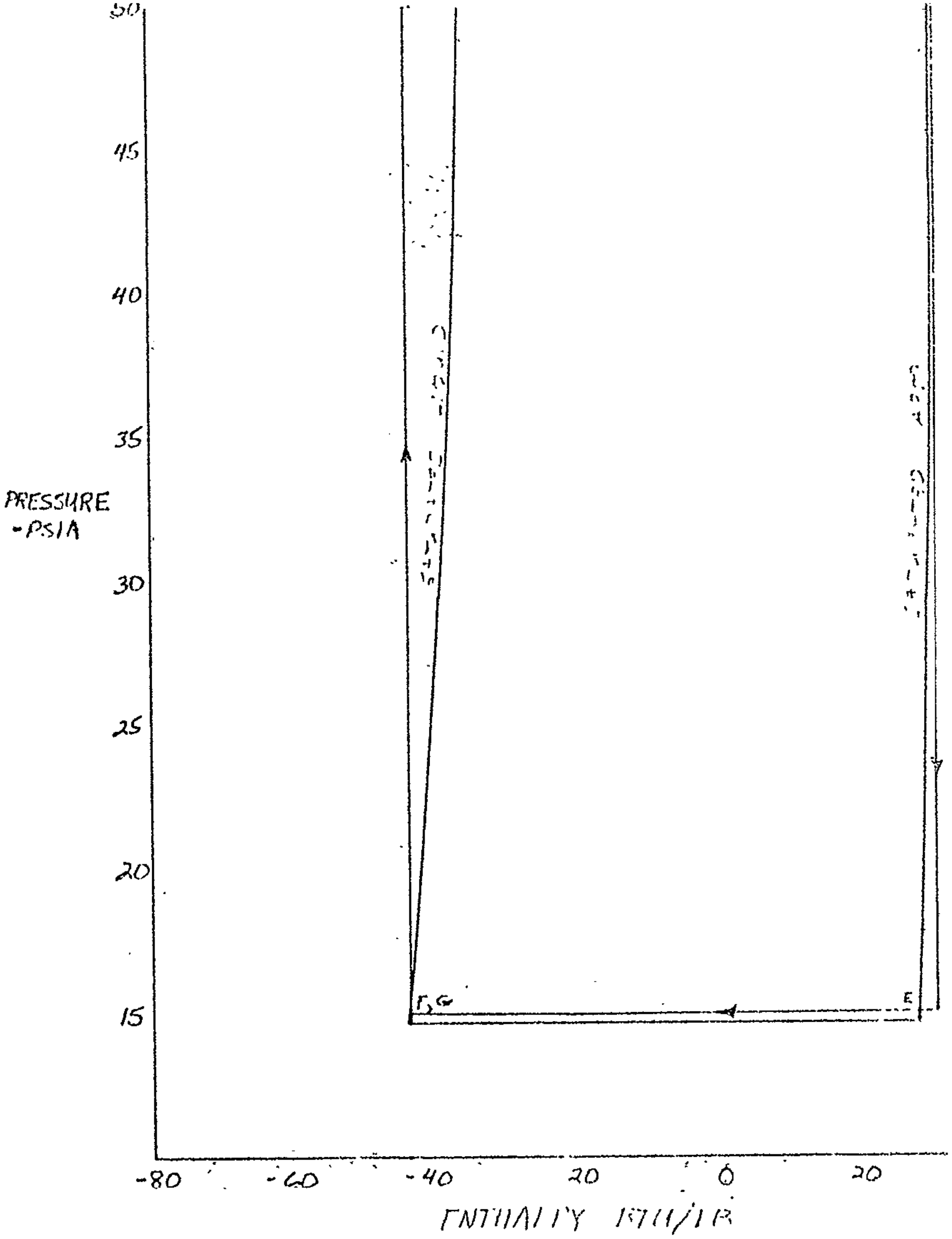

CALC	T.E.O'FALLON	9-15-64	REVISED	DATE	P-H DIAGRAM FOR CONDENSER WITH NO GAS COMPRESSION
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Therefore QB-C = 0.14 BTU/SEC for vacuum jacketed line to recondenser on LUT
1.4 BTU/SEC for insulated line to recondenser on LUT
14.0 BTU/SEC for uninsulated line to recondenser on LUT
0.56 BTU/SEC for vacuum jacketed line to recondenser on PAD
5.6 BTU/SEC for insulated line to recondenser on PAD
56.0 BTU/SEC for uninsulated line to recondenser on PAD

Equation:

$$\Delta H_{B-C} = \frac{QB\text{-}C}{MA}$$

and at constant pressure

$$\Delta H_{B-C} = Cp(T_c - T_B)$$

or and from T-S or PH Diagram find T_c based on ΔH_{B-C} (178°R from Figure B-14)

Therefore

$$T_c = \frac{\Delta H_{B-C}}{Cp} + T_B$$

$$Tc = \frac{QB - C}{M_A \ Cp} + T_B \ (178°R)$$

Process C - D

$P_C = P_A$ (50 psia)
Tc = 178°R (Based on Process B - C)
$Mc = M_A$ (80 lb/sec) superheated vapor

Equation:

$$\Delta H_{C-D} = 0$$

Therefore T_D can be determined from T-S diagram

Process D - E

P_D = 15 psia (Ambient plus to prevent ingassing)
T_D = 167.5 (Based on Process C-D).
$M_D = M_A$ (80 lb/sec) superheated vapor

Equation at constant pressure

$$\Delta H_{D-E} = Cp\ (T_D - T_F)$$

or T_E can be determined from T-S diagram.

Therefore

$$T_E = T_D - \frac{\Delta H_{D-E}}{Cp}$$

Process E - F

P_E = 15 psia (Ambient plus to prevent ingassing)
T_E = 153.5°R (Based on Process D - E)
$M_E = M_A$ (80 lb/sec) saturated vapor

Equation:

$$\Delta H_{E-F} = \frac{Q_{E-F}}{M_A} \qquad \text{or} \quad \Delta H_{E-F} = -\frac{\text{Heat of Vaporization}}{\text{Lb.}}$$

Process F - G

P_F = 15 psia (Ambient plus to prevent ingassing)
T_F = 153.5°R
$M_F = M_A$ (80 lb/sec) saturated liquid

Equation:

$$\Delta H_{FG} = 0^*$$

* Note: Process F - G is not necessary and states F and G are the same as shown on T-S and P-H diagrams.

Process G - H

P_G = 15 psia (Ambient plus to prevent ingassing)
T_G = 153.5°R
$M_G = M_A$ (80 lb/sec) saturated liquid

Equation:

$$\Delta S_{G-H} = 0$$

and from P-H diagram

$$\Delta H_{G-H} \approx 0$$

Process H - A′

P_H = 50 psia
T_H = 171.75°R (Based on T-S diagram)
$M_H = M_A$ (80 lb/sec) subcooled liquid

Equation:

$$\Delta H_{H-A'} = \Delta H_{B-C} = \frac{Q_{B-C}}{M_A}$$

and at constant pressu

$$\Delta H_{H-A'} = C_P \, (T_{A'} - T_H$$

Therefore: $T_{A'} = \dfrac{\Delta H_{H-A'}}{C_P} + T_H$

$$T_{A'} = \frac{Q_{B-C}}{M_A\,(CP)} + T_H = 174.7°R$$

Process A' - A

$P_{A'} = 50$ psia
$T_{A'} = 174.7°R$
$M_A = M_A = \dfrac{80\ \text{lb}}{\text{sec}}$ (subcooled liquid)

This process occurs within the tank and will not be further analyzed.

B.3.2 Sizing the Boiloff Gas Recondenser

There are many heat exchanger designs which can be used for recondensing the boiloff from the S-IC. Figure B-16 shows a horizontal shell and tube design in which the condensate is outside the tubes and the boiling nitrogen is inside the tubes. Figure B-17 shows a vertical shell and tube design in which the condensate is inside the tubes and the boiling nitrogen is outside the tubes. In this particular design, the FLOX boiloff gas is fed into the top of the tubes and drawn off at the bottom. The only problem with this heat exchanger design is the separation of any non-condensables such as helium. Figure B-18 shows a vertical shell and tube design in which the FLOX boiloff gas is fed in near the bottom and drawn off near the bottom. This allows the non-condensables to be drawn off at the top of the heat exchanger tubes. This design has another advantage. The FLOX gas inlet flow is opposing the condensate flow on the inside of the tubes. This will cause turbulent flow and an increase in heat transfer through the thinner film on the tube wall. This design, Figure B-18, will be used in the rest of the calculations.

B.3.2.1 Method for Calculating Number of Tubes

The following equations were used to size the heat exchanger for use in recondensing the FLOX boiloff gases from the S-IC.

$$q = U_o\, A\, \Delta T \qquad (1)$$

where

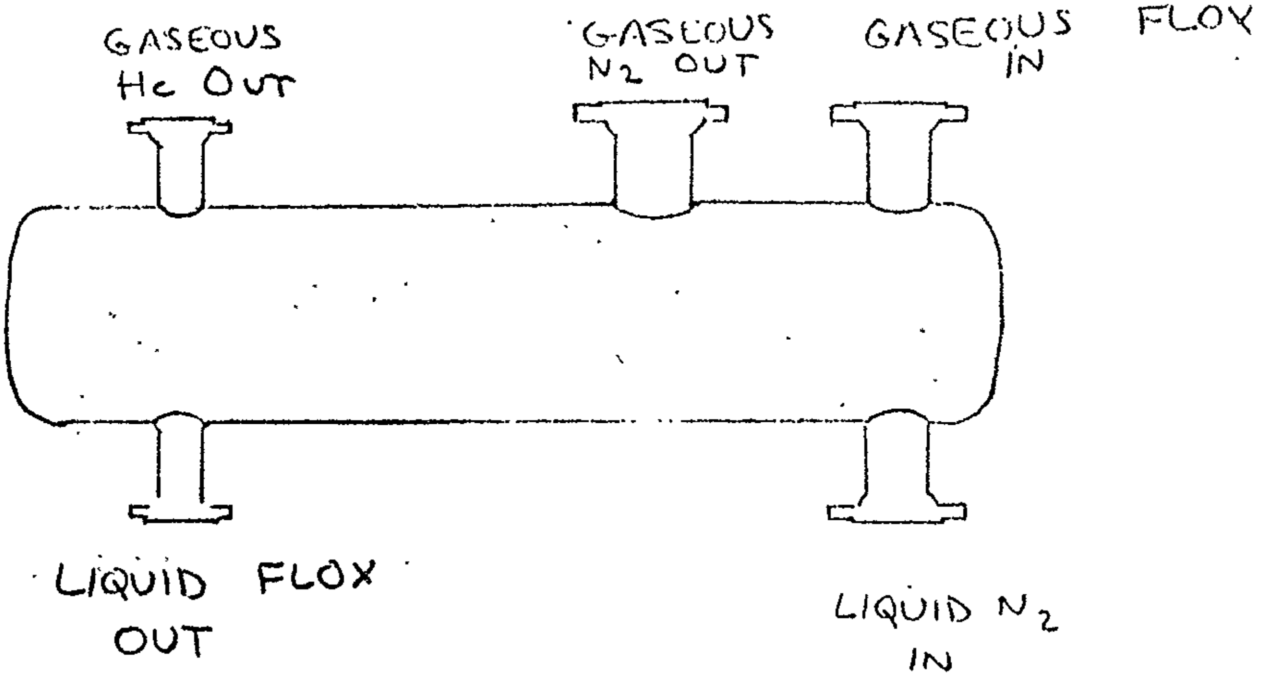
q = heat transfer in $\dfrac{\text{BTU}}{\text{hr.}}$

U_o = overall heat transfer coefficient in $\dfrac{\text{BTU}}{\text{hr.ft.}^2\,°R}$

A = effective heat transfer area in ft.^{2}

ΔT = temperature difference in °R

The problem is to define these terms and rearrange the equation to solve for the size of the recondenser.



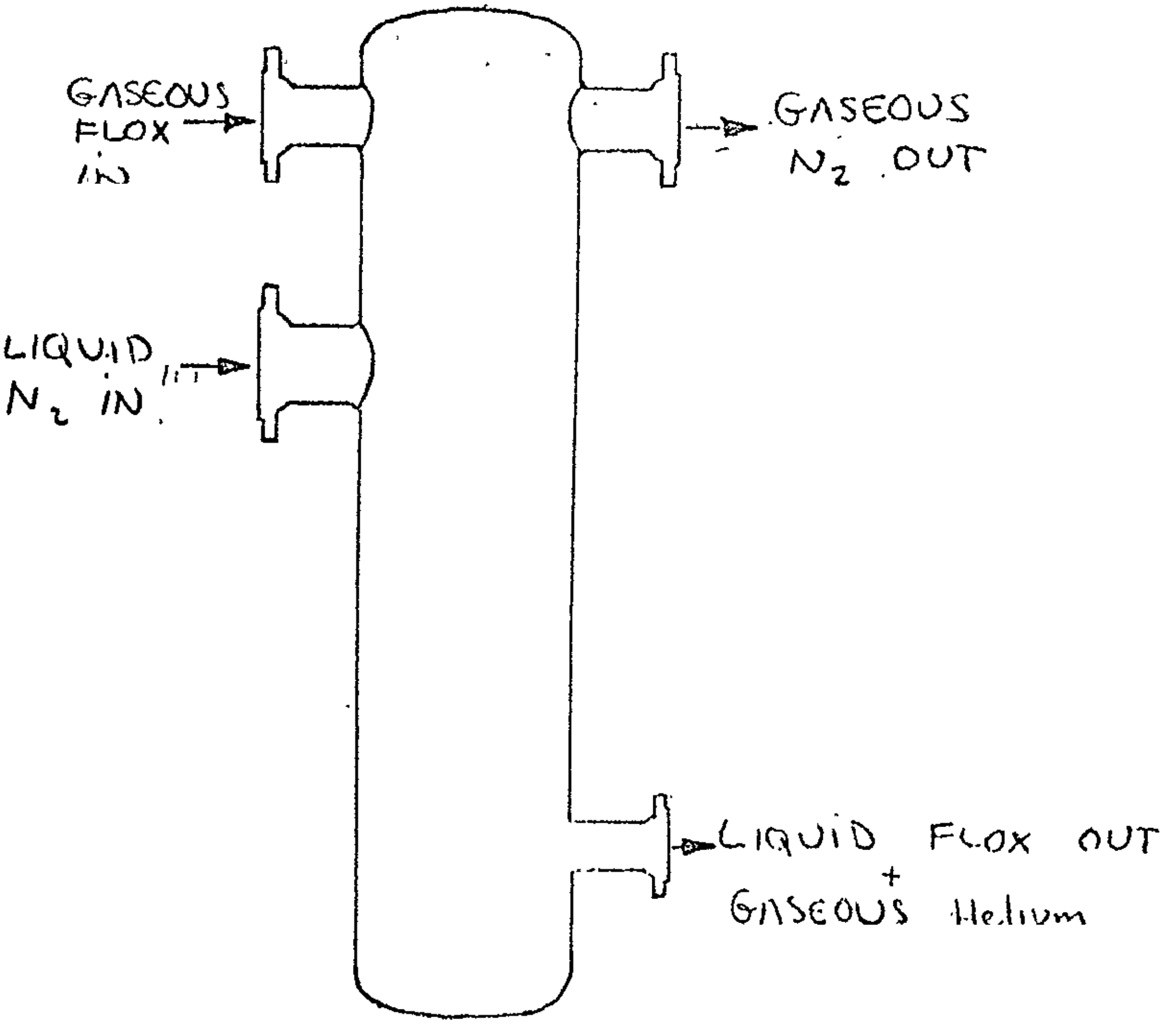
HORIZONTAL SHELL & TUBE HEA
EXCHANGER

CONDENSATE OUTSIDE TUBES.
BOILING LIQUID N$_2$ INSIDE TUB

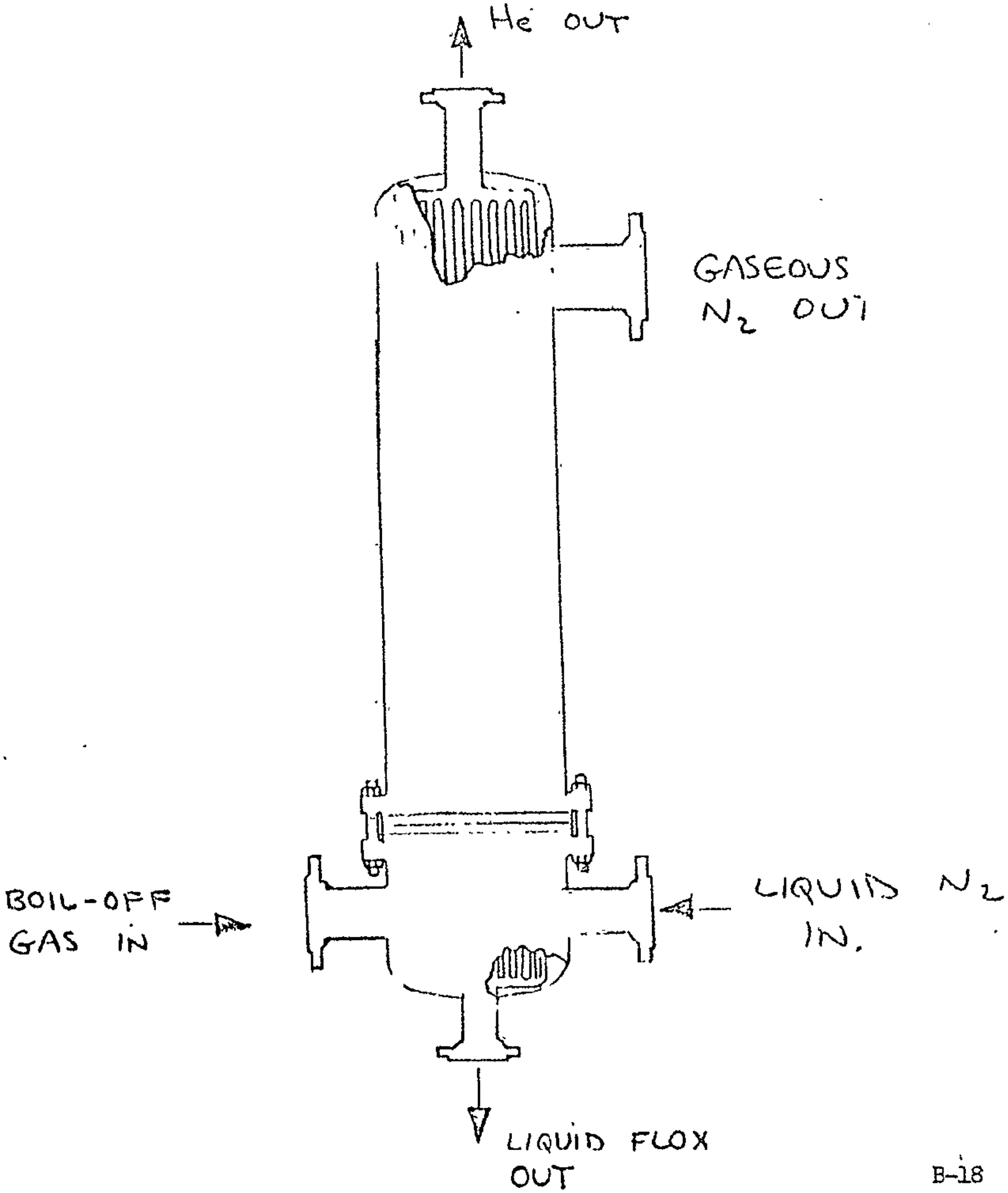
VERTICAL SHELL & TUBE HEAT EXCHANGER

CONDENSATE INSIDE TUBES

BOILING LIQUID N_2 OUTSIDE TUBES



VERTICAL TUBE HEAT EXCHANGER
CONDENSATE INSIDE TUBES.
BOILING LIQUID N_2 OUTSIDE TUBES



The heat transfer (q) required will be assumed to be equal to the heat transfer into the S-IC oxidizer tank as shown in Figure B-6. As shown in Figures B-12, B-13, B-14 and B-15, this represents about 95% of the heat transfer required and will be accurate enough for the remainder of the calculations.

The overall heat transfer coefficient will be calculated as follows. The major portions of the overall heat transfer coefficient are summed as follows:

$$\frac{1}{U_o} = \frac{1}{h\text{Flox}} + \frac{X}{K\text{tube}} + \frac{1}{h\ \text{nitrogen}} \qquad (2)$$

where

h_{flox} = heat transfer coefficient of condensing FLOX in $\frac{BTU}{hr.ft.^2 °R}$

X = tube wall thickness in ft.

K_{tube} = Thermal conductivity of the tube wall in $\frac{BTU}{hr.ft.°R}$

$h_{Nitrogen}$ = heat transfer coefficient of boiling nitrogen in $\frac{BTU}{hr.ft.^2 °R}$

The heat transfer coefficient of condensing FLOX (h_{flox}) is calculated as follows based on Ref.

$$h_{FLOX} = .0077 \left[\frac{4W}{\mu \pi D_i}\right]^{.4} \left[\frac{K^3 \rho^2 g}{\mu^2}\right]^{.33} \qquad (3)$$

where w = flow rate in lb/hr per tube

μ = viscosity in lb/hr.ft.

D_i = inside diameter of tube in ft.

K = thermal conductivity of FLOX in $\frac{BTU}{hr.ft.°R}$

ρ = density in $\frac{lb}{ft^3}$

g = acceleration of gravity in $\frac{ft.}{hr.^2}$

The flow rate (w) is taken from Figure B-8 which is the boiloff rate from the S-IC.

The viscosity (μ) is taken from Reference (5) and is calculated to be a weighted average value between oxygen and fluorine at the temperatures involved.

The inside diameter (D_i) of the tube is based on standard 1 inch outside diameter tubing and is equal to .075 ft.

The thermal conductivity (K) is taken from Reference (5) and is calculatec to be a weighted average value between oxygen and fluorine at the temperatures involved.

The density (ρ) is taken from Reference (5) and is calculated to be a weighted average value between oxygen and fluorine at the temperatures involved.

The acceleration of gravity (g) is constant at 4.18×10^8 ft/hr^2

The thickness of the tube (X) is based on standard 1 inch outside diameter tubing and is equal to .00416 ft.

The thermal conductivity of the tube (K_{tube}) is taken from reference (6) for 304 stainless steel and is an average value of 5 BTU/hr.ft°R for the temperature range.

The heat transfer coefficient of boiling nitrogen ($h_{nitrogen}$) is taken from Reference (7) for boiling nitrogen at 14.7 psia.

The effective heat transfer area (A) is calculated as follows:

$$A = n\pi D_o L \tag{4}$$

where n = Unknown number of tubes
D_o = Outside tube diameter in ft.
L = Tube length in ft.

The outside tube diameter (D_o) is assumed to be .0833 ft.

The tube length (L) is assumed to be 10 ft.

The temperature difference ΔT is calculated as follows:

$$\Delta T = T_{SAT\ FLOX} - T_{SAT\ NIT} \tag{5}$$

where $T_{SAT\ FLOX}$ = temperature of saturated FLOX the variable pressure and concentration
$T_{SAT\ NIT.}$ = temperature of saturated nitrogen at 14.7 psia.

The method continues by substituting equations 2, 3, 4 and 5 into equation 1.

$$q = \left[\frac{1}{\dfrac{1}{.0077\left[\dfrac{4\,W'}{n\mu\pi D_i}\right]^{.4}\left[\dfrac{K^3\rho^2 g}{\mu^2}\right]^{.33}} + \dfrac{X}{K_{tube}} + \dfrac{1}{h_n}}\right] \times \left[n\pi D_o\,L\right]\left[T_{SAT\ FLOX} - T_{SAT\ NIT}\right] \tag{6}$$

where W' = total flow rate in lb/hr

All the quantities in equation (6) are known at a particular FLOX pressure except the number of tubes (n). The resultant equation is a function of n and $n^{.4}$ and must be solved by iteration.

Sample Calculation

At 70% FLOX by weight and at a condensing pressure of 40 psia

$q = 2.304 \times 10^7$ BTU/hr
$w = 3.2472 \times 105$ lb/hr.
$\mu = .372$ lb/hr.ft.
$\pi = 3.1416$
$D_i = .075$ ft.
$K = .0821$ BTU/hr.ft.°R
$\rho = 82.6$ lb/ft.^{3}
$g = 4.18 \times 10^8$ ft./hr^2
$X = .00416$ ft.
$K_{tube} = 5$ BTU/hr.ft.°R
$h_n = 920$ BTU/hr.ft.^{2}°R
$D_o = .0833$ ft
$L = 10$ ft.
$T_{SAT\ FLOX} = 173.6$°R at 40 psia and 70% F by weight
$T_{SAT\ NIT} = 139.3$°R at 14.7 psia

Substituting into equation (6) and reducing $44250 = 89.8n + 2040\, n'^4$

solving by iteration n = 828 tubes

The results of this and numerous others like it are plotted in Figure B-19. Because of the magnitude of each calculation, only the predicted pressure extremes of the condenser operation are calculated defining an envelope. Since a safety factor will be used in actual sizing, this envelope is valuable as an order of magnitude gage.

Using standard 1 3/8 inch square pitch pattern for placement of tubes, a standard 48 inch diameter shell will hold approximately 380 tubes.

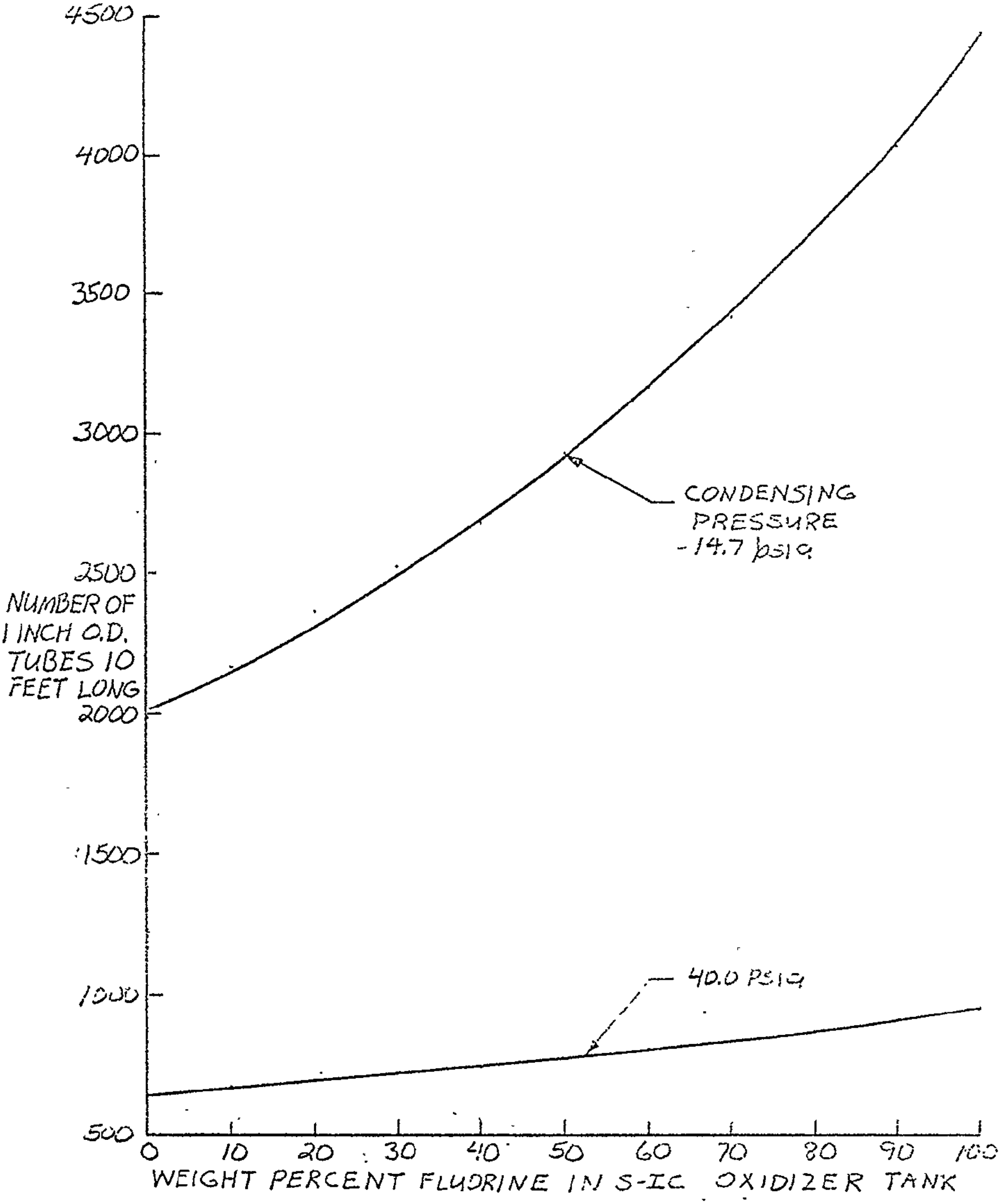
Based on the sample calculations above, it would take 3 of these standard units in parallel to recondense the FLOX boiloff gases. Each of these units would cost approximately $10,000.

B.3.2.2 Method of Calculating Pressure Drop

In order to show the feasibility of this type of a recondenser, system pressure drop must be calculated between the tank vent and the pump. This calculation must be divided into two parts (A) from the vent to the recondenser inlet and (B) to the pump.

Part A

$$\Delta P = \frac{f\ L\ G^2}{2\ g\ m\ \rho_{AVE}} \qquad \text{from Reference (8)}$$



RECONDENSER SIZE

B-19

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where

ΔP = pressure drop in lines in psf
f = friction factor
L = line length in ft.
G = mean mass velocity lb/sec ft.^{2}
g_c = acceleration of gravity in ft/sec^2
m = hydraulic radius$(\frac{D}{4})$ ft.
ρ_{AVE} = average gas density in lb/ft^3

The friction factor will be taken from the graph on page 811 of reference (8) but requires a knowledge of the Reynold's Number which is calculated using the following equation:

$$R_e = \frac{DV\rho}{\mu}$$

where

D = Diameter in feet
V = Velocity in ft/sec
ρ = Density in lb/ft^3
μ = Viscosity lb/ft.sec.

$$Re = \frac{\frac{(10)}{12}\ 85\ 144\ .31}{(12)(.31)\underset{10}{(100)}(.785)(.000004702)} = 277 \times 10^5$$

therefore, $f = .00155$

then,

$$\Delta P = \frac{(.00155)(200)(85^2)(144)^2}{(2)(32.2)(.208)(.31)(.785)^2 \cdot 100^2} = 1820 \text{ lb/ft}^2 \text{ or } 12.6 \text{ psi}$$

Part B

From Reference (9) the Martinelli-Lockhart Equations

$$\left(\frac{\Delta P}{\Delta L}\right)_{TP} = \phi_L^2\left(\frac{\Delta P}{\Delta L}\right)_L = \phi_G^2\left(\frac{\Delta P}{\Delta L}\right)_G$$

where

ΔP = pressure drop in psi
ΔL = tube length in ft.
ϕ_L = function of X in equation (2)
Subscript TP = two phase
Subscript L = liquid
Subscript G = gas

and

$$X^2 = \frac{(\Delta P/\Delta L)_L}{(\Delta P/\Delta L)_G} = \frac{(Re_G)^m C_L {W_L}^2 \rho G}{(Re_L)^n C_G {W_G}^2 \rho_2}$$

where R_c = Reynolds number
C = constant for particular type flow
m = constant for particular type flow
n = constant for particular type flow
W = flow rate in lb/sec
ρ = density in lb/ft.^{3}

Calculating R_e as on the previous page of this report

$Re_L = 2400$
$Re_G = 75{,}300$

then from Table 5.4 of Reference (9)

$m = .2$
$n = .2$
$C_L = .046$
$C_G = .046$

Substituting into equation (2) and solving for X

$$X^2 = \frac{(75{,}300)^{.2}\ (.046)(85)(0.31)}{(2400)^{.2}\ (.046)(85)(94)}$$

$X = .0882$

then from the Figure 5.7 of Referance (9)

$\phi_L = 24$
$\phi_G = 1.86$

Calculating the single phase pressure drops as on page 30 of this report

$$\left(\frac{\Delta P}{\Delta L}\right)_L = .00306\ \frac{\text{psi}}{\text{ft.}}$$

$$\left(\frac{\Delta P}{\Delta L}\right)_G = .515\ \frac{\text{psi}}{\text{ft.}}$$

Substituting in equation (1) and solving for the two phase pressure drop

$$1.76 < \left(\frac{\Delta P}{\Delta L}\right)_{TP} < 1.86\ \frac{\text{psi}}{\text{ft.}}$$

multiply by 10 feet

$$17.6 < \Delta P < 18.6 \text{ psi}$$

Therefore, the total pressure drop considering both Part A and Part B is approximately 30.7 psi. Adding this value to ambient pressure, we arrive at the approximate S-IC oxidizer tank pressure of 45 psia.

B.3.3 Effects on Other Systems

B.3.3.1 Storage

It is becoming apparent that because of transfer distances and the difference in requirements, the storage recondenser and the stage boiloff gas recondenser will be two separate recondensers. It will be much more economical to condense the storage boiloff in a smaller recondenser located very close to the storage tank itself. This recondenser will have less external area exposed to the atmospheric conditions resulting in lower liquid nitrogen requirements. It will also have less heat leak through the transfer lines resulting in lower nitrogen requirements. It will require less internal transfer area because of the difference in the boiloff rates from the storage tank and the stage oxidizer tank. The ratio is approximately 400 to 1. Because of these facts, the most efficient system design at the present time seems to be two separate condensers. Therefore, the stage boiloff gas recondenser will have no effect on the storage system as far as recondensing.

With a closed loop system, the boiloff from the stage will be returned to the stage eliminating the need for replenishing equipment. This would make it possible to resize the storage tanks and eliminate the replenishing pumps. One fact, the versatility of FLOX operation, still presents the possibility of LOX being used in which case it may be necessary to retain the present tanks and replenish lines.

B.3.3.2 Transfer

Transfer Lines

The only additional transfer lines that will be required are a large (approximately 10 - 12 inches) transfer line to direct the stage boiloff gases to the recondenser and a smaller (possibly the present replenish lines) to return the condensed liquid back to the stage. As is shown by the preliminary design work, the heat transfer through these transfer lines only represents a small part of the total heat input to the FLOX.

Umbilicals

A large, FLOX-compatible, quick disconnect umbilical coupling will definitely present one of the major problems to any proposal to recondense FLOX boiloff gases. This problem is mentioned but will not be discussed further as part of this section.

B.3.3.3 Stage Systems

The upper bulkhead of the S-IC oxidizer tank is constructed so that the vents are located 90° and 180° from the LUT. The upper bulkhead will have to be rearranged in order to locate at least one vent valve in a position compatible with the LUT and the umbilicals.

B.3.4 Comparison with Boiloff Gas Disposal

Disposal is the other method for handling the toxic boiloff gas from the S-IC stage. Several of the major problems still exist. Umbilical connections will have to be provided. Transfer lines will have to be provided to direct the boiloff gas to the disposal equipment which will have to be located much further from the launcher than the recondenser. Replenishing equipment will have to be provided to maintain the proper FLOX concentration in the oxidizer tank. The replenishing must be done at a different concentration than that required for fill because of the preferential boiloff of fluorine. The greatest savings from a recondenser can be seen in an example of the cost of the disposal of fluorine over a typical countdown time from FLOX loading to firing time. The present countdown sequence has LOX loaded and boiling for about 4½ hours before firing time. Let us assume that for a period of 4½ hours boiloff occurs at a nominal rate of 50 lb/sec. This amounts to 810,000 lb. of FLOX which must be disposed of. It has been derived earlier that the cost of disposing fluorine by burning with solid carbon is about \$.022/lb F_2 and the cost of disposing of oxygen by burning with solid carbon is about \$.052/ lb. O_2. The estimated cost of the fluorine itself is about \$.50/lb.F and the estimated cost of the oxygen itself is about \$.0176/ lb.O. Therefore, the cost of disposing the boiloff of a typical 70% fluorine launch can be determined as follows:

$$\begin{aligned}
\text{Total cost} &= (\text{lb.F})(\text{Cost F/lb.F}) = (810{,}000)(.8)(.50) = 324{,}000 \\
&+ (\text{lb.F})(\text{Cost C/lb.F}) = (810{,}000)(.8)(.022) = 14{,}260 \\
&+ (\text{lb.O})(\text{Cost O/lb.O}) = (810{,}000)(.2)(.0175) = 2{,}830 \\
&+ (\text{lb.O})(\text{Cost C/lb.O}) = (810{,}000)(.2)(.052) = 8{,}420 \\
\hline
&\qquad\qquad\qquad\qquad\qquad\qquad \$\ 349{,}510
\end{aligned}$$

For one launch, the disposal of the boiloff gases would cost about \$350,000 not including the cost of the charcoal reactor itself.

APPENDIX C

FLOX THERMODYNAMIC PROPERTIES

C.0 FLOX THERMODYNAMIC PROPERTIES

Physical, thermodynamic and transport properties of gaseous and liquid flourine-oxygen mixtures have been calculated. Properties of the mixtures were calculated by the rule of additivity based on the properties of pure components, $P_{12} = P_1^o X_1 + P_2^o X_2$, where the property of the mixture, P, is the summation of the products of property of the pure component P^o and its mole fraction X.

Rocketdyne (Reference (10)) has shown by the measurement of three unrelated properties (vapor pressure and liquid viscosity and density) that flourine-oxygen mixtures behave ideally. When the intermolecular forces in a solution are sufficiently independent of composition for ideal solution laws to hold, it is reasonable to assume that changes in temperature would affect all of these forces in very much the same way so that the properties of the individual molecules will remain practically independent of the composition. No one temperature has any specific significance in this connection and we may expect that if a solution is truly ideal at any temperature, it will be ideal throughout a range of temperature. The same may be said with respect to the effect of pressure. These suppositions are in accord with experimental data. Therefore, the extrapolation to higher temperatures and pressures in the absence of experimental data seems justified. Mixtures are shown as weight percentages, unless otherwise specified.

Viscosity: Data from References (11) and (12) were extrapolated to 500°K (Figures C-2 and C-3). The viscosity of gaseous oxygen at higher pressures and temperatures is shown for comparison (Figure C-4).

Thermal Conductivity:

The thermal conductivity of gaseous fluorine and gaseous oxygen are nearly identical over the measured temperature range. (Figure C-6) It is assumed that the experimental data for oxygen can be used to represent gaseous fluorine-oxygen mixtures. (Figure C-7 and C-8)

Specific Heat:

Data for gaseous fluorine-oxygen mixtures at higher pressures are not given but can be estimated from the oxygen curves in Figure C-13. Pressure effect on the specific heat at higher temperatures (to 3000°K) is insignificant (Reference(13)).

In several cases, where interpolations would only increase the complexity of the curves, only properties of the pure components are shown.

TABLE C-1

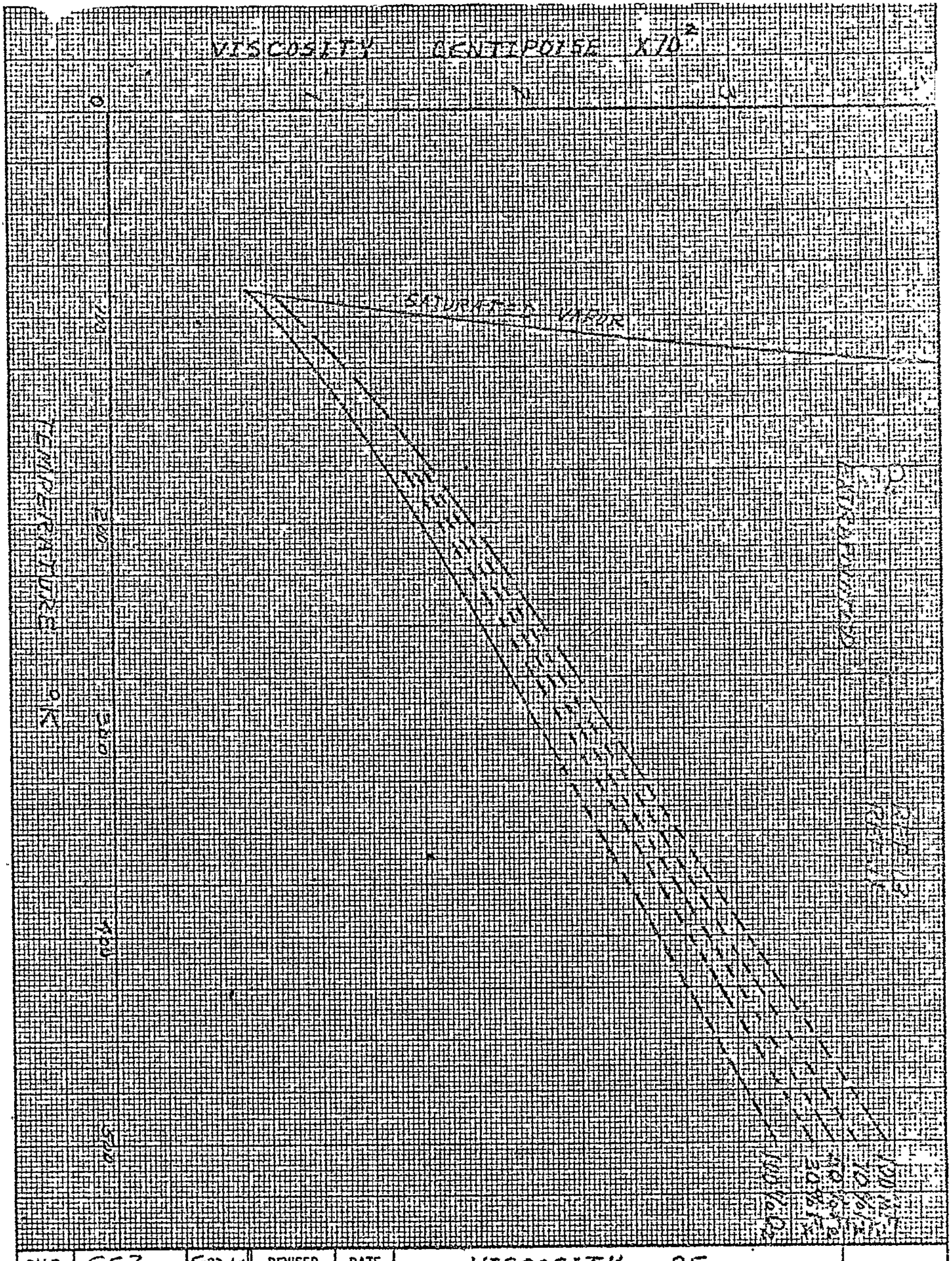
Viscosities of Fluorine-Oxygen Solutions at 76.2°K

F_2 Weight, Percent	Poise
0	2.91×10^{-3}
10.17	2.93×10^{-3}
30.02	2.96×10^{-3}
50.09	2.97×10^{-3}
70.38	3.01×10^{-3}
100	3.12×10^{-3}

TABLE C-2

Viscosities of Fluorine-Oxygen Solutions at their Normal Boiling Points

F_2 Weight, Percent	Boiling Point, C	Poise
10.2	-183.7	2.49×10^{-3}
30.0	-185.0	2.41×10^{-3}
50.1	-185.9	2.30×10^{-3}
70.3	-186.9	2.29×10^{-3}



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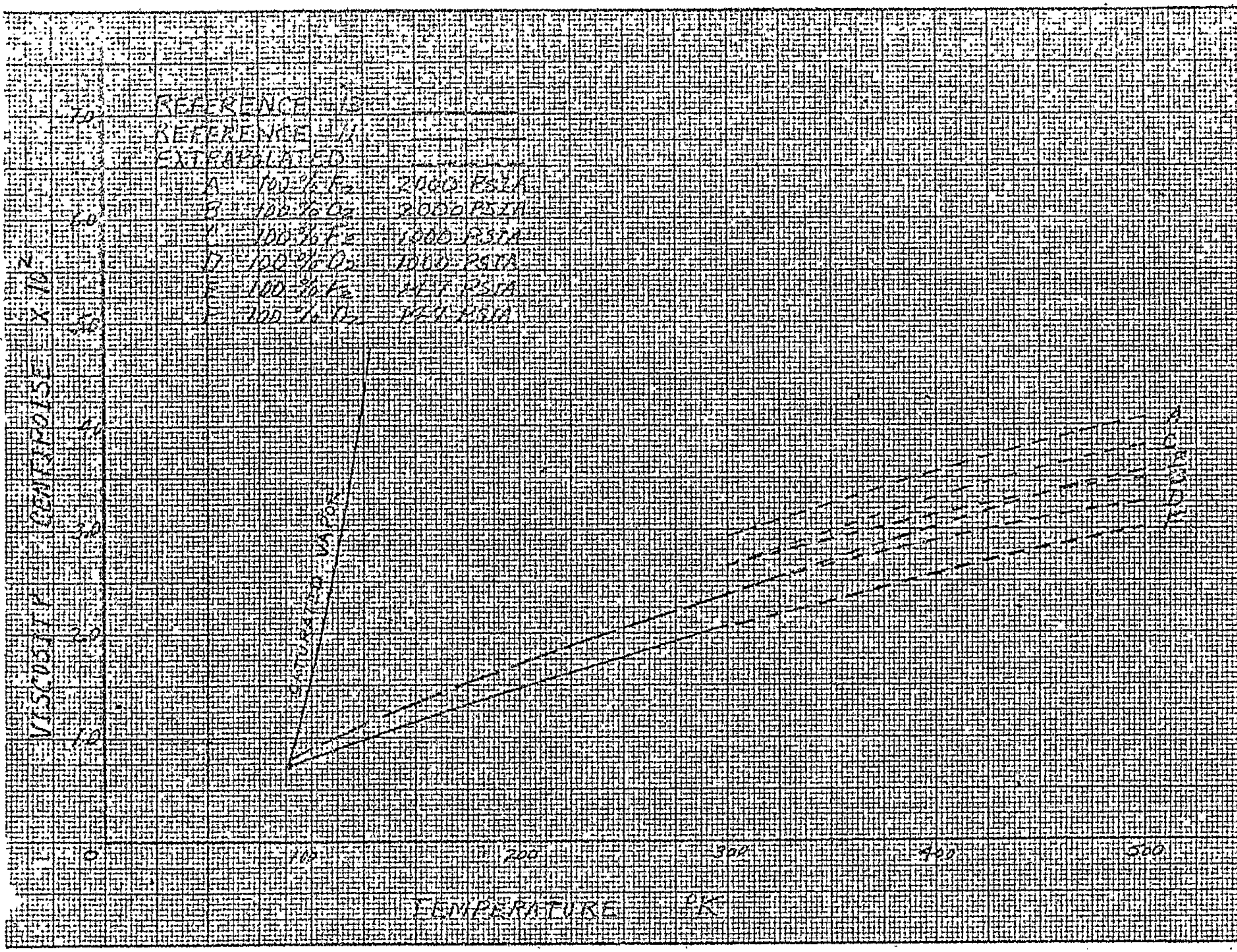

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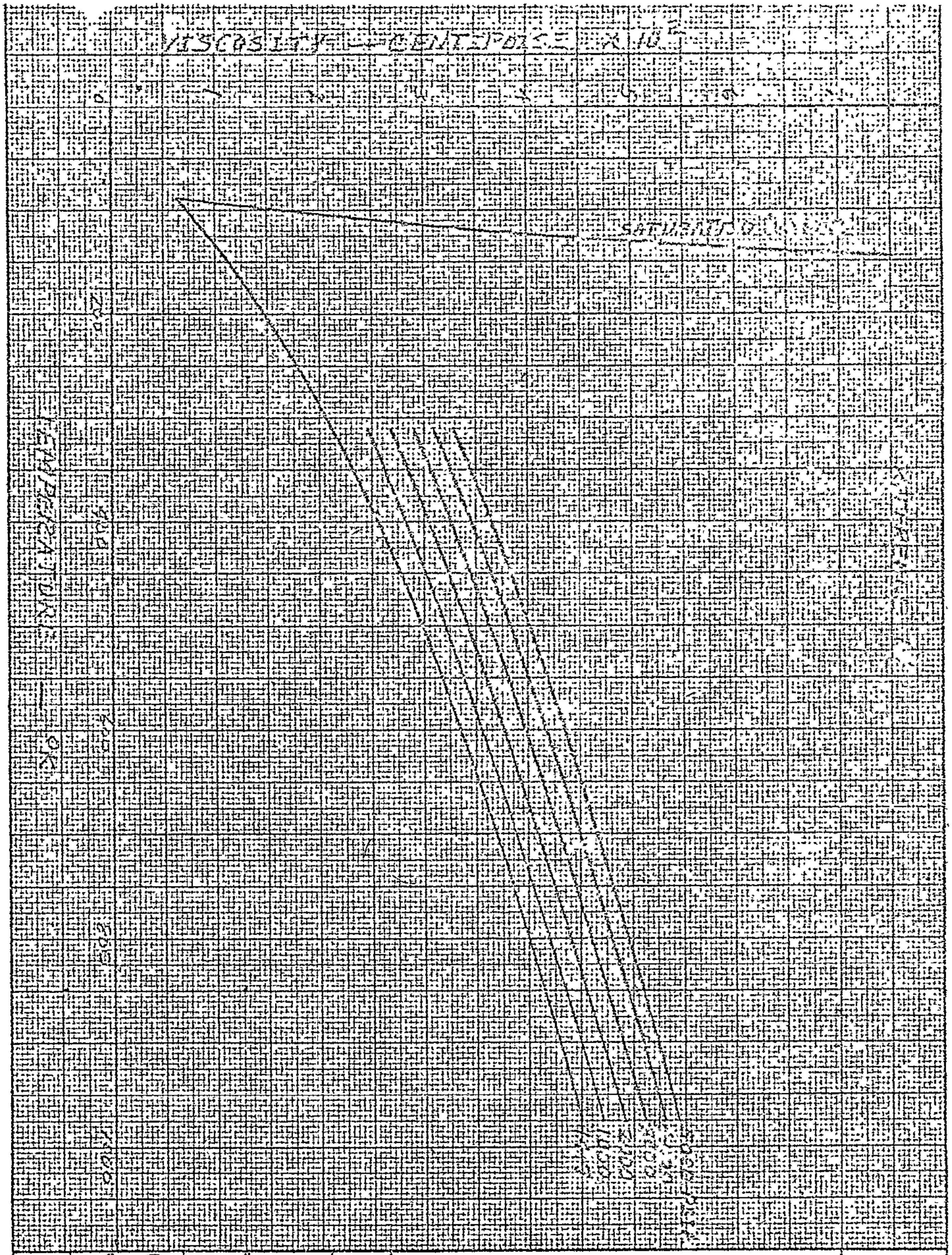

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VISCOSITY OF GASEOUS OXYGEN AT SEVERAL PRESSURES

C-4

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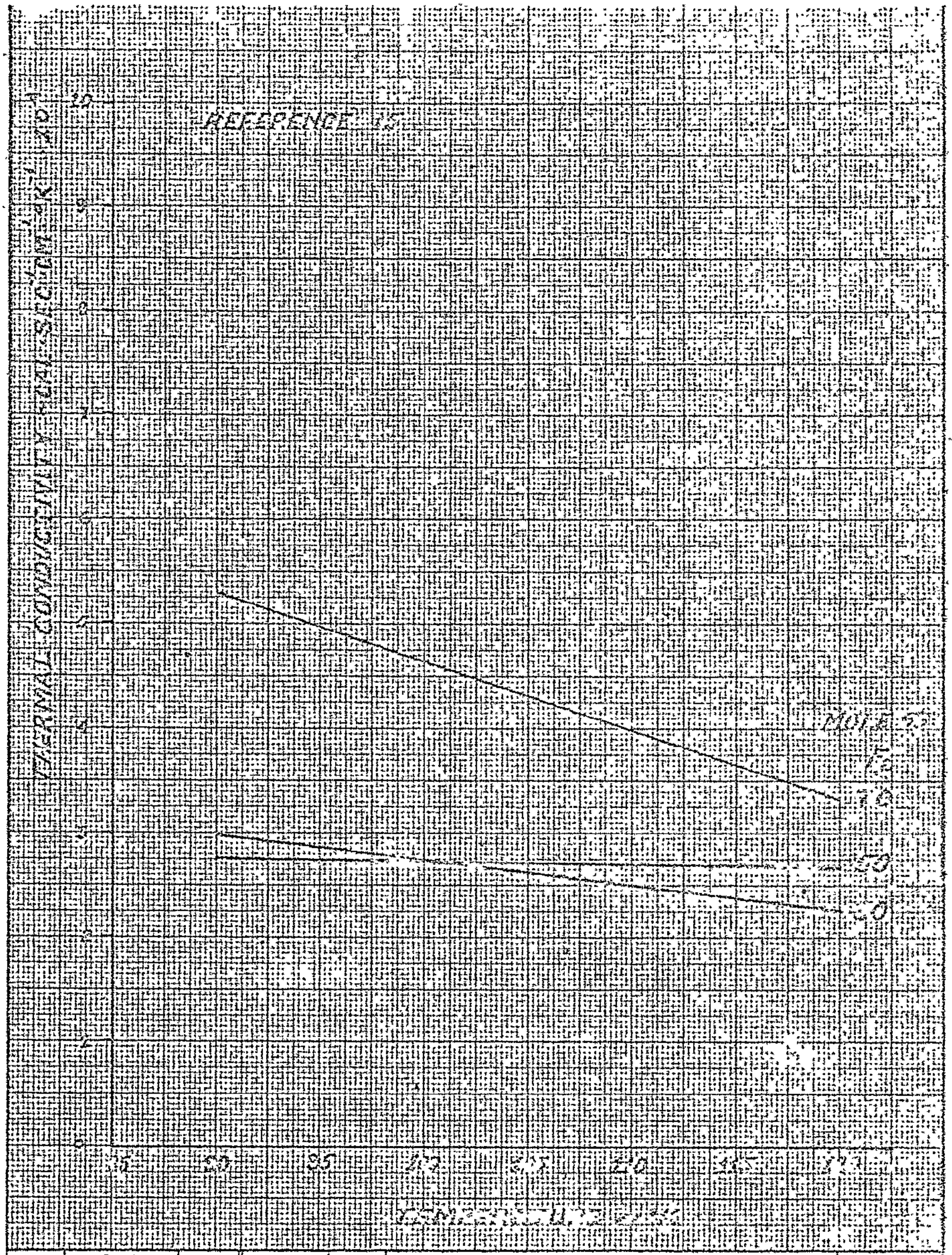

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THERMAL CONDUCTIVITY OF LIQUID FLUORINE - OXYGEN MIXTURES D5-11431-1

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THE BOEING COMPANY Sect. C

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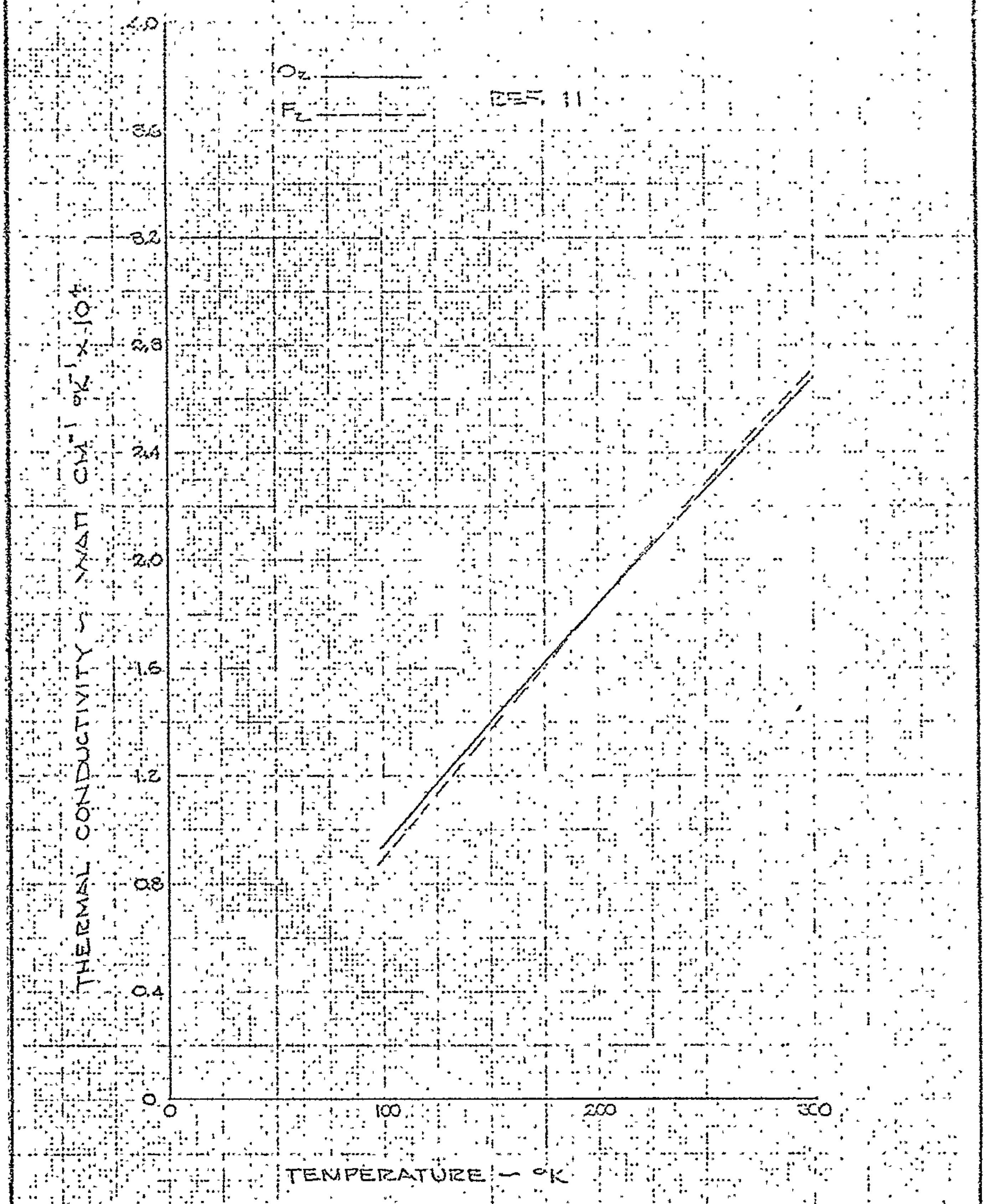

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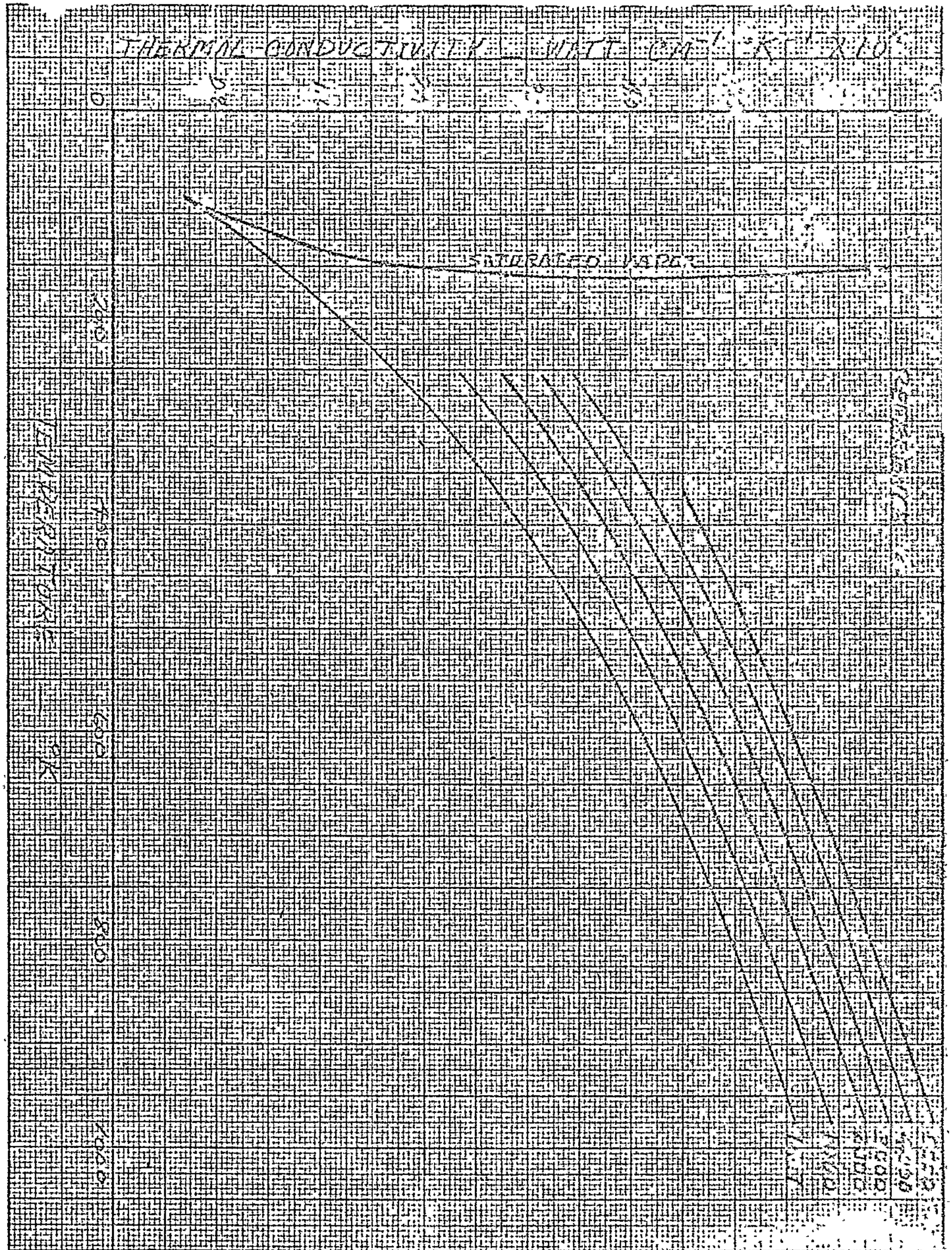

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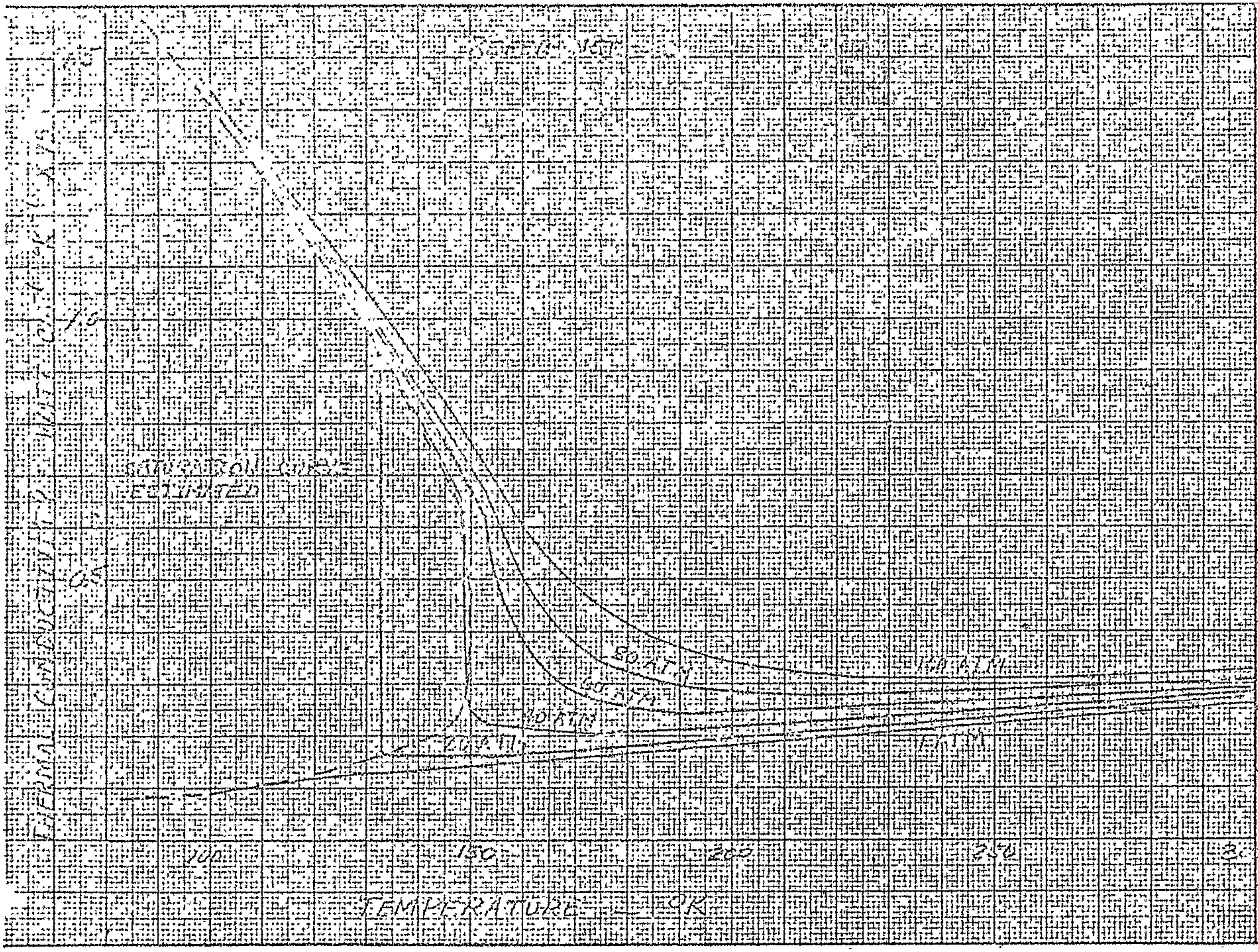

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THERMAL CONDUCTIVITY
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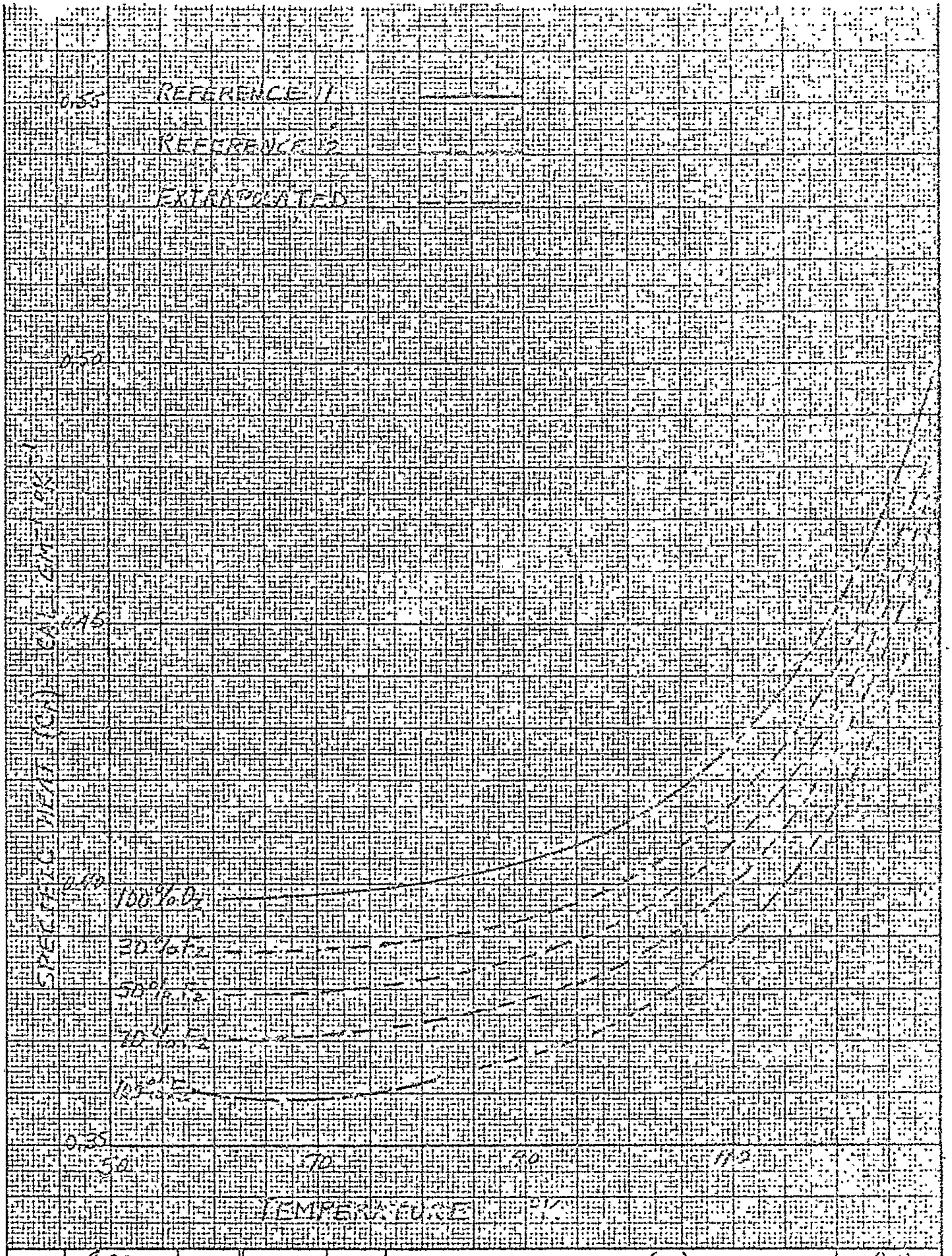

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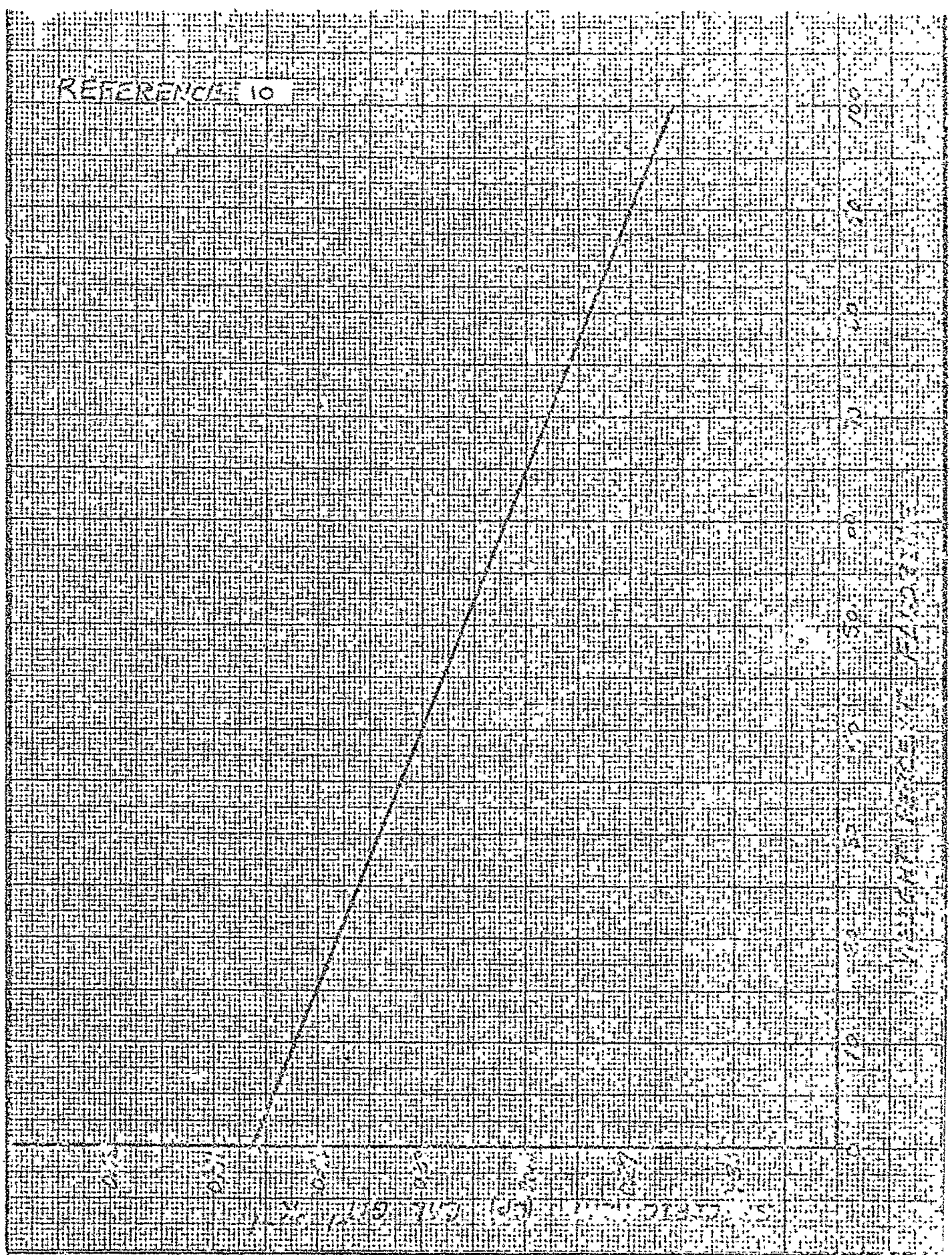

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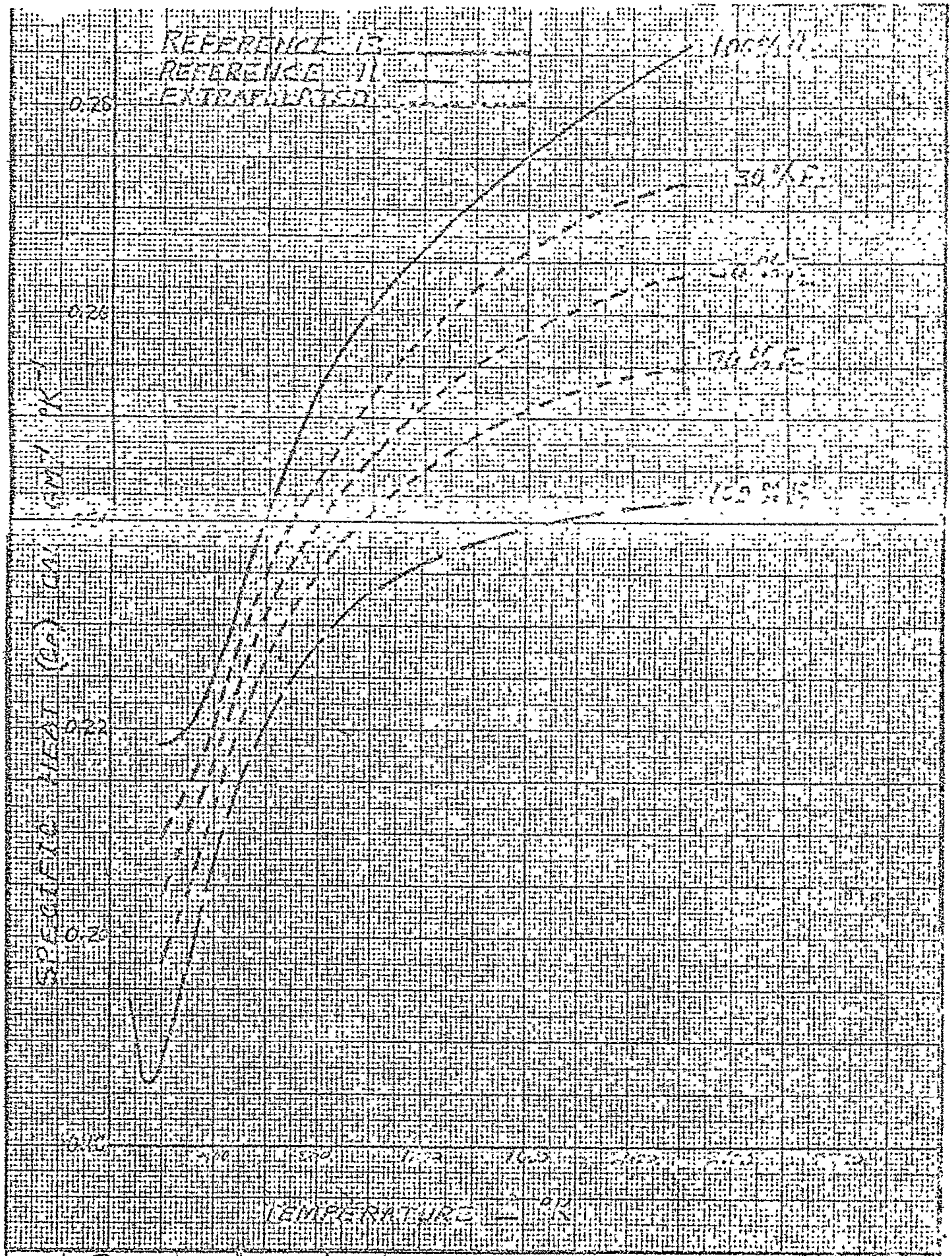
DIETZGEN 190M ASEPROOF VELLUM



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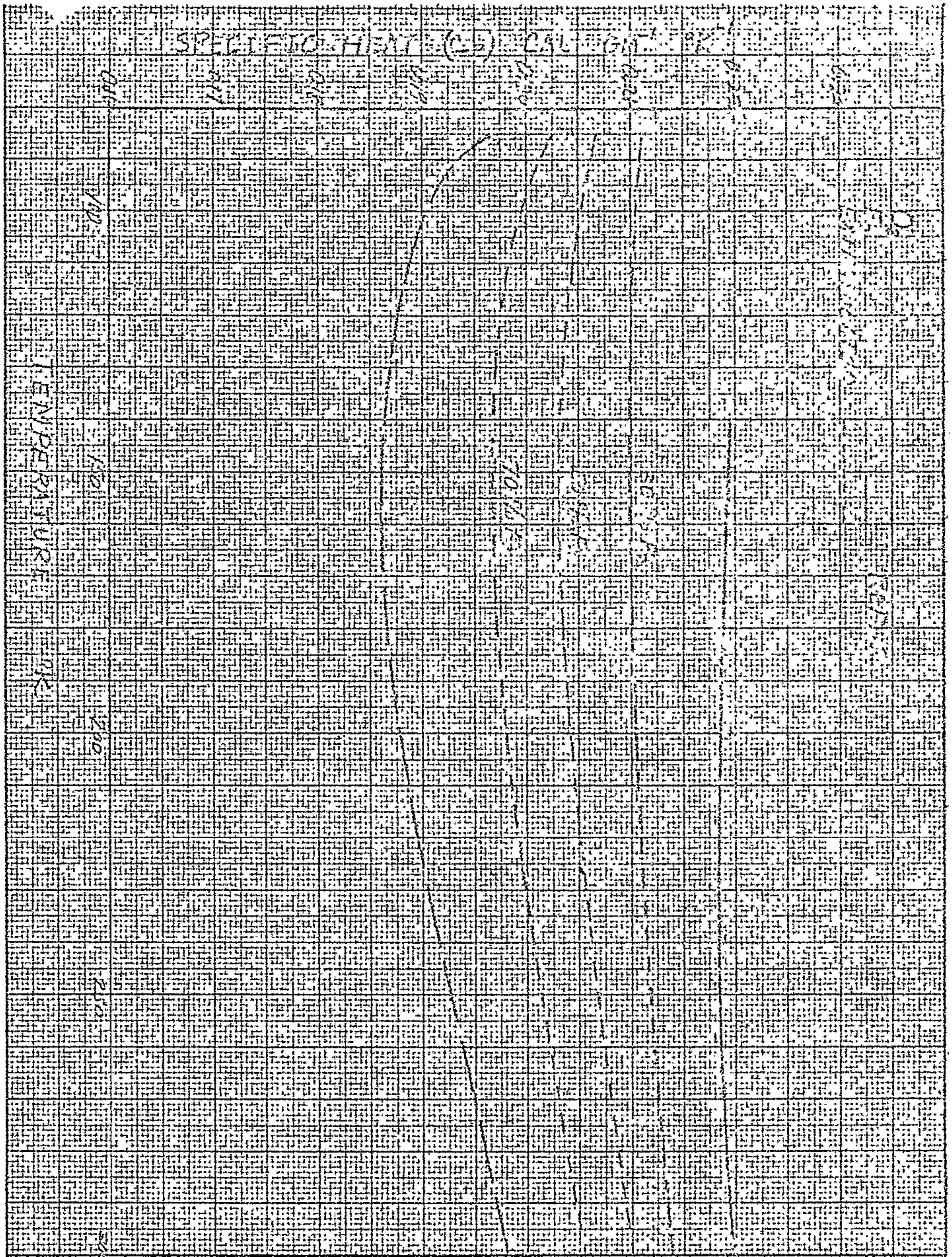

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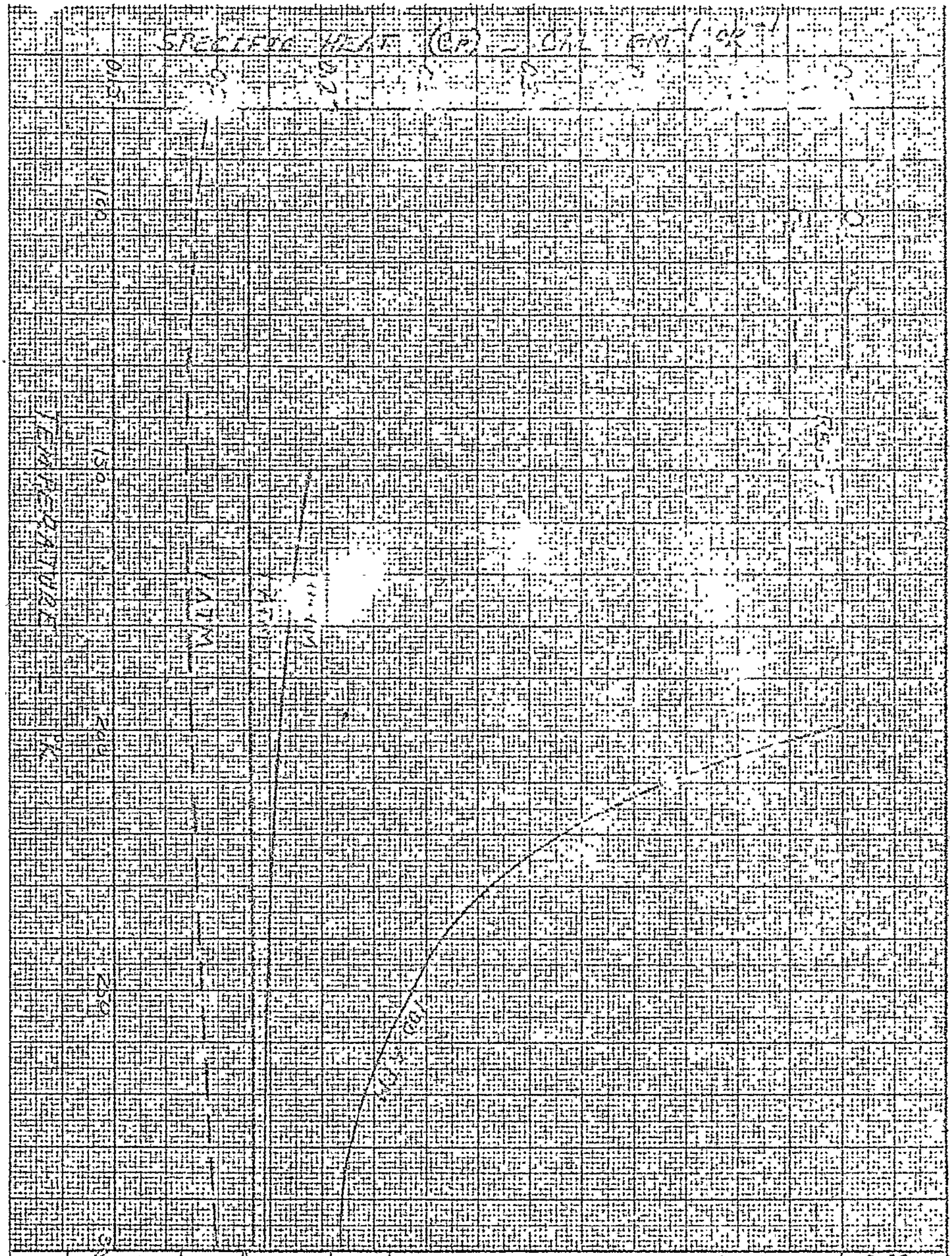

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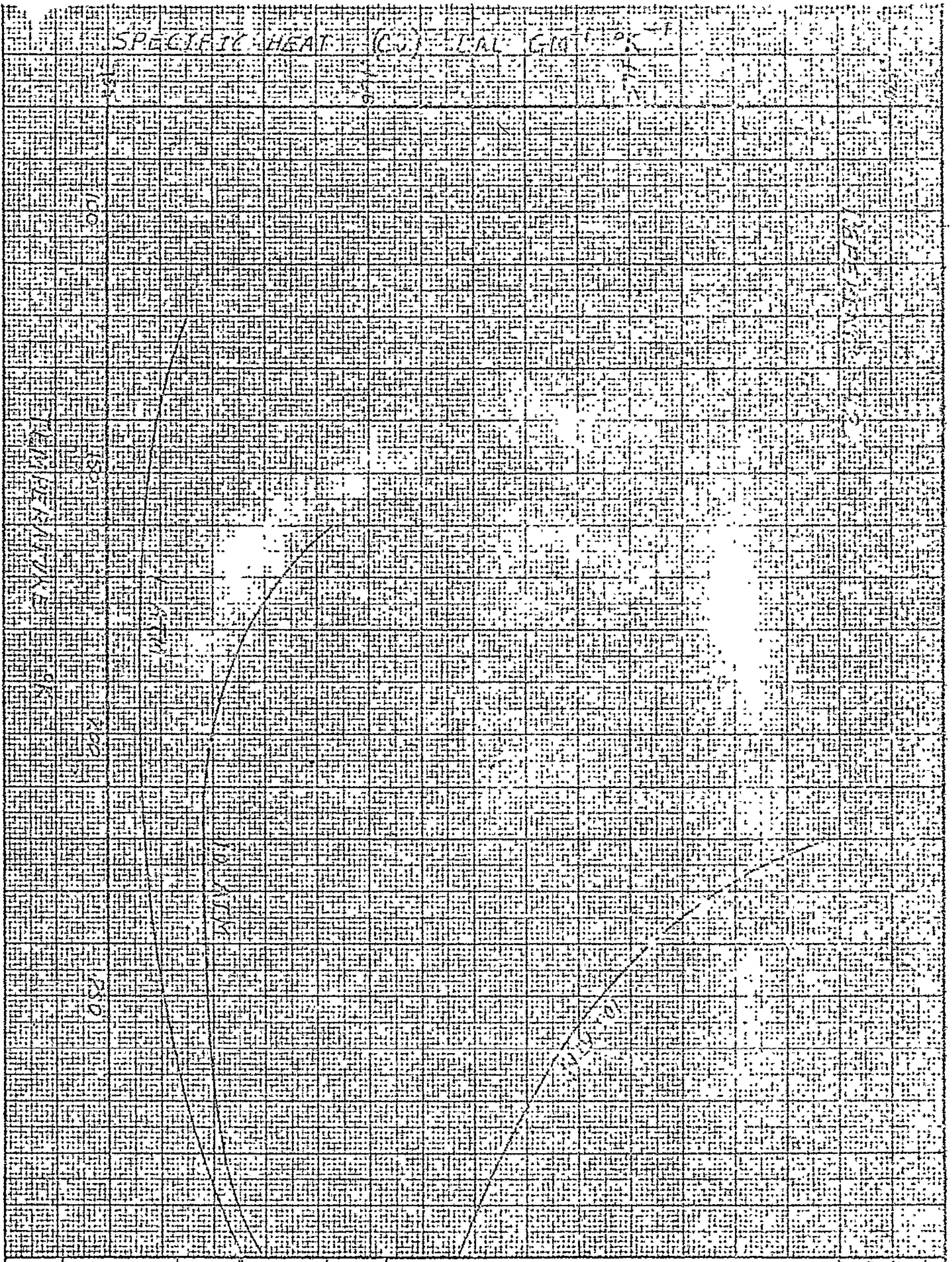

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SPECIFIC HEAT (C_v)
OF GASEOUS OXYGEN

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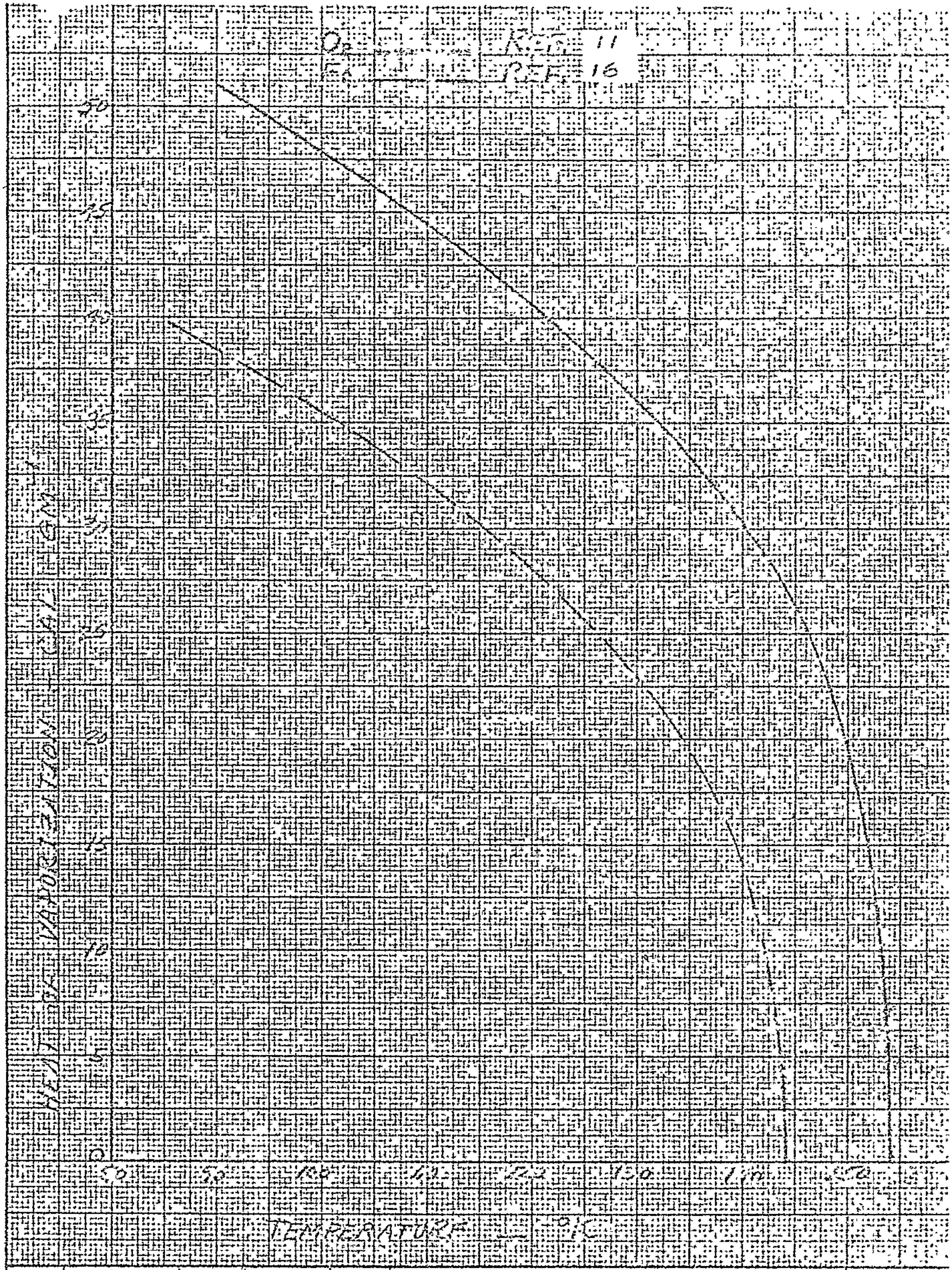

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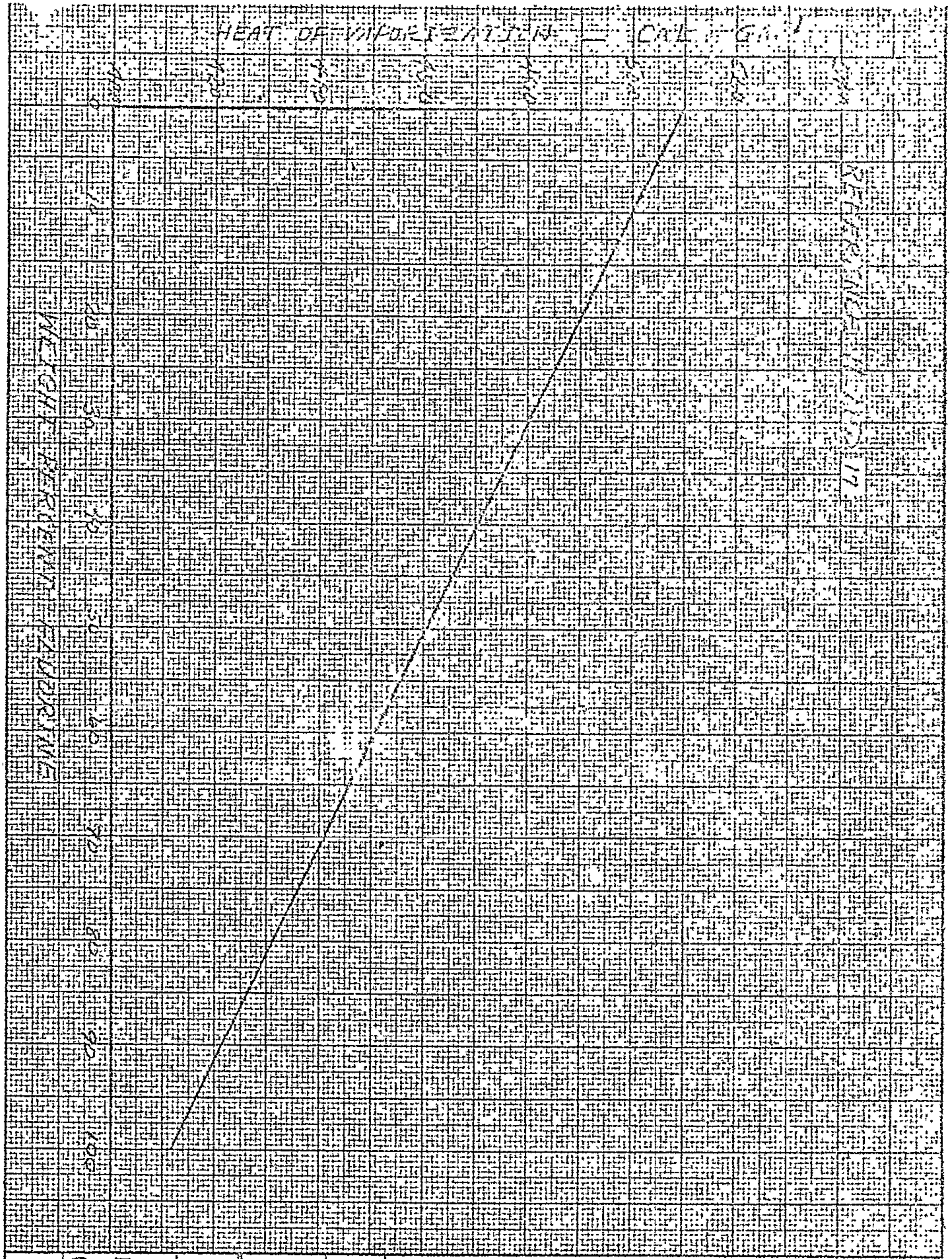
HEAT OF VAPORIZATION OF FLUORINE — OXYGEN MIXTURES

THE BOEING COMPANY Sec. C



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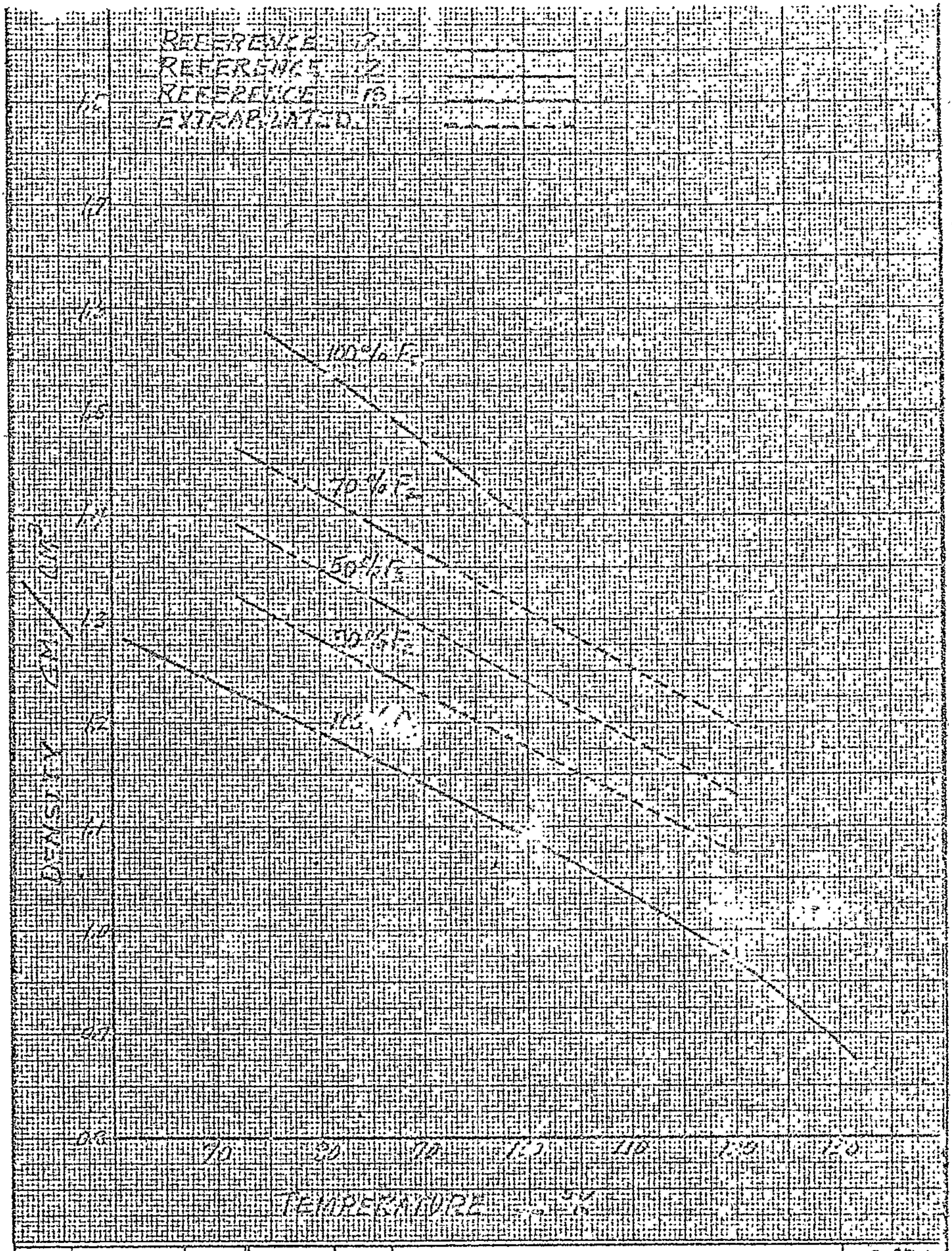

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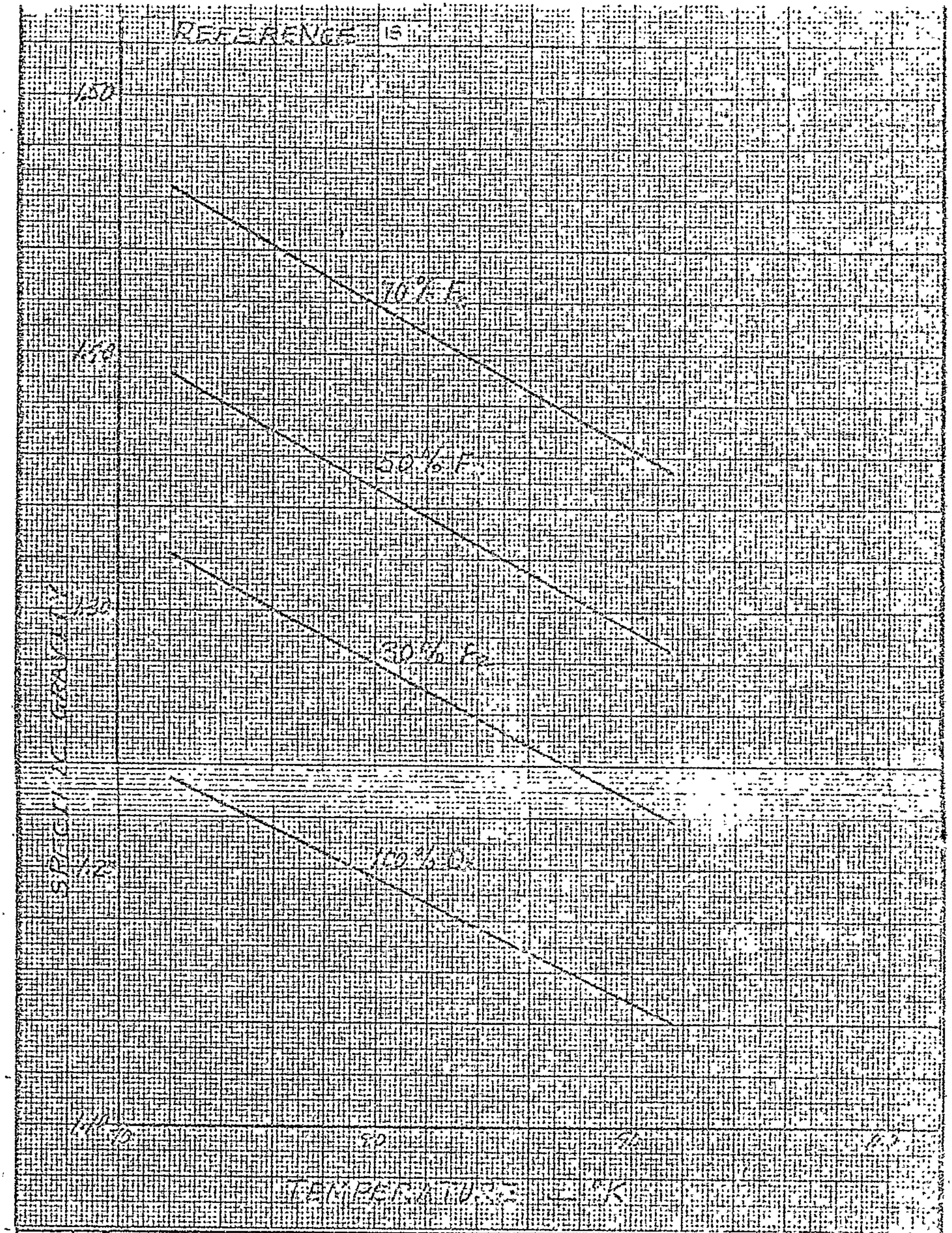
U3 4013 8000 DIETZGEN 1964 AGEPROOF VELLUM



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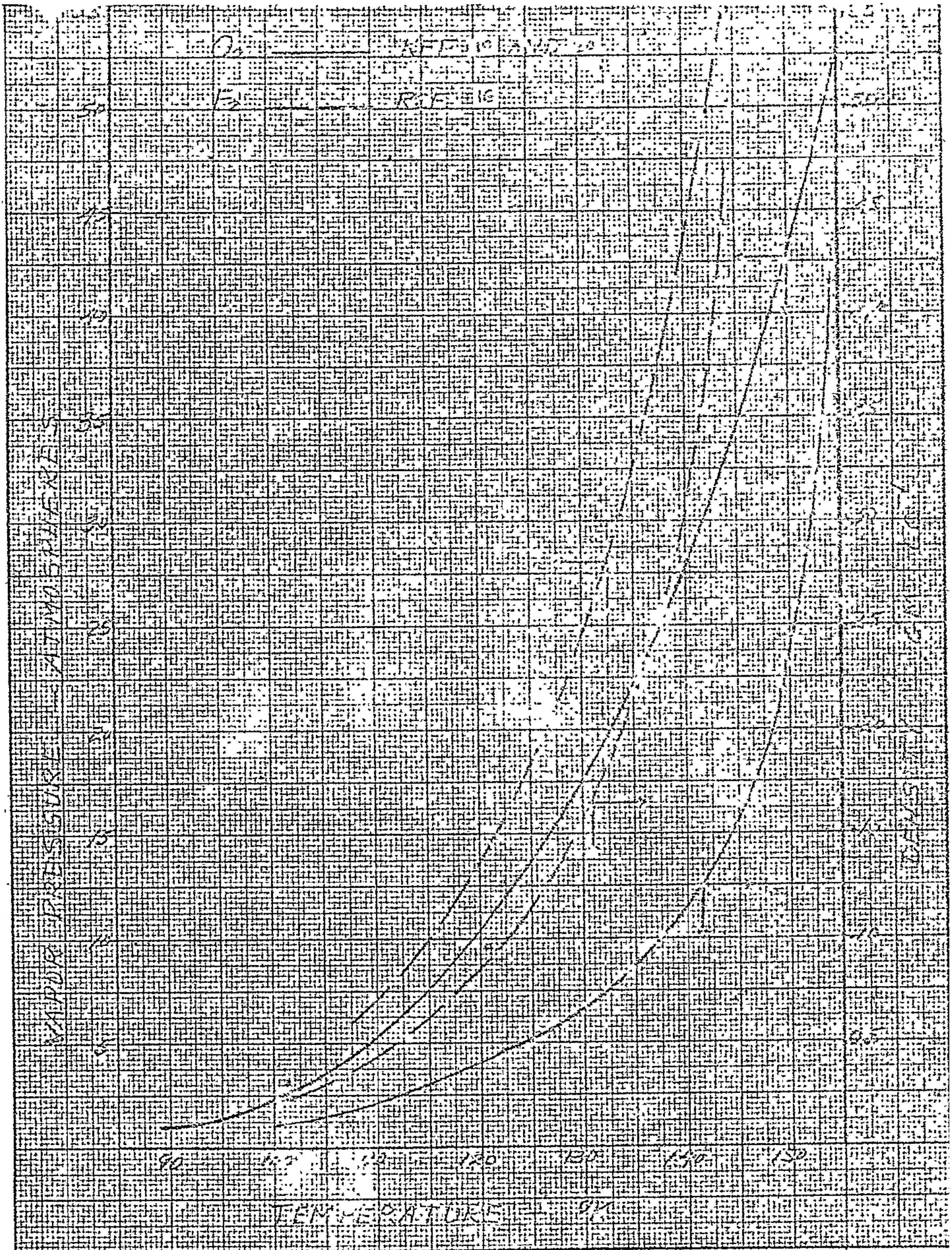

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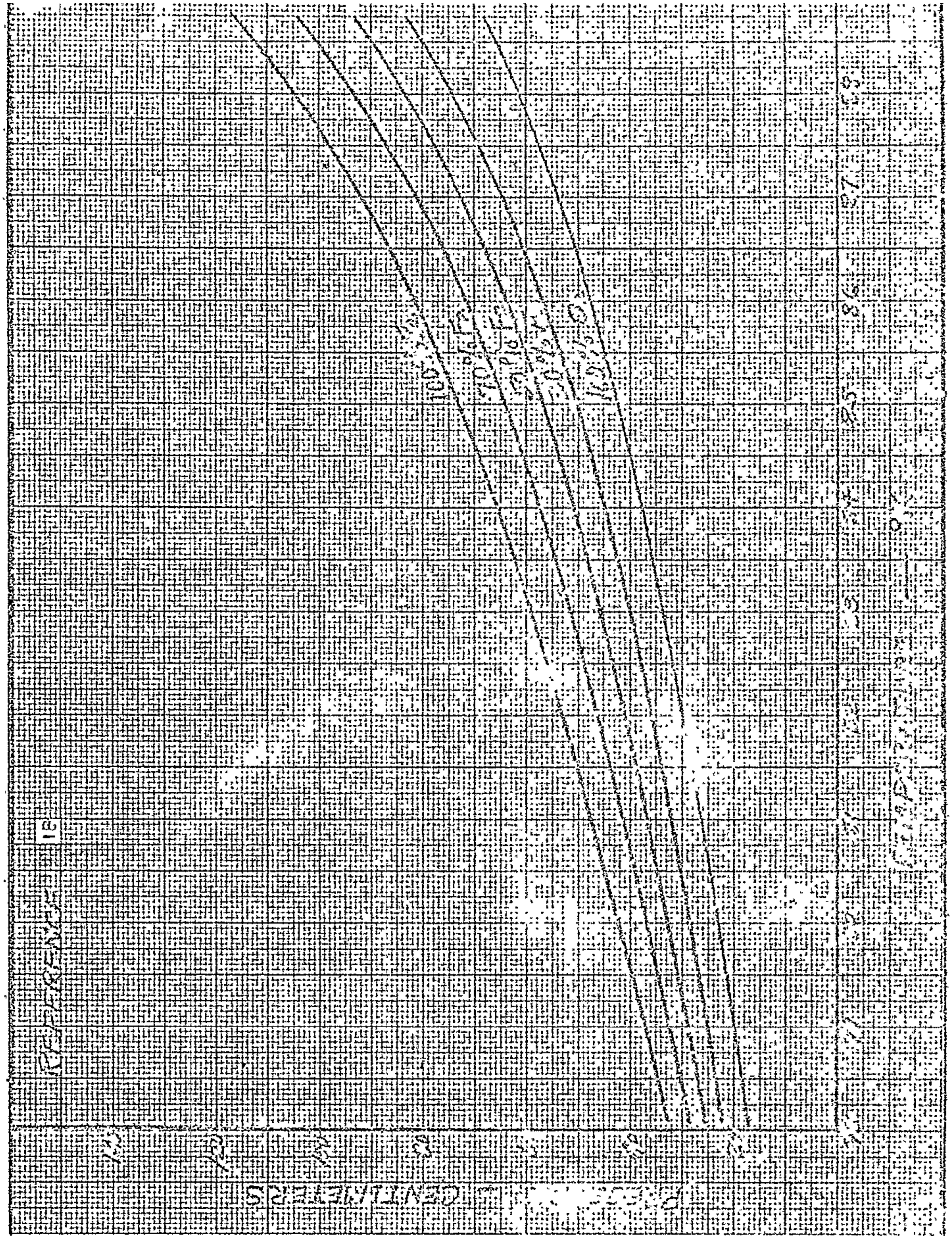

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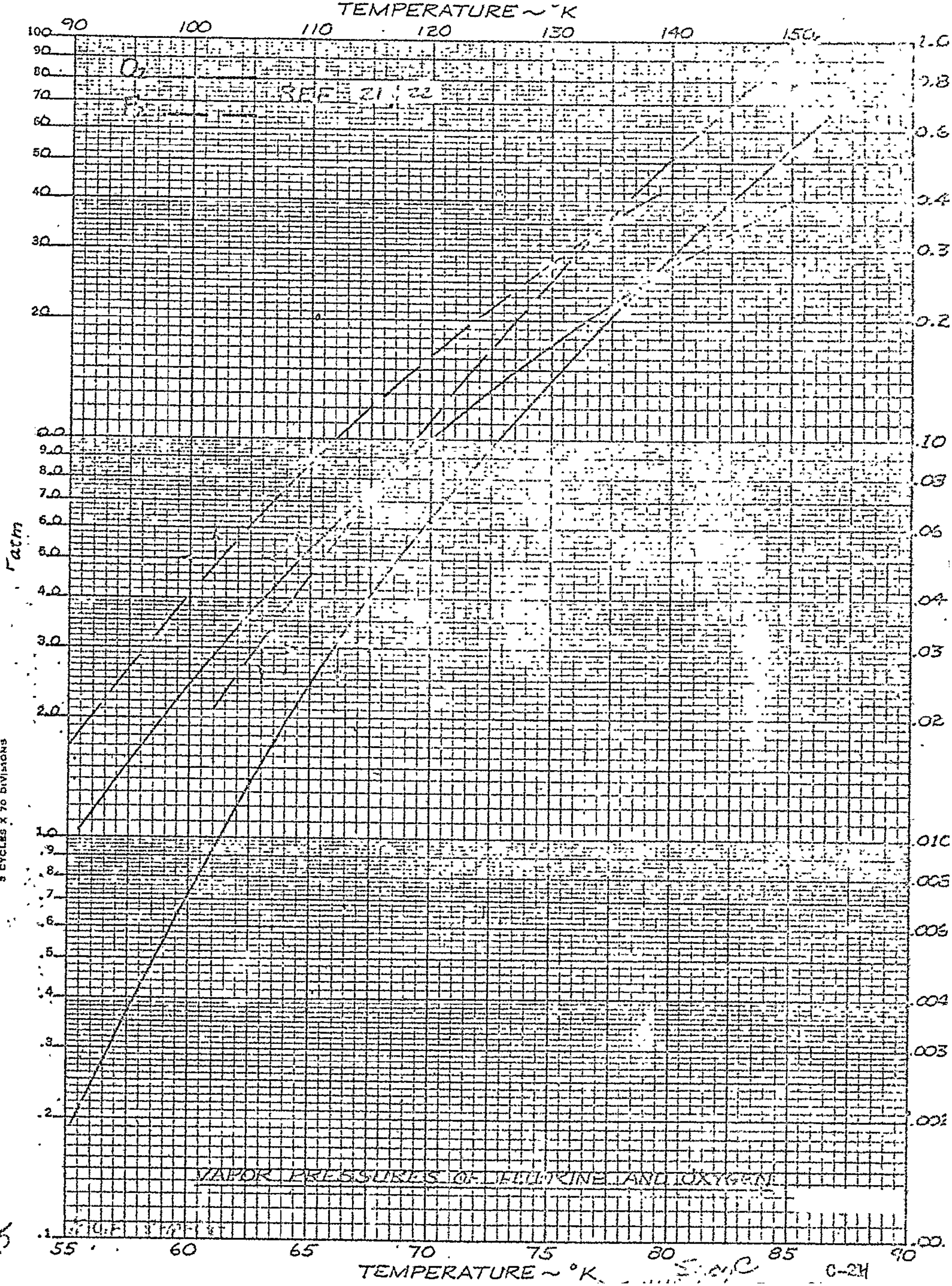

VAPOR PRESSURES OF FLUORINE AND OXYGEN

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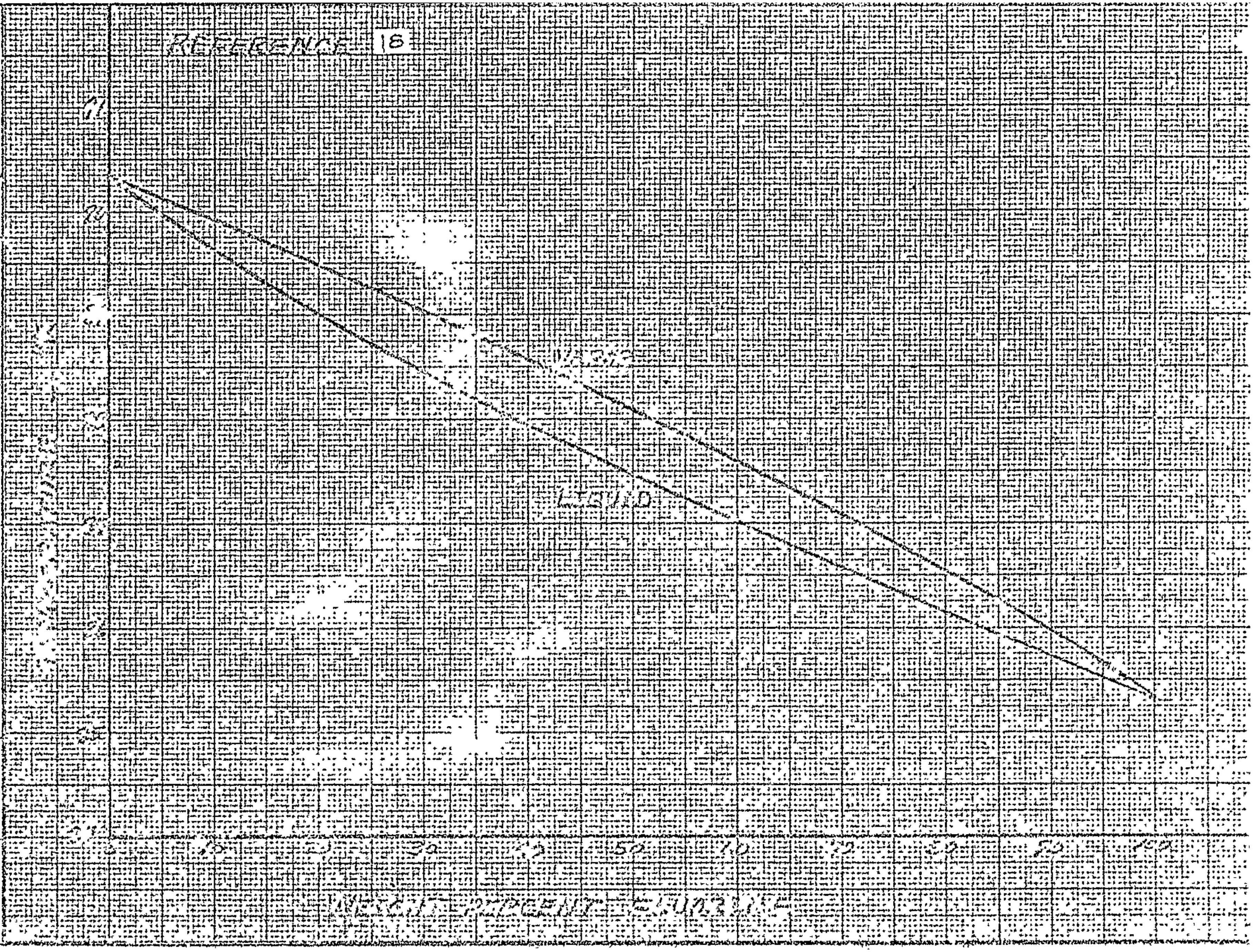

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BOILING POINT COMPOSITION DIAGRAM FOR FLUORINE — OXYGEN MIXTURES — 1 ATM

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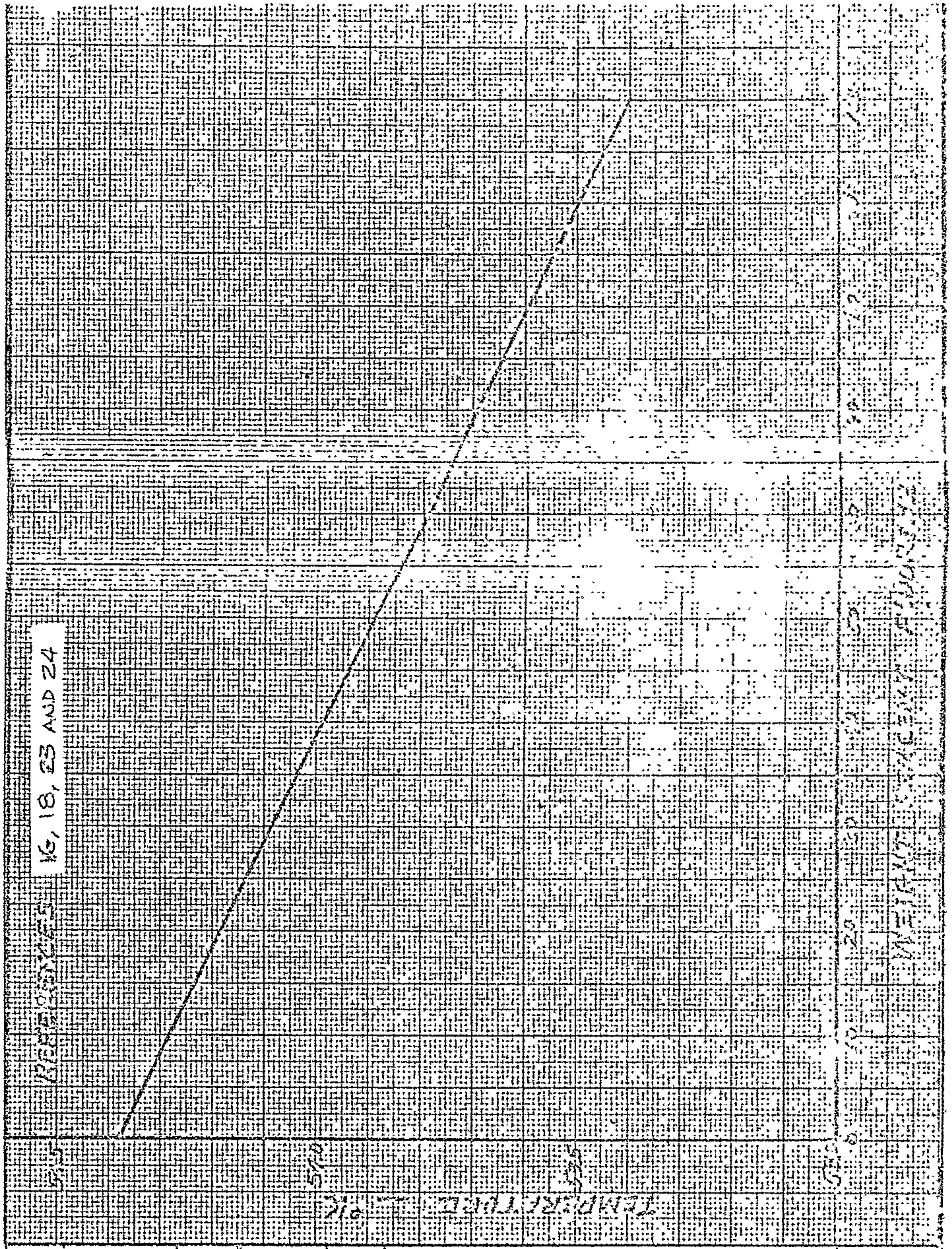
THE BOEING COMPANY



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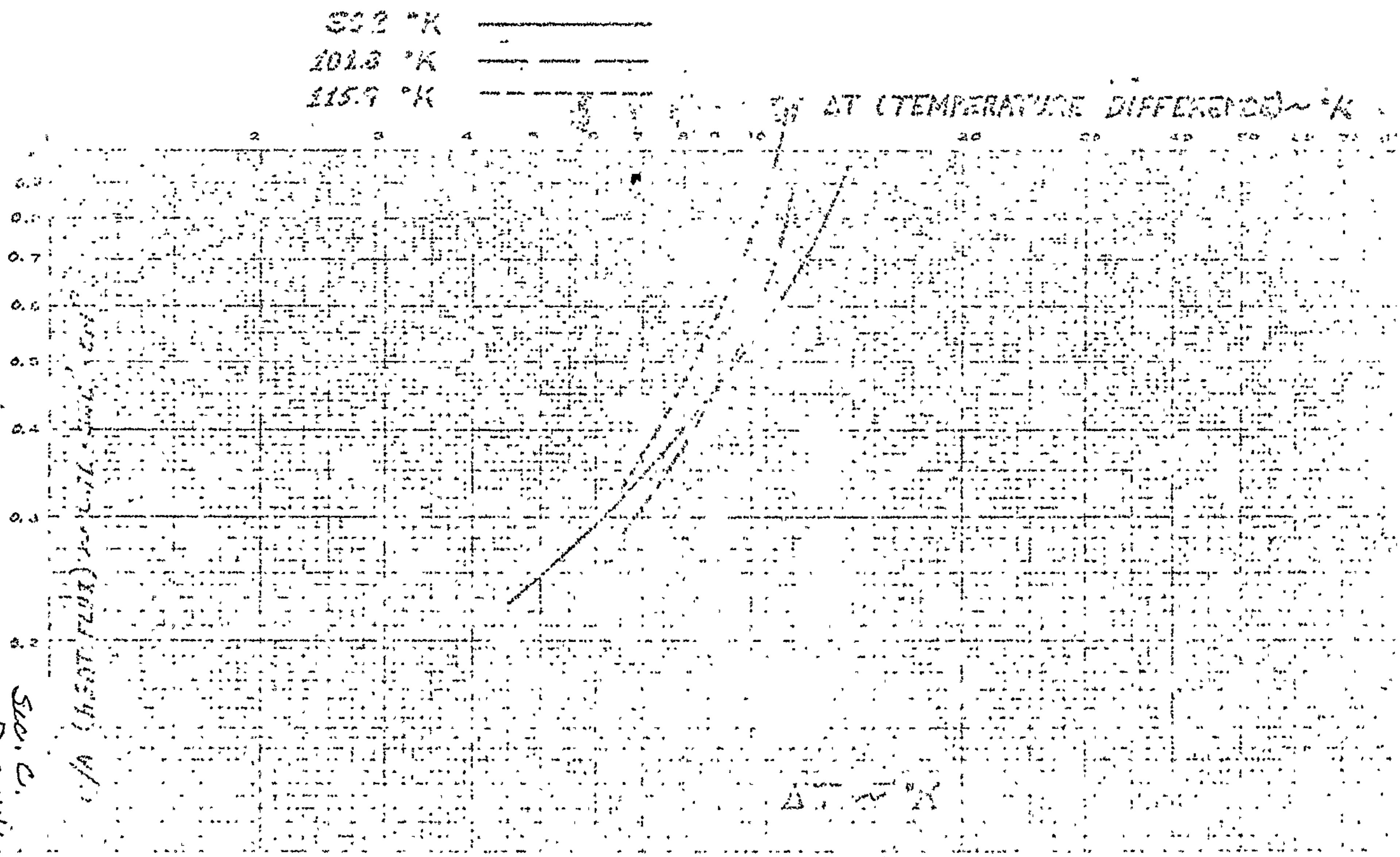

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[illegible]
30 mole % [illegible] Copper

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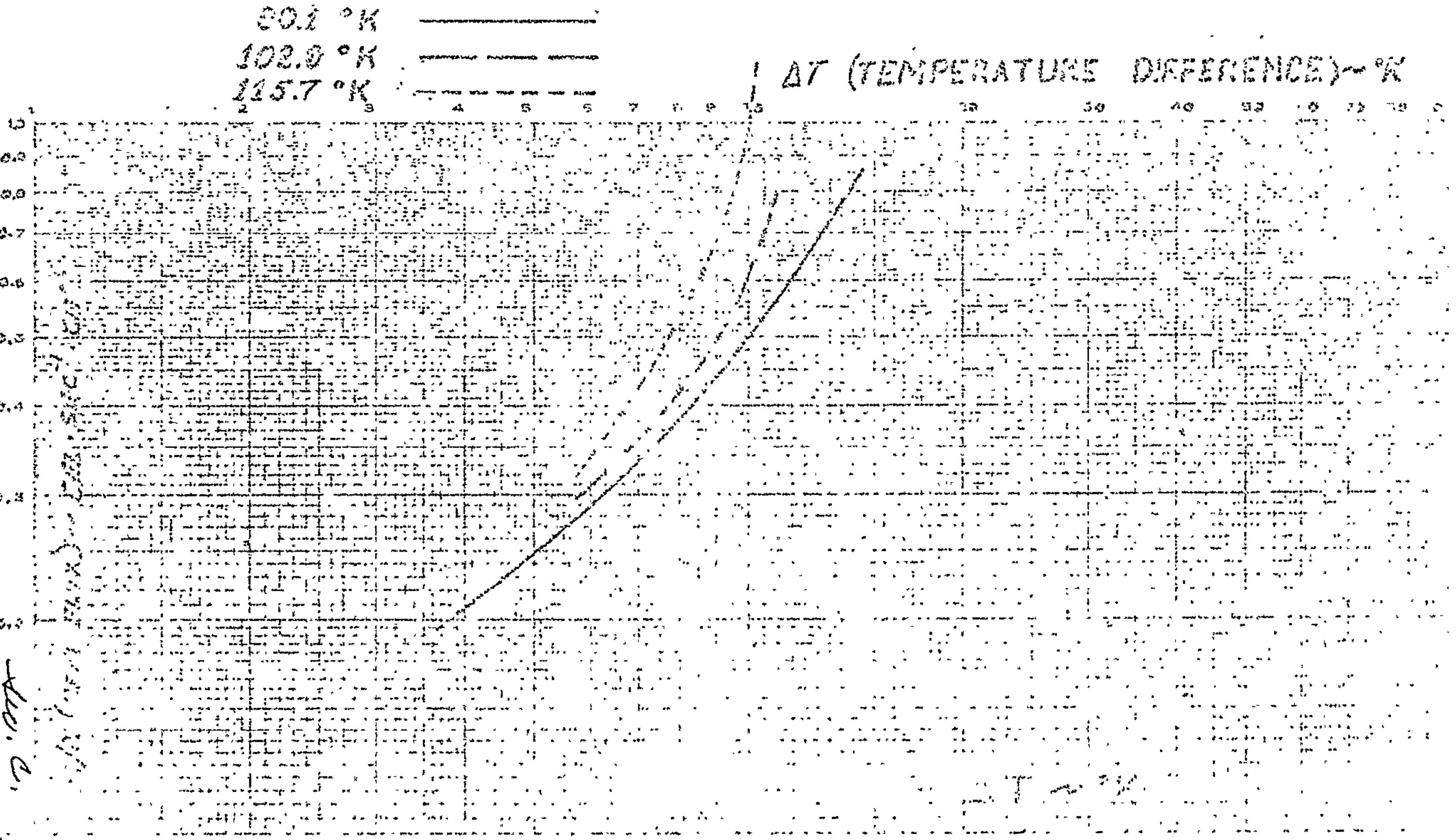

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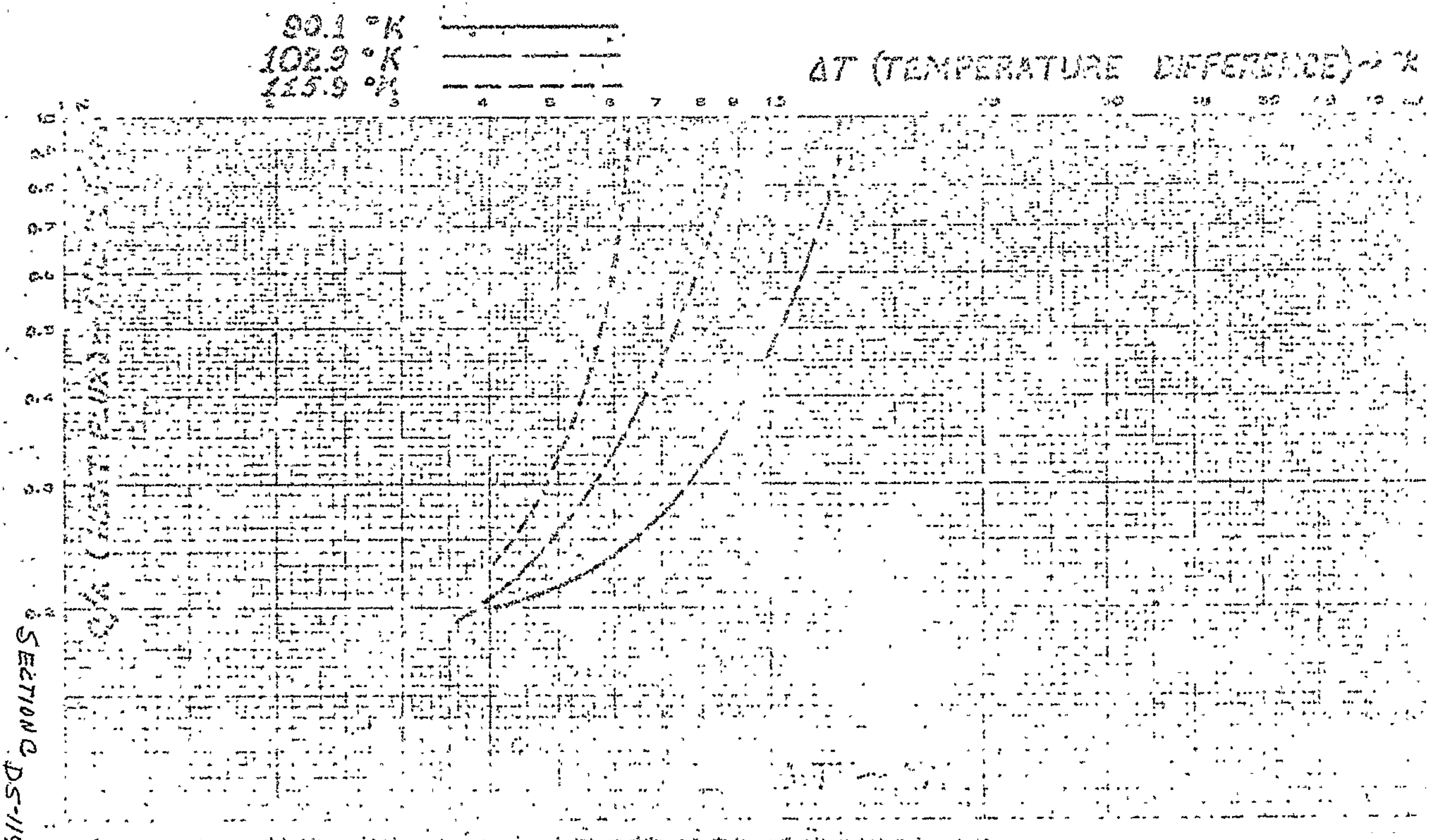

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Nucleate boiling heat transfer for 70 mole % Fluorine in Oxygen

C-26

APPENDIX D

BACKGROUND OF FLOURINE-FLOX STUDIES

D.0 BACKGROUND OF FLUORINE-FLOX STUDIES

The Boeing Company conducted, under NAS8-5608 (TAO-22) with RP&VE direction, a feasibility study of FLOX application to the S-IC. The study contract required identification of performance and proposed solutions to stage problem areas. Identification of problems, but not necessarily solution, of test and launch operations was required.

The results of the noted study, plus Boeing funded R&D work, coordination with other contractors and NASA suggests that substantial effort is justified in the pursuit of a suitable means of applying this highly potent oxidizer. Fluorine/FLOX, in fact, represents a "step-function in space age performance potential." A tremendous potential improvement (65% escape payload increase) exists without change to S-IC stage size. F-1 engine changes at this performance level are associated with combustion chamber pressure increase and coolant flow requirements, however, the changes appear to be within reasonable design. Performance improvement of a more modest but still significant level (up to 20%) appears possible without change to either the engine cycle or stage except for some material changes and structure modifications necessary to carry the greater payload.

Many problems remain unsolved; the one of primary importance is air pollution in terms of near-area hydrogen fluoride concentration. Initial studies indicate that the S-IC can be launched, and not contaminate in the down wind direction above 75 PPM-minutes at a 10-mile range provided the local weather conditions are reasonably favorable. Suitable meteorological conditions for launch are believed to exist whenever the ground level air temperature is one or more degrees Fahrenheit positive (higher at ground level compared to the temperature at approximately 16 feet) and the wind velocity is 10 miles per hour or more.

Several other factors that are pertinent to pursuit of FLOX application have not yet been fully identified. These areas are proposed for study and are covered in some detail in the attachments (Sections I through IV). A summary of these sections follows:

Section I - Toxic Tolerances and Toxic Cloud Behavior

It is proposed in this phase of study to define or confirm applicability of contemporary toxic cloud analysis techniques to the situation resulting from rocket operation during hold down and launch operations. The behavior of the hydrogen fluoride cloud during normal static firing (hold down) and launch will be defined. Conditions associated with facility, GSE or vehicle failure should be analyzed and methods of toxic cloud analysis be determined. It is suggested that coordination (NASA Safety Division, U.S. Academy of Sciences, U.S. Air Force and certain contractors) along with minimum testing could establish toxicity tolerance levels.

Section II - Overall Program & Vehicle Oriented Areas

This section contains a proposal to conduct preliminary design of logical FLOX S-IC vehicle(s).

Overall program timing and economic factors relative to vehicle engine, launch and test facilities require analysis to define overall suitability of S-IC operation with FLOX.

It is further proposed that the individual and total performance of Saturn V stages with fluorine/FLOX as the oxidizer be defined in order to establish comparative data to other methods of performance uprating.

Section III - Aspects of Launch with FLOX Vehicles

This section covers a proposal to apply the data generated in the study of toxic cloud behavior to the Kennedy Space Center launch site from which suitable launch periods and durations thereof can be determined.

Also, it is proposed that design concepts for associated GSE launch rates and equipment modification, including cost effects, be determined.

Section IV - Analysis of Production Check-out - Static Test

This section also proposes that toxic cloud analysis be conducted to define percentage of suitable times for conducting firing at the Mississippi Test Facility. Prior to, or concurrent with this work, it is proposed that a complete analysis be made of the merits of using LOX in lieu of FLOX as a substitute oxidizer at Mississippi Test Facility.

TECHNICAL STATEMENT OF WORK

Section I

Investigation of Fluorine, Hydrogen-Fluoride Tolerance Limits and Toxic Cloud Behavior as Related to Use of Fluorine/FLOX on Launch Vehicles

Toxic Cloud Behavior & Toxic Tolerances

A. General Description

This section describes a study proposal for investigation of the toxicity aspects of launch vehicles using fluorine-FLOX.

It is proposed that toxicity-tolerance levels for design be established and that the behavior of the toxic cloud be defined under conditions of normal operation and failure.

It is believed that toxicity tolerances can be determined on the basis of work already accomplished by numerous authorities in this field of endeavor. The necessity for a program to augment or support analysis at a qualified university or other center should be defined.

Exhaust cloud behavior needs definition. Contemporary prediction methods should be further analyzed as to their adaptability to unique conditions created by rocket exhausts and at varying operating conditions. Also, the effects of energy release rate and elevated cloud temperatures need to be analyzed. The necessity of confirmation tests should be defined.

B. Program Objective

The objectives of the study proposed in this section are:

1. Establish the magnitude of the toxicity tolerances for hydrogen fluoride and fluorine gas for design as related to test and launch operations.
2. Establish techniques for analysis of toxic clouds generated from dry and water-quenched hold down rocket operation, from normal launch, and from accidents with either GSE or the vehicle.

C. Technical Approach

Review of technology relative to determining the behavior of various air pollutants in the atmosphere indicates that considerable effort has been expended to analyze the particular problems at hand. For obvious reasons, considerable work has been accomplished on analysis industrially generated gases. Also, the military has necessarily analyzed the behavior of toxic clouds from explosions and accidental releases in terms of threats to population, wild life and vegetation.

In the field of rockets and missiles, several contractors and/or governmental agencies who have experience with toxic propellants (with good logic) have developed empirical relationships to augment standard text book approaches to cloud diffusion studies. Some have established micro-meteorological observation techniques which are used to determine "go or no go" conditions for firing or other operations.

As far as can be determined, in each vehicle or engine program where toxics are involved, the approach to design and control is tailored to the particular installation, firing area, with varying degrees of calculated risk. This is not intended to imply that a better method now exists or that current methods are either inadequate or conservative, rather it is intended to point out that work needs to be done toward definition of more exact analysis techniques which can be applied directly to static test or the launch procedure from release of hold down arms up to a defined altitude above which the gases are of no concern. Finally, the prediction of the results of a minor spill up to complete catastrophe during which propellants react in a matter of seconds requires further definition work.

Assuming definition of toxic cloud behavior is predictable, it obviously becomes necessary to work to a realistic standard of toxicity that can be tolerated in the affected areas.

Concerning toxicity tolerances, review of pertinent literature, reveals diversity of findings and opinions. For example, 50 to 250 PPM are quoted as dangerous to life by one authority, whereas, another states 1800 PPM. The wide variations may very well result from different analysis techniques and varying conditions.

The toxic cloud from rocket launch is a unique, short-duration and a relatively rare occurrence and should be considered on that basis when tolerances are established. On the other hand, R&D tests of either the stage or engine are expected to be more frequent occurrences and, therefore, may constitute a reason for more stringent requirements. As in the case of cloud behavior, the status of toxic tolerance definition is such that considerable coordination work is suggested, backed up by additional analysis and possibly tests.

The items mentioned above are important variables but are generally considered secondary to the influence of weather conditions on the overall problem. This study, then, proposes to define the toxic limits for design and the expected extent and degree of toxic cloud exposure. The primary steps suggested in this section are listed below.

Toxicity Tolerance Definition

Summarize the results of existing work relative to hydrogen fluoride-fluorine tolerances.

Identify a trend of exposure level as a function of time and also the maximum reasonable exposure level based on current work.

Coordinate and review the analyzed toxicity data with various scientific and medical authorities.

On the basis of the aforementioned items, toxicity tolerances for design studies should be defined and program requirements for further determination or justification of toxic levels should be determined.

Cloud Behavior Studies

Conduct a comparative analysis of the current techniques used for dispersion predictions in the industry.

Perform a theoretical analysis of the effects resulting from the dynamic conditions of static operation, launch or accidental conditions including the effect of elevated gas temperatures.

Collect time-distance referenced photographs of rocket plumes with visible tracer additives. Collect weather conditions and related phenomenon and compare results with analysis techniques.

Conduct specific tests as necessary to evaluate the effects of heat release rate and water quenching.

D. Study Outputs - (Recommended Results)

1. Toxicity Tolerance Definition

   Provide:

   a. Summary, tabulation and plots of existing toxicity data.

   b. Plots of allowable dosage level limit, max allowable exposure, time limits for humans, vegetation and animals. Show projected nuisance levels and de-toxification rates, if applicable.

   c. A report of a coordinated tolerance level for design.

   d. A definition of follow-on analysis and test requirements.

2. Toxic Cloud Behavior

   a. Report current methods of analysis. Comparative plots of dosage range, wind velocity, temperature and quantity variations with the various methods. Estimated plots of effective dwell time of toxic cloud at various ranges.

   b. Plots of water-quenching effects on rate of rise and diffusion from static firing, efflux angle versus cloud height, exhaust to air mixing rate, velocity degradation and gas buoyancy analysis from a rising rocket and failure conditions.

   c. A comparative data presentation of predicted cloud characteristics versus time-distance referenced photographs of actual firings.

   d. Plots of effects of heat release rate on diffusion behavior.

   e. Additional testing and analysis requirements.

TECHNICAL STATEMENT OF WORK

Section II

Definition Study of Performance, Design and Resources Analysis of the S-IC/Saturn V with Fluorine-FLOX

Design & Performance & Resources Study

A. General Description

The contracted work under TAO-22 revealed approximately 80% increase in Saturn V payload.is possible by operating at 70% FLOX in the current S-IC geometry. Approximately 20% of this gain was lost, however, because of the required inert weight increases on all stages to carry the larger payload through the "FLOX trajectory." The vehicle inert weight change at this maximum performance point implies considerably more redesign than that expected to result simply from the addition of the fluorine enriched oxidizer. Definite limitations on both the current stage and engine exists in relation to achieving the best performance at intermediate and high percentages of FLOX. Higher thrust values suggest revision to the stage thrust structure and, of course, modification to accommodate the increased payload and propellant weight. One of the factors that causes significant increase in structural requirements from optimum FLOX vehicles is the change in loads at (q max) maximum dynamic pressure and the increase in acceleration at burnout.

In the oxidizer pressurization system area, because of the criticality of contaminants and the requirements for elevated temperatures, an alternate design that eliminates the engine heat exchanger pass and associated plumbing appears desirable. It is proposed that full advantage be taken of Boeing R&D work and MSFC contracted studies in this area to assess a possible improvement

The work completed under TAO-22 identified the magnitude of performance and the general feasibility of FLOX. It is apparent, however, that additional work is required toward definition of a design(s) which will include the very significant factors noted above. The nominal performance approach with minimum cost and time requires comparison to maximum-performance design at greater cost and time. Of major significance in this problem and not included in the previous contract, is the program and cost impact of GSE and facility changes associated with operation with FLOX, regardless of percentage. Also, the effects and adaptability of upper stages to FLOX application needs to be considered.

B. Program Objective

The objective of this proposal is a further study of the stage design and performance trades in order to select logical vehicle(s) for possible FLOX application. Program implementation aspects and inputs from related test and launch studies should be included.

C. Technical Approach

1. S-IC Design Studies

a. Analyze the unchanged and the maximum performance vehicle - engine design point configuration identified in the previous studies in terms of the influence of maximum dynamic pressure and burnout acceleration. Investigate and propose means to reduce structural loads.

b. Conduct additional performance optimization studies on the S-IC and Saturn V system including relocated S-IC bulkheads and use of FLOX or fluorine in the S-II and S-IVB. Define effects of FLOX-fluorine on various uprated Saturn V configurations to identify maximum performance potential for use in future vehicles. Include specifically the MLV-Sat V-3 and selected strap-on solid motor configurations.

c. Define implementation plan for S-IC FLOX vehicles. Consider program timing, economic factors, resources requirements and program impact.

D. Study Outputs & Results

Provide:

1. Configuration descriptions of logical FLOX vehicles.
2. Plots of three-stage performance with fluorine-FLOX.
3. Plots of uprated Saturn V vehicle(s) with fluorine-FLOX.
4. Plots of engine requirements to meet logical vehicle configurations.
5. Summary reports of program cost risk, timing and resources.
6. Description of "best buy" vehicles considering performance, design, development, GSE, program timing and launch rate and an implementation plan.

TECHNICAL STATEMENT OF WORK

Section III

Investigation of the Aspects of Launch with FLOX Vehicles at Kennedy Space Center

S-IC FLOX – Kennedy Space Center

A. General Description

Two primary areas require examination relative to solving problems associated with vehicle launch. One of these is FLOX GSE, facilities design and handling equipment. The other area is the question of whether the toxic cloud will diffuse to a tolerable level within a reasonable distance of the launch site. An additional problem, believed of secondary magnitude at this time is related to the immediate launch area and concerns personnel safety and equipment corrosion.

The problem of defining the best design approach to handling and storage of FLOX resolves into economics and practicability especially when considering a specific launch rate or number of launches. For example, the approach to strictly an R&D operation would probably be different from a facility planned for use over a period of years. The permanent facility planned for long term use is recommended for study.

A previous section, (I), of this proposal covered the development of both design values of toxic tolerances and analysis techniques of cloud behavior. A detailed examination of the prevailing weather conditions including statistical analysis to define probable launch periods is required. Also adaptability and necessity of a weather monitoring and cloud prediction system is proposed.

B. Objective

The study in this section covers an analysis of the overall adaptability of Kennedy Space Center, Complex 39 area, to S-IC FLOX application and proposes to analyze and define schematically (with supporting engineering drawings as necessary) the FLOX handling, sampling, storage, pumping, etc. systems.

C. Technical Approach

1. Launch Area Toxicity Studies

Statistical analysis of the recorded weather data from the Kennedy Space area is required. These data should be applied to the appropriate dosage range (civilian boundaries) and be based on the toxic analysis techniques and projected quantities and rates of fluorine, or hydrogen fluoride generation. (I.e., % FLOX and/or total tank quantity) Weather data of particular interest is wind velocity, temperature and humidity at the immediate launch site and at representative points five to ten miles inland in the normal downwind direction. Two spectrums of data are required with varying degrees of accuracy or deviation allowed. Ground level to 300 feet is of primary interest. Knowledge of small deviations is necessary in this range with special emphasis on the first 100 feet. Normal observation data are required from 300 feet to a minimum of 4,000 feet. A definition of the sea breezes and normal low to high altitude wind circulation pattern is necessary. The meteorological data should be statistically analyzed in terms of suitable combinations of wind, temperature, and humidity and percent FLOX. Also, the probabilities of the time (duration) that favorable conditions exist should be determined.

The primary steps of this study are summarized below:

a. Collect and analyze Kennedy Space Center weather data.

b. Apply diffusion techniques to the data and determine the most critical operational or failure modes and the magnitude of the problems with each.

c. Define the probability and duration of suitable launch periods.

d. Conduct feasibility analysis to determine if reasonable methods exist to relieve the critical problems.

e. Based on the above data, define the operational limits in terms of percent FLOX, propellant quantities, transfer rates, and launch thrust to weight.

2. GSE and Facilities Design Studies

Work conducted under TAO-22 has indicated the following general areas of GSE design warrant definitive study.

Storage Facility Design for Liquid Fluorine or FLOX

Transfer System Design for Liquid Fluorine or FLOX

Recondensation of Boiloff Gases

Neutralization and Disposal of Boiloff Gases

Neutralization and Disposal of Spills

Neutralization and Disposal of Combustion Products from the Water Cooling Systems

The problems mentioned above are not of a major technical nature relative to state of the art but do require generating a number of solutions and choosing from these the safest, most reliable, and economical for the Saturn V/S-IC.

Possible solutions for the storage facility design are the liquid nitrogen jacketed tank, the internally subcooled tank, the internally recondensed tank, and the externally recondensed tank.

The safest and most reliable liquid fluorine or FLOX storage appears to be a liquid nitrogen jacketed tank because no fluorine gas is released to the atmosphere, the least equipment is exposed to the fluorine or FLOX and there are almost no moving parts.

A liquid nitrogen jacketed tank has about a 30% higher installation cost and probably a higher liquid nitrogen consumption rate than a tank with a recondenser. Propellant transfer with a liquid nitrogen jacketed tank is somewhat easier since the fluorine or FLOX enters the transfer process in a subcooled state, however, cost advantage may exist by modifying existing tanks and adding recondensers.

The safest and most reliable transfer system appears to be the liquid nitrogen jacketed lines for the same reasons as noted for the storage system. However, transfer lines without a LN_2 jacket are less expensive to install and may be adequate if the transfer distance is small or if the fluorine or FLOX is subcooled before transfer.

Recondenser design for the capacity involved with the FLOX-filled S-IC has not been completed, however, a variety of designs are possible. The simple shell and tube design is probably the most reliable but also the most expensive as far as refrigerant costs. If recondenser design proves to be uneconomical, neutralization and disposal techniques for the boiloff gas will have to be used. Several methods of gaseous fluorine disposal exist such as reactions with carbon. hydrocarbon fuels, and ammonia.

Neutralization and disposal of spills depends on the size and location of the spill. Soda ash does the best job of neutralizing but is hard to apply since it is a solid, as is the residue. Water seems to provide easy application, is available and disposable. Deluge water systems exist on the current facilities and probably need only to be resized and modified for fluorine spill disposal.

Neutralization and disposal of combustion products to some extent appear necessary to accommodate operation on planned or existing facilities because of the water quenched exhaust. This operation reduces the concentration of toxic products in the exhaust cloud but has possible detrimental effects by cooling the cloud and introduces additional corrosion problems.

In this study, it is recommended that each subsystem and system of GSE design be analyzed considering the following factors.

Initial cost
Operating cost per launch
Safety
Reliability
State of the Art
Existing LOX equipment at KSC
Integration of FLOX subsystems

The primary steps in this study phase are:

a. Determine the storage requirements (weights, pressures, flows, etc.) and evaluate the performance of the liquid nitrogen jacketed, the internally subcooled, the internally condensed, and the externally condensed storage tanks.

b. Determine the transfer requirements (flow rates, pressures, etc.) and evaluate the performance of liquid nitrogen jacketed, vacuum jacketed, etc. transfer lines.

c. Determine the recondensation requirements for the boiloff gases (weights, flowrates, pressures, refrigerants, etc.) and evaluate the performance of different types of recondensers.

d. Determine the neutralization and disposal requirements for boiloff gases (weights, flowrates, pressures, reactants, catalysts, etc.) and evaluate the performance of the disposal systems using charcoal, hydrocarbon fuels and ammonia.

e. Determine the neutralization and disposal requirements for spills weights, flowrates, etc. and evaluate the performance of water deluge and soda ash systems.

f. Evaluate the performance of water deluge and water scrubber systems for application to S-IC with FLOX.

g. Develop and list different concepts for total FLOX usage involving the different individual concepts for storage, transfer, recondensation, disposal, etc. Evaluate each concept with respect to its individual merit and feasibility and with respect to the others. Select the optimum concept(s) to further develop more exact flow arrangements.

D. Study Outputs & Results

Provide:

1. Plots and tabulations of predicted suitable FLOX launch periods for a month by month or weekly basis, if practical, including the duration of safe periods.

2. Definitive recommendations on percent FLOX, total propellant quantities alternate design concepts or operational restrictions at Kennedy Space Center.

3. Design concept definition cost and timing of launch area facilities and GSE.

TECHNICAL STATEMENT OF WORK

Section IV

Investigation of Production Checkout - Stati Test Aspects of Fluorine-FLOX Vehicles at Mississippi Test Facility

A. General Description

The problems covered in previous Section III (Launch Area Studies) generally apply to operation at MTF.

In this section, it is proposed that an identical study applicable to MTF be made with the exception that an initial or preliminary phase be added to evaluate the possibility of using LOX as a substitute oxidizer during production static testing.

Informal discussion with Rocketdyne indicates that this approach is consistent with their philosophy.

The question to be resolved is whether mission reliability or safety is compromised in any way by using LOX instead of FLOX for the production test operation. A broad qualitative analysis does not indicate any particular advantage either way.

Using FLOX in the anticipated percentage of the launch during static test assures that actual operating conditions are experienced in the systems. Testing with LOX, if backed by proper developmental tests, would appear to allow complete functional and performance evaluation at approximately the same levels as experienced with FLOX.

The primary advantage of LOX operation at MTF is elimination of the toxicity problem in a critical geographical-meteorological area, reduction of testing costs, and elimination of the risks from fluorine exposure to components and the consequent effects during refurbishment, shipping and assembly for launch.

B. Objective

1. The intent of the preliminary phase of this proposal is an objective analysis of the suitability of using LOX as the oxidizer for static test operations.
2. The intent of the second phase of this proposal, if proved necessary, is definition of suitable static test time periods and the effects on facilities and GSE as described in Section III of this document.

C. Technical Approach

For the initial phase of the study, a complete analysis of the engine and stage systems and subsystems performance with FLOX and LOX is required. Comparison of the operating levels are required to determine any critical areas. Assuming LOX substitution appears feasible, definition of the additional R&D static testing required needs definition and a comparison of the comparative costs of each approach is required.

Should the substitution of LOX be proved unfeasible, the study should proceed on the same basis defined in Section III.

D. Study Outputs and Results

See item "C" above and Section III, item D.

APPENDIX E

TAO-22 STATEMENT OF WORK - USE OF FLOURINE (FLOX) FOR PERFORMANCE IMPROVEMENT ON THE S-IC

APPENDIX E

E.0

TAO-22

STATEMENT OF WORK - USE OF FLUORINE (FLOX) FOR PERFORMANCE IMPROVEMENT ON THE S-IC

(Effective Date May 4, 1964)

Introduction

This program outline is The Boeing Company response to TAO-22 (Use of Fluorine (FLOX) for Performance Improvement on the S-IC) and outlines the statement of work necessary to provide the answers to general feasibility. This document is an interpretation of the program requirements at its initiation and is subject to further negotiation as a better understanding of the technical problems is developed.

I. General Summary

In order to define and implement the work outlined in MSFC memo R-P&VE-PPF-64-M-92 in a manner consistent with best utilization of manpower and expenditures, the MSFC work items have been oriented toward identification of actual performance, primary problems and logical solutions, design and operational aspects (to the extent of determining judgment factors relative to costs, timing) with use of FLOX on the S-IC.

Logical pursuit of this program with minimum time and expense requires free interchange of technical information among MSFC, Boeing and Rocketdyne. MSFC guidance and coordination is required to obtain data in areas from previous or parallel government programs.

The following ground rules relative to reporting have been established for the work covered by TAO-22.

1. Monthly progress reports are required with the first being due about 1 June. It is desired that these reports be oral presentations and discussions with the minutes comprising the official report.
2. The final report on the program should include all analytical work performed as well as results, conclusions, and recommendations.

MSFC will provide available information relative to FLOX-fluorine. Boeing may expand the information base and will supply additional references to MSFC.

Manpower requirements are approximately 10,000 manhours through August 31, 1964.

II. General Description

A considerable increase in the performance of the S-IC stage appears to be possible with the use of fluorine as an oxidizer additive to LOX. The apparent improvement is of significant magnitude to warrant a detailed examination of the performance and the more significant problems.

Experimental and theoretical work have not yet established what the non-equilibrium performance of FLOX in any actual nozzle will be, therefore, the currently estimated performance gains for FLOX need further examination. For this reason, it is important that the performance increment be established as early as possible in the program in order to determine the merits of this additive.

Serious problems exist in the use of FLOX in any stage but in particular with a booster stage because of hazardous exhaust products. Since several of the problems could be prohibitively expensive to solve, this study will proceed first with the most difficult problems. Periodic check points to examine the total concept for overall feasibility will be established for review with MSFC. If the solution to one or more problems appears to be extremely expensive or impractical, MSFC will be notified immediately for program review or reorientation.

III. Objectives

The objectives of this study are as follows:

(a) Estimate costs or magnitude of problems associated with achieving reasonable safety for life and property. The GSE, facilities and testing problems related to S-IC will be identified and reported to MSFC. Analytical solutions for the problems are not part of this program.

(b) Estimate costs or magnitude of problems associated with modifying the stage for FLOX use. This will include material compatibility, subsystem operation and design, engine operation and design and operational requirements.

(c) Establish more precisely the magnitude of the performance increment that may be achieved with the addition of fluorine to the S-IC stage LOX/RP-1 propellant system. This will include theoretical propellant considerations and practical stage and MSFC supplied engine factors.

(d) Identify areas that require testing to determine or confirm feasibility.

IV. Technical Approach

1. Technical Data: The contractor will review state-of-the-art data supplied by MSFC. Further examination or "state-of-the-art" trips will be coordinated with MSFC

2. Safety

A review will be made of MSFC supplied information relative to investigation of the handling and safety factors involved in using FLOX on the S-IC stage.

(a) First order investigations of static firing problems.

   (1) Problems associated with the filtering, neutralization or disposal of vented fluorine or FLOX.

   (2) Exhaust gas collection, neutralization, or disposal techniques.

   (3) Problems associated with disposal of FLOX during emergency drain on pad.

(b) First order studies on handling.

   (1) Cleaning and passivation requirements.

   (2) Propellant loading and replenishing.

   (3) Maintaining desired fluorine concentrations.

3. Theoretical Propellant Performance

For percentages of 0 to 70% fluorine concentrations in LOX, performance will be calculated as a function of mixture ratio.

Available data on physical, thermodynamic and transport properties of FLOX mistures (0% - 70%) will be assembled. These include data currently being experimentally determined in a Boeing funded R&D program. Required but unavailable data will be estimated or calculated.

4. Process Control and Materials Parameter Study

The contractor will analyze the information and test data obtained from the MSFC supplied information. Upon completion of the data compilation and analysis, the contractor will, if required, prepare and estimate a level of effort for a further program to obtain the parametric solution techniques required in establishing S-IC FLOX feasibility and design requirements. Areas of primary concern include static and dynamic conditions including corrosion and sensitivity, environmental effects, toxicity effects, cleaning and contamination. These data are necessary for a first order determination of required material replacement as a function of percentage of fluorine. This will form the basis for a portion of the cost effectiveness studies on the stage.

5. Practical S-IC Stage Considerations

The use of increasing percentages of fluorine may impose more critical requirements on all of the S-IC stage systems. This study will pinpoint anticipated problem areas and make recommendations for follow-on work on pressurization, vent, propellant delivery systems and base heating. Analytical work on geysering will be applied to establish the existence, if any, of a geysering problem.

Inert stage weights for performance studies of this phase will be based on Boeing Saturn V uprating studies. Stage performance studies will be conducted to translate other stage work into payload versus percent fluorine. Structural design problems, other than materials, are expected to be developed in the normal manner. The LOR mission will be emphasized; however, data will also be generated for earth orbit missions. Trajectories and time histories will be generated and trade studies will be conducted to show the influence on performance from the significant variables. Items that will receive primary consideration in the system and stage optimization studies are engine mixture ratio, propellant loading or stage mixture ratio, thrust limits and Isp effects.

The feasibility of eliminating the present ignition system in favor of hypergolic FLOX/RP-1 ignition and its associated reliability and weight improvements will be determined.

The following problem areas will be identified with emphasis on critical areas. A listing of items peculiar to MILA or MTO will be supplied to MSFC.

(a) Problems associated with the filtering or disposal of vented fluorine or FLOX gases.

(b) Problems associated with disposal of FLOX during emergency drain on launch pad or static firing site.

(c) Range safety problems such as shut-down capability at the pad, abort considerations, etc.

(d) Stand-by problems associated with stratification, boil-off, and frost build up.

6. Cost Effectiveness

The results of the literature searches and analytical work will form the basis for a cost study. Since it seems desirable to reduce the solution to a cost basis, the output of this work will be cost per pound of payload increase as a function of increasing percentages of fluorine. This will be compared with other uprating techniques based on available data.

V. Study Outputs

1. Overall feasibility of FLOX on the S-IC Stage

Overall feasibility of FLOX on the S-IC stage will be evaluated in terms of the cost per pound of payload. Cost data, related assumptions, and estimated schedules will be included in the final report. Recommendations will be made for continued FLOX work if it seems attractive or for reoriented efforts.

2. Performance Gains

Expected performance gains will be presented as a function of fluorine percentage, and an operational mixture ratio will be recommended.

Areas where redesign or material substitution are necessary will be identified.

3. Test Recommendations

Recommendations for testing will be presented.

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