C&R TECHNOLOGIES®

Sample Problem Appendix | User's Manual | October 2005

SINDA/FLUINT

General Purpose Thermal/Fluid Network Analyzer

Version 4.8

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SINDA SAMPLE PROBLEM: SATELLITE DEPLOYMENT

This problem predicts the thermal transients during deployment of a cubic “satellite” from within a cubic “cargo bay.” This problem was chosen to demonstrate the following SINDA features:

1. the use of submodels and BUILD commands
2. the use of steady-state, transient, and parametric runs
3. the use of array data and time-varying sources
4. the use of external radiation analysis programs such as Thermal Desktop/RadCAD®
5. the use of user character array (CARRAY) data
6. the use of user-defined files (USER1 and USER2)
7. the use of sink temperatures for model reduction

S.1 Problem Description

A hollow cubic satellite is hovering centered (i.e., negligible conductive contact) within a hollow cubic cargo bay in low earth orbit. Within the satellite a small solid cube hovers. The cargo bay is initially in a planet-oriented equatorial (β=0˚) low-earth orbit, and is open on the side facing away from earth. When the spacecraft passes behind the earth, the satellite is deployed in the same orbit, and is reoriented to be sun-facing (see Figure S-1 and Figure S-2). The initial and final orbital-average conditions of the satellite are desired, as well as a simulation of the deployment event. Also, the sensitivity to internal emissivity in the stowed condition is desired,

The relevant characteristics are:

Cargo bay (insulated on outside):		
	Number of panels	5
	Overall size	2 ft x 2 ft x 2 ft
	Panel thickness	negligibly thin
	Material	Aluminum
Satellite:		
	Number of panels	6
	Overall size	1 ft x 1 ft x 1 ft
	Panel thickness	1/8 inch
	Enclosed solid cube size	1 in. x 1 in x 1 in.
	Material	Aluminum
All active surfaces:		
	IR emissivity	0.8
	Solar absorptivity	0.2
	Insulated at edges.	

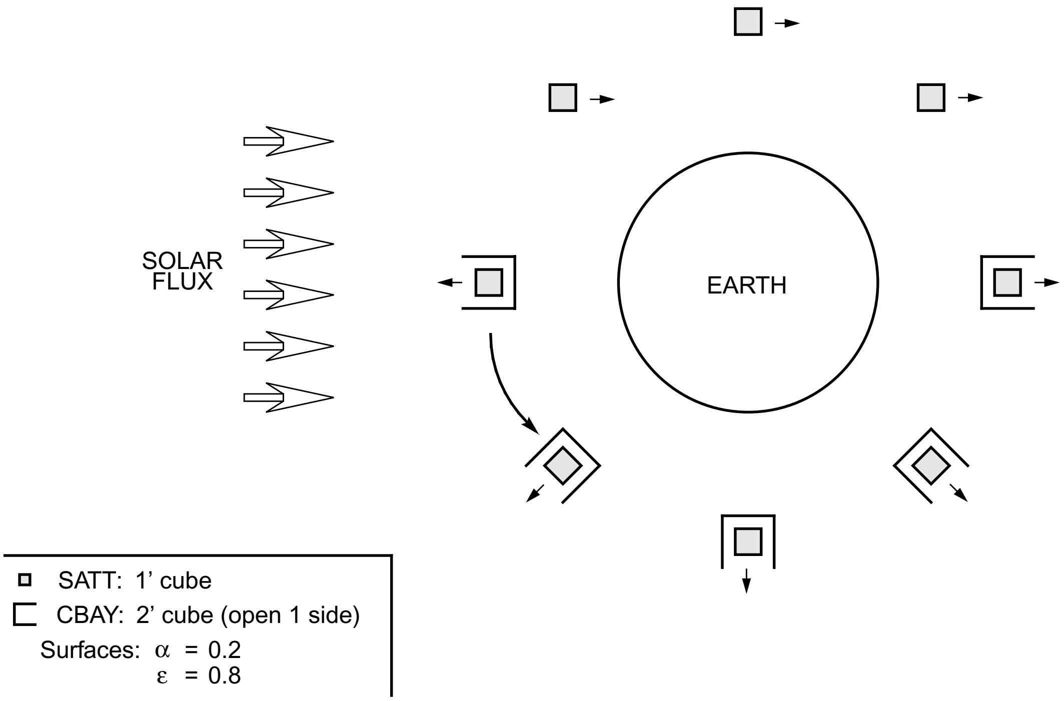

Figure S-1 Satellite Deployment Scenario

S.2 A SINDA Model

The modeling choices reflect the importance of radiation exchange in the simulation and the lack of conduction between surfaces. The lack of conduction means that each surface can be characterized by a single temperature, and therefore can be adequately modeled by a single node. This assumes that the temperature drop through the thickness of the thin satellite panels is negligible; a single node is used to characterize both internal and external radiative exchange. Similarly, only one node is chosen to represent the response of the 1 inch solid cube. The thermal capacitance of the cargo bay is ignored; arithmetic nodes are used to represent panels of negligible mass. This would be a good approximation if the cargo bay were insulated internally.

A separate analysis is required to characterize the radiation exchange between the sun, the earth, the satellite, and the cargo bay, and to determine the heat flux deposition history on the spacecraft surfaces. In this sample, such factors were supplied by the RadCAD® module of C&R’s Thermal Desktop, which can output SINDA/FLUINT style inputs including submodel distinctions.* Most of the input file was therefore computer generated. However, because a discussion of such procedures is beyond the scope of this manual, the reader may disregard the method by which these inputs were derived.

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* Use of Thermal Desktop as a means of supplying data for SINDA/FLUINT Insert Files is considered an anachronism. Such an outdated mode is preserved here because the emphasis is on demonstrating SINDA/FLUINT usage as a stand-alone program. Normally, the model would be built entirely within Thermal Desktop and launched using the Case Set Manager.

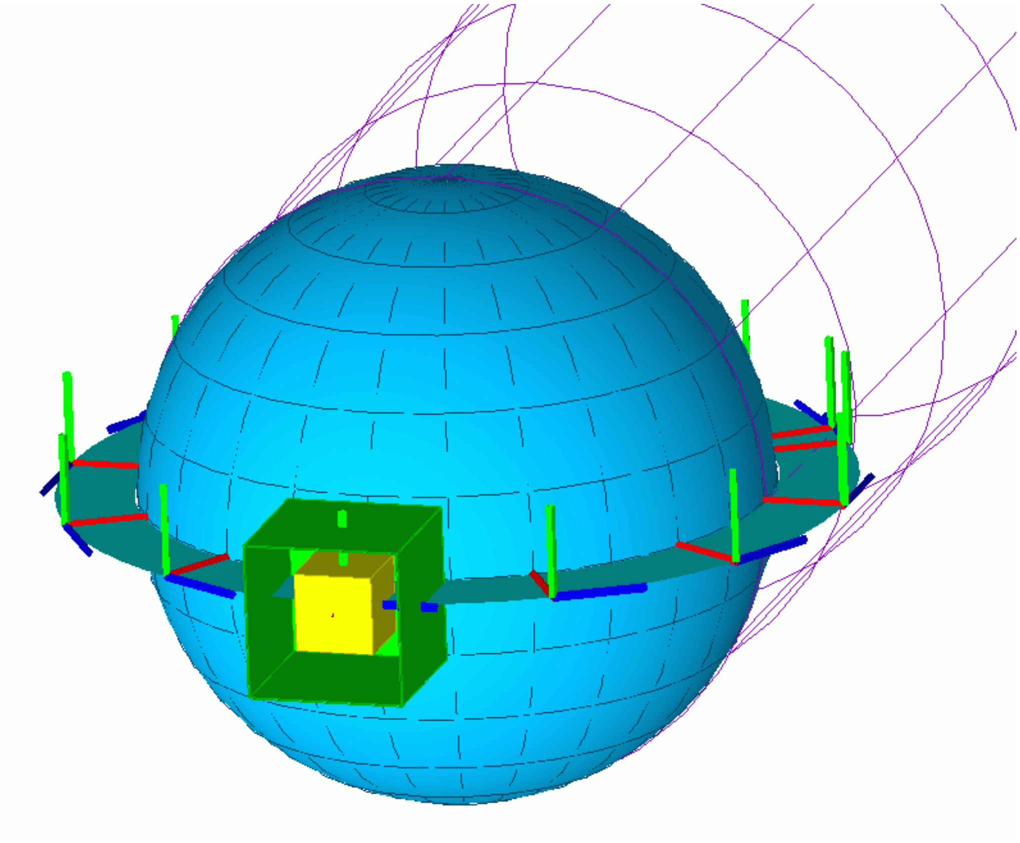

Figure S-2 RadCAD Depiction of Model in Orbit at Initial Position

The scope of such inputs include:

1. Radiation conductors (“RADKs”) between the satellite, the cargo bay, and deep space before deployment,
2. Radiation conductors between the satellite and deep space after deployment (a trivial calculation), and
3. Arrays of impressed heat sources (absorbed earth IR, albedo, and solar) on all exposed surfaces as a functions of time, including initial and final orbital averages.

The radiative exchange within the satellite can be approximated without a geometric radiation analyzer by using an Effective Radiation Node (ERN) approximation, commonly called an “ERN node.” Under this approximation, a nonphysical arithmetic node is introduced to represent the effective temperature of an enclosure, and all internal surfaces are linked to this node (but not directly to each other) by radiation conductors of value εσA, where ε is the surface IR emissivity defined by the register EMISSin, σ is the Stefan-Boltzmann constant (defined by the built-in constant “sbcon” for standard English units), and A is the area of the surface in question. This approximation is very accurate as long as temperature gradients are not severe and no two surfaces have dominant views of each other compared to other surfaces. Because only one node is used to represent the interior solid cube, the radiation conductor for this cube is based on the total surface area (6 in^2).

To summarize the model thus far, there are five arithmetic nodes representing the cargo bay, seven diffusion nodes and one arithmetic node representing the satellite (six surfaces, the interior cube, and the arithmetic ERN node), and one boundary node which is required to represent deep space. The sun and earth appear only as heat sources.

The remaining decisions regarding the model have to do with submodel decisions: Which nodes and conductors belong in how many submodels? To answer these questions, the user must reflect upon the analysis operations to be performed: Which nodes will be active before and after deployment? Which conductors? For this sample, all nodes will be active before deployment, but the cargo bay will disappear after deployment. A different set of radiation conductors will be needed before and after deployment. Therefore, the following decisions are made:

1. The five cargo bay nodes will be contained in a submodel named CBAY along with the entire set of radiation conductors to the interior satellite.
2. The eight satellite nodes will be contained in a submodel named SATT along with the internal radiation conductors.
3. A separate submodel named SPACE will be built that contains a single node: deep space.
4. Another submodel named DEPLOY contains no nodes at all: it contains instead the radiator conductors between SATT and deep space when deployed. It also contains the heat rates and logic associated with this deployed state.

The BUILD and analysis sequences are then:

1. Build SATT and CBAY and SPACE. Get initial conditions using predeployed orbital average fluxes and a steady-state analysis.
2. Start at the subsolar point and run for half an orbit using a transient analysis.
3. Stop, and rebuild with SPACE and SATT and DEPLOY (neglecting CBAY).
4. Complete the orbit using a second transient analysis.

For clarity and convenience, deployment is assumed to occur after only a half orbit has elapsed since the time the analysis was started using orbital average initial conditions. In most true orbital analyses, there is no time-independent state that can be used for initial conditions. Orbital averages are used as good initial guesses, and transients must be run for several complete orbits to launder the effects of an unrealistic starting point. The above short cut would only be acceptable if the characteristic thermal time constant (perhaps CSGMAX) were an order of magnitude smaller than the orbital period.

The above breakdown is certainly not the only possible one. Recall that if both ends of an intermodel conductor are not currently built, then that conductor is ignored and no heat is transferred through it. This helps simplify some of the above decisions: once the CBAY submodel is “unbuilt,” all conductors to it vanish at the same time independent of the submodel into which they are placed. The user therefore need only make sure that all desired conductors are present in each configuration.

This example illustrates an important and powerful use of submodels and should be studied carefully, especially by users of old SINDA versions. Submodels allow more than just easy merging of models or convenient ways to organize a big model. By the methods similar to those outlined above, whole sets of boundary conditions can be exchanged parametrically in one run. To illustrate this point, a single SINDA/FLUINT run can encompass a rocket sitting on the pad for days, launching, staging, and then deploying a payload. Many powerful tools are available to the user who has mastered the use of submodels, including features such as DRPMOD and ADDMOD.

S.3 Preparation for Reduced Model

In addition to the transient orbital analysis, the sensitivity of the model to the internal IR emissivity is desired in the stowed state using orbital average (and therefore steady) conditions.

In a model as simple as this, such a parametric run would be made on the full model. However, to demonstrate the use of sink temperatures for model reduction, the complete model will be used to help build a second reduced model consisting only of the satellite. The environmental effects (heat loads plus radiation connections to the cargo bay) will be replaced in this second model by pairs of sink temperatures and conductors to these sinks: one pair for each external surface.

The “file mode” of the TSINK utility will be used to build a submodel (also called “TSINK”) that can replace the CBAY submodel and all environmental terms. This operation will allow faster second run to be made (on a second and independent input file) exploiting this model reduction technique.

Refer to Section S.6 for a description of this second input file.

S.4 The Input File (First Run: Orbital Analysis)

The input file is listed immediately following the last section.

OPTIONS DATA—Note that two user files (USER1 and USER2) are named. These files will contain summary listings of the transient event. Additional user files will be named later (in OPERATIONS using the USRFIL routine) in order to contain the results of the TSINK call. A map file is also opened to contain comparisons (nodal maps created by NODMAP) between the full and reduced models.

CONTROL DATA—English units are chosen, with units of °F (the default). SIGMA is set to sbcon (1.713E-9 in English units) because this value is *not* already contained within the radiation conductor values in CONDUCTOR DATA. NLOOPS is the maximum iterations attempted for steady-state runs, and is set to 200. OUTPUT is the output interval for transient runs, and is set equal to 1/20th of the orbital period (defined later by the register ORBIT to be 1.531 hours). DTIMEH, the maximum time step for the transient integration routines, is set to 1/500th of the orbital period. This prevents large time steps that would otherwise skip over important changes in boundary conditions, which in this case are orbital flux variations.

REGISTER DATA—The registers defined include: ISS, ORBIT, RhoCpAl, thick, EMISSin, EMISSout, CubeVol, and CubeArea. ORBIT contains the orbital period in hours. RhoCpAl contains the product of density times specific heat for aluminum, and "thick" contains the thickness of the satellite panels.

EMISSin is the emissivity for the internal surfaces of the satellite. Initially EMISSin is equal to 0.8. This value is held constant until the second run, at which time a parametric analysis (Section S.6) is performed. EMISSout, which is constant during the run, is the emissivity of external surfaces.

CubeVol and CubeArea contain the volume and surface area of innermost cube.

Finally, additional user file unit numbers (integer registers NUSER3 and NUSER4) are allocated. These values will be filled via calls to USRFIL in OPERATIONS.

NODE DATA—Three thermal submodels are input: SATT, CBAY, and SPACE. DEPLOY contains no nodes, so need not be input here. GEN commands are used in SATT and CBAY to generate similar nodes. Separate "3 blanks" (plain node) commands are used to generate the remaining nodes. Note the usage of register-containing expressions in the node definitions to perform m•Cp calculations and unit conversions.

Nodal designations are shown in Figure S-3. The names and types of the elements are as follows:

CBAY.1-5. . . . . cargo bay interior (arithmetic)
SATT.11-16 . . . satellite panels (diffusion)
SATT.20. . . . . . enclosed solid cube (diffusion)
SATT.99. . . . . . ERN node
SPACE.999 . . . deep space (boundary)

The temperature of the boundary node is set to "abszro" which a reference to the processor variable: the control constant ABSZRO. This assures they will still be at absolute zero even in the model's units are changed in the future.

CONDUCTOR DATA—Three of the thermal submodels have conductors. DEPLOY is a conductor set whose endpoint nodes are wholly contained within SATT and SPACE, and is used to swap with those conductors contained in the CBAY submodel. GEN commands would have been more convenient in many places, but these sections were generated by computer (file cbay.k). For this reason, the conductor identifiers are not very informative. Note the use of the submodel name to denote nodes not contained within the current submodel (as named on the current HEADER CONDUCTOR DATA record).

ARRAY DATA—(Files cbay.hra and deploy.hra). These blocks contain the arrays referenced in the VARIABLES 1 interpolations described below. These arrays were computer generated as were the interpolation logic itself.

A separate array is added for the submodel SATT: an integer list of the surface nodes for which equivalent sink conditions should be generated using the TSINK utility.

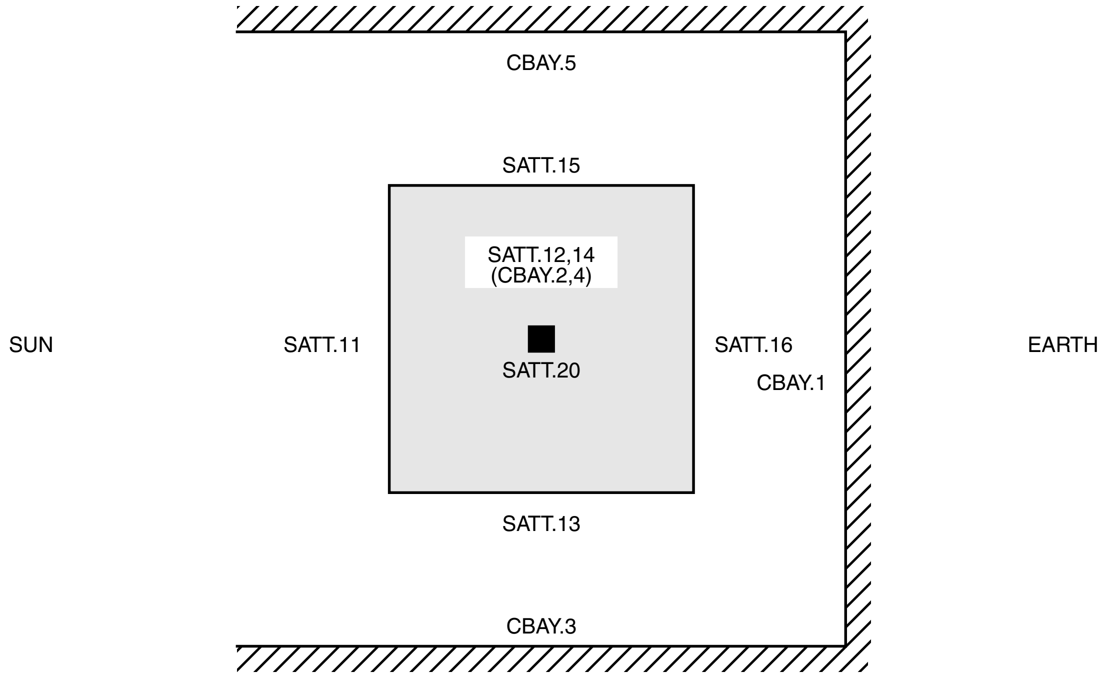

Figure S-3 Nodal Designations Shown in Initial Position

VARIABLES 0—(Files cbay.hrl and deploy.hrl). This logic block is called every time step and every steady-state iteration. It is used here to supply orbital average heat rates (Q values) during the two steady-state runs.[*] Q values in both CBAY and SATT are reset in the variables block for CBAY to reduce logic. A separate VARIABLES 1 block for DEPLOY resets Q values for SATT in the final configuration, when CBAY is not active.[†] Because this logic is only active in steady-states, a check to NSOL is made.

Recall that:

FASTIC . . . . . . NSOL=0 (also called “STEADY”)
STDSTL. . . . . . NSOL=1
FWDBCK. . . . . NSOL=2 (also called “TRANSIENT”)
FORWRD . . . . NSOL=3

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[*] The more modern version of RadCAD uses more advanced methods that avoid excessive preprocessing and are more flexible

[†] Recall that submodel CBAY is not built into the second configuration. No CBAY VARIABLES blocks will be called if CBAY is not active. However, referencing CBAY Q values as done here will not cause problems even when CBAY is not built; those Q values will be changed but never used.

As an aside, note that the fluxes were actually averages for *half* orbits. This violated symmetry for nodes CBAY.3, CBAY.5, SATT.13, and SATT.15. To regain a true orbital average, the fluxes for opposite sides were averaged. This is a minor point made for clarification purposes only.

In transients, interpolation calls are made to keep the sources updated as functions of time. These calls were generated by RadCAD.

OUTPUT CALLS—This logic block defines the output to be produced at each output interval. A call is made to the generic temperature printing routine TPRINT, which will write to the file named in OPTIONS DATA after OUTPUT. Also, a compressed line of important temperatures is written to the user file USER1, and important heat rates are similarly written to user file USER2. Note that the first Fortran line avoids reiterating initial conditions in steady-state runs.

CARRAY DATA—A single character array is used to contain an output status line.

OPERATIONS—This block details the analytic operations to be performed. First, the default model name is set to SATT to avoid extra input. Then, the headers in the user summary files are written.

The first operation is to build a configuration named WHOLE consisting of the submodels SATT, SPACE, and CBAY. Any subsequent operations will be performed as if the DEPLOY submodel were never input. A steady-state is called representing the initial (stowed) orbital average.

The results of this solution are used to generate equivalent sink conditions for a subsequent run using the TSINK utility. The nodes for which sink information is needed is listed in integer array SATT.100: the surface nodes on the cube. The internal nodes (in this case, only the cube and the ERN) are added in the “keep list” (those nodes which will be retained in the subsequent model and which therefore should be excluded from the equivalent sink calculations) simply by stating that all nodes in submodel SATT are to be retained (the third argument in TSINK). Only radiative sinks are needed, and sources are to be included (Qm=1.0) in the sink calculation since they will be absent in the reduced model. The results of the TSINK routine are written to two files (named by the two USRFIL calls preceding the TSINK call). These will become INCLUDE files in the later run.

Node maps are generated for nodes SATT.11 and the ERN, SATT.99. These maps will be compared with those of the reduced model as a check (see Section S.6).

After sink temperatures and node maps are produced using the results of the first solution, a transient is run for the first half of the orbit. This transient uses the orbital average conditions (the results of the last solution) as initial conditions: all solution operations in SINDA/FLUINT are cumulative by default.*

In the second part of the analysis operations, a new configuration PART is built consisting of SATT, SPACE, and DEPLOY. The nodes and conductors in CBAY have now disappeared since they were not named, and have been replaced by the conductors in DEPLOY. The orbital transient is completed, and then a steady-state run is performed.

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* See SVPART, RESPAR, etc. in Section 7 of the main volume for alternative solution sequences.

Remember, even if a model consisted of one and only one submodel (analogous to an old SINDA run), the configuration must be built faithfully with the BUILD command (perhaps using the shortcut “BUILD ALL”), and the default submodel must still be named explicitly with the DEFMOD command to avoid repeating the submodel name in all translated variables.

S.5 Output Description (First Run: Orbital Analysis)

The user summary files and selected printings from the OUTPUT file are listed following the input file. Plots of the temperature histories are presented in Figure S-4.*

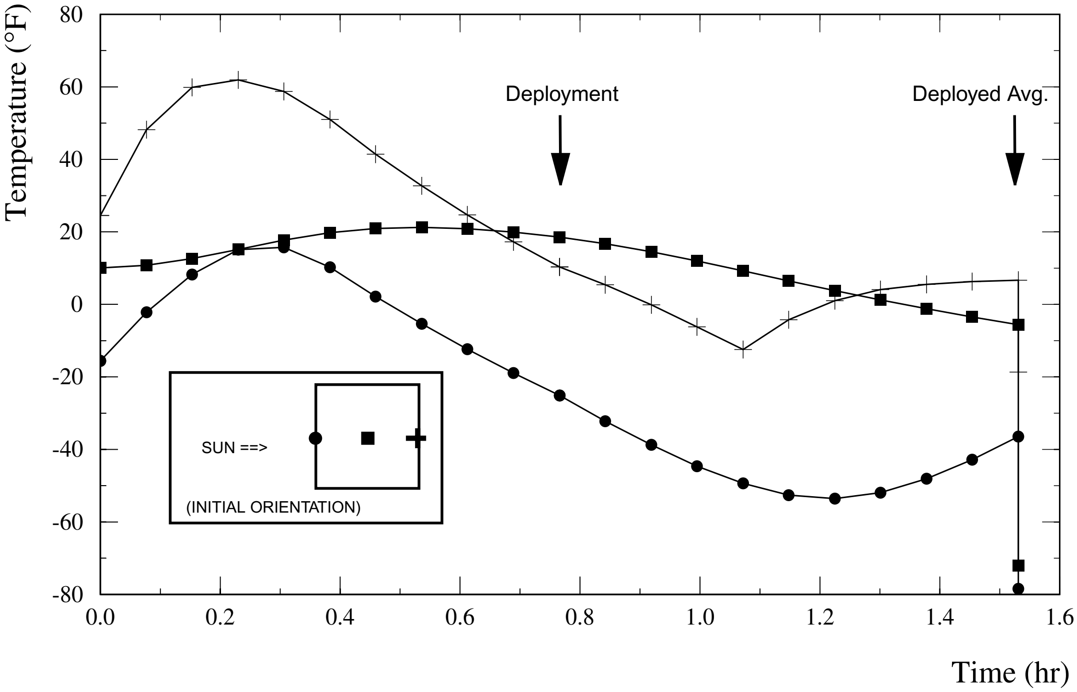

Figure S-4 Initial, Transient, and Final Deployed Temperatures

Because only a half-orbit was run before deployment, the transient results are not especially indicative of system response, except to note maximum temperature swings and the relative isolation of the innermost cube.

More intriguing are the initial and final orbital averages, even though they do not necessarily correspond to a realistically achievable state. For instance, one of the hottest temperatures in the entire initial system is node SATT.16 even though that node never has a direct view of the sun. The reason it is the hottest point is that it has an excellent view to reflected sunlight for half of the orbit, but never has a good view to deep space. This counterintuitive result is caused by the optical properties and the view factors, and underscores the importance of codes like RadCAD in a space environment.

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* Early versions of this sample problem used the obsolete TRASYS program instead of RadCAD. The TRASYS predictions of absorbed fluxes were found to be in error -- they were low by about 10-15%, causing predictions of temperatures that were low by 20 to 30 degrees.

The results of the parametric analysis of internal emissivity (Section S.6) variations are shown in Figure S-5. As the emissivity of node 11 is increased it loses more energy, which results in a decrease in temperature. The remaining nodes increase as they gain the energy lost by node 11.

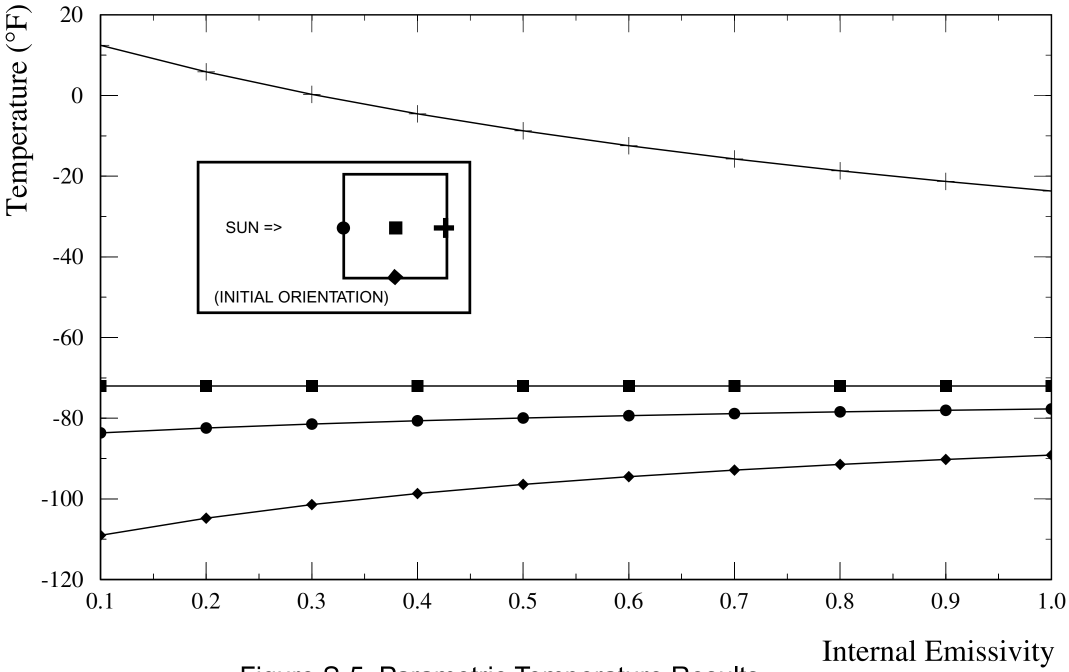

Figure S-5 Parametric Temperature Results

S.6 Reduced Model and Parametric Variations

This variation illustrates the importance of registers and their use in facilitating parametric analyses and sensitivity studies, and should be studied carefully, especially by users of old SINDA versions.

Perhaps performance changes in response to degradations in the internal optical properties of the satellite are of interest, or perhaps a design study must be performed to investigate the effects of different internal paints or coatings on the temperature performance of the satellite. In either case, the above sample problem will be slightly modified to include a quick parametric study of the effects of internal emissivity (EMISSin) variations on the satellite temperatures, using the stowed orbital average fluxes while varying internal panel optical properties for each steady-state run.

In order to further demonstrate the use of sink temperatures (via the TSINK1 or TSINK utilities), the full model will not be used. Rather, the environmental fluxes and conductors (“RADKs”) will be replaced by equivalent sink temperatures with associated conductors: one pair (node/conductor) per surface node on the satellite. Subsequent runs can then eliminate all but the SATT submodel, as long as the same condition (stowed orbital average) applies. The call to TSINK has been described in the previous run. The results of this call can be seen in the sinsampTs.inc and sinsampGs.inc files, which are show below along with the second input file which INSERTs them.

Most RadCAD files can now be excluded (heat rates and associated logic, and most RADKs and the nodes to which they connect), since they have been replaced by the new submodel "TSINK." One exception are the radiation conductances that exist between the surfaces themselves (nodes SATT.11 through SATT.16). Due to reflections, even surfaces without a direct view of each other are connected thermally. Although they are small, they are included for completeness (see the file cbay2.k, whose contents are listed below). This file was formed by editing the former cbay.k file, eliminating excess conductors but also renaming the block SATT instead of CBAY, since the CBAY submodel is now missing.

Because the internal radiation conductors were defined using the register EMISSIN, variations in all such conductors can be quickly explored using the dynamic register feature in SINDA/FLUINT. A series of steady-state runs will be performed using the PSWEEP utility (which is nearly identical in this case to a simple Fortran DO LOOP in OPERATIONS) to evaluate the temperature response of the deployed satellite to internal emissivity variations. The results of this parametric are shown at the end of this example, following the output for the first run.

What if external emissivities had instead varied?* Such a variation would not only eliminate the applicability of a sink temperature assumption, it would require RadCAD calculations to be repeated with each new emissivity value. Fortunately, this is possible using Thermal Desktop's dynamic mode, in which SINDA/FLUINT can re-invoke Thermal Desktop and RadCAD calculations during the coarse of a parametric analysis. Refer to the Thermal Desktop manual for more details.

S.7 A Message to the Novice

A reader new to SINDA may be surprised by the large size of the input deck relative to the simplicity of the system. This is partly due to the "tool box" nature of SINDA/FLUINT; the system must be described within the context of a generalized network which consists of building blocks and tools that model fundamental phenomena. In this sample, the length of the input file is also due to the dominance of radiation. Unlike conduction, where each node only communicates with a few neighboring nodes, a radiating surface can "see" almost all other surfaces because of reflections.

Also, the novice should not be discouraged by failed first attempts. This program is large and intended to be learned over the course of months, not hours. The user will find the learning process well worth the effort. An experienced user can usually stretch the program to fit almost any system, which is infinitely better than reinventing the wheel with a hard-wired, design-specific, user-specific code. Take heart in the fact that even the so-called "expert" who wrote this sample (as well as parts of the code) took about five attempts to get it through the preprocessor, and another five runs to fine-tune the model and the logic to achieve desired results. The moral: start with small models and *think* about the system being modeled.

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* For example, what if the external optical properties needed to be adjusted to better fit test data? See also Section 5 of the main volume for automated calibration of models to test data.

Input File: First Run (Orbital Analysis)

```
HEADER OPTIONS DATA
TITLE SINDA SAMPLE PROBLEM DEMONSTRATING SUBMODELS, PART ONE
         OUTPUT   = sinsamp1.out
         USER1    = sinsamp1.usr
         USER2    = sinsamp1.qsr
         qmap     = sinsamp1.map
C
HEADER CONTROL DATA,GLOBAL
         ABSZRO   = -459.67         $ DEGREES F USED
         SIGMA    = sbcon           $ STEFAN BOLTZMANN (english units)
         NLOOPS   = 200             $ 200 MAX STEADY STATE ITERATIONS
         OUTPUT   = ORBIT/20.0      $ 1/20 ORBIT OUTPUT INTERVAL
         DTIMEH   = ORBIT/500.0     $ 1/500 ORBIT MAX TIME STEP
C
HEADER REGISTER DATA
C ORBIT PERIOD
         ORBIT    = 1.531
C DEFINE THE EMISSIVITY FOR INTERNAL SURFACES
         EMISSin  = 0.8
C DEFINE THE EMISSIVITY FOR EXTERNAL SURFACES
         EMISSout= 0.8
C Density times Density times Cp of Aluminum
         RhoCpAl  = 169.*0.214
C
C Panel thickness (1/8” in feet)
C
         thick    = 0.125/12.0
C
C Cube Volume (1 cu in), and surface area (6 cu in)
C
         CubeVol  = (1.0/12.0)^3
         CubeArea= 6*1.0/12.^2
C
C USER FILE UNITS (TREATED AS INTEGERS IN LOGIC, SET BY USRFIL CALLS)
C
         INT:NUSER3= 0
         INT:NUSER4= 0
C
```

```
HEADER OPERATIONS
C
DEFMOD SATT
         WRITE(NUSER1,1)’TEMPERATURES’,’  TIME’
         WRITE(NUSER2,1)’HEAT RATES’,’  TIME’
1        FORMAT(‘  SUMMARY TABLE OF SINDA SAMPLE PROBLEM: SIMPLIFIED’,
     .   ‘ SATELLITE DEPLOYMENT  ++ ‘,A,’ ++’//
     .    A,T12,’CUBE’,8X,’OUTSIDE’,5X,
     .   ‘INSIDE’,6X,’OTHER SIDE PANELS’,29(‘-’),5X,’STATUS SUMMARY’//)
C
C FIRST HALF OF ORBIT: START WITH ORBITAL AVERAGES
C
BUILD WHOLE,SATT,CBAY,SPACE
         UCA1     = ‘ORBITAL AVERAGE IN CARGO BAY’
         CALL STEADY
C
C WRITE OUT SINK TEMPS FOR FUTURE PARAMETRIC SWEEP WITH REDUCED MODEL
C
         CALL USRFIL(NUSER3,’/space/asta/sinsampGs.inc’,’unknown’)
         CALL USRFIL(NUSER4,’/space/asta/sinsampTs.inc’,’unknown’)
         CALL TSINK(‘SATT’,SATT.NA100,’SATT’,’R’,1.0,NUSER3,NUSER4)
         call nodmap(‘satt’,11,1)
         call nodmap(‘satt’,99,1)
C
         UCA1     = ‘HALF ORBIT IN CARGO BAY’
         TIMEND   = ORBIT/2.0
         CALL TRANSIENT
C
C SECOND HALF OF ORBIT: DEPLOY SATT AND FINISH WITH ORBITAL AVERAGES
C
BUILD PART,SATT,DEPLOY,SPACE
         TIMEND   = ORBIT
         UCA1     = ‘HALF ORBIT AFTER DEPLOYED’
         CALL TRANSIENT
         UCA1     = ‘ORBITAL AVERAGE AFTER DEPLOYED’
         CALL STEADY
C
HEADER ARRAY DATA,SATT
         100 = 11,12,13,14,15,16$ LIST OF NODES FOR WHICH SINK NEEDED
HEADER OUTPUT CALLS,SATT
         IF(NSOL .LE. 1 .AND. LOOPCT .EQ. 0)RETURN
         CALL TPRINT(‘ALL’)
C
C USER FILE (CONDENSED OUTPUT)
C
         WRITE(NUSER1,100)TIMEN,T20,T11,T16,T12,T14,T13,T15,UCA1(1:30)
         WRITE(NUSER2,100)TIMEN,q20,q11,q16,q12,q14,q13,q15,UCA1(1:30)
100      FORMAT(1X,F6.3,T10,1P,7G12.5,5X,A)
C
```

```
HEADER CARRAY DATA,SATT
         1=OUTPUT STATUS LINE
HEADER NODE DATA,SATT
C        11       "OUTSIDE" INITIALLY SUNFACING, FACES SPACE AFTER DEPLOY
C        16       "INSIDE" OPPOSITE 11, FACES SUN AFTER DEPLOY
C        12-15    OTHER SIDES, 12 OPPOSITE 14, 13 OPPOSITE 15
C        20       ENCLOSED 1 INCH CUBE
C        99       ENCLOSURE EFFECTIVE RADIATION NODE
C
         GEN 11,6,1,70.0,RhoCpAl*thick        $ PANELS (1 NODE EACH)
         20,70.0,RhoCpAl*cubeVol              $ 1 INCH CUBE (1 NODE)
         99,70.0,-1.0                         $ ERN NODE
C
HEADER CONDUCTOR DATA,SATT
         GEN -11,6,1,11,1,99,0,EMISSin*1.0$ PANELS TO ERN
         -20,20,99,EMISSin*CubeArea$ ERN TO CUBE
HEADER NODE DATA,SPACE
         -999,abszro,0.0                      $ SPACE SINK
HEADER NODE DATA,CBAY
         GEN 1,5,1,70.0,-1.0                  $ CARGO BAY PANELS
C
C CONDUCTORS TO SPACE WHEN DEPLOYED
C
HEADER CONDUCTOR DATA, DEPLOY
         GEN -1001, 6, 1, SATT.11,1, SPACE.999, 0, EMISSout
C
C GET RADCAD-GENERATED FILES:
C
INSERT cbay.k
INSERT cbay.hra
INSERT cbay.hrl
INSERT deploy.hra
INSERT deploy.hrl
```

```
C CONTENTS OF CBAY.K ===============================================
HEADER CONDUCTOR DATA, CBAY
C      SINDA/FLUINT data created with Thermal Desktop 3.0 Beta 4
C      Generated on Thu Jun 25 09:50:33 1998
C
C          Generated from database BASE-RcOptics.rck
C          Bij/Bji cutoff factor   0.00000
C          Conductor units are: ft^2
C          (more information at end of file)
C
C    format:
C    cond_id     node_1     node_2     area*Bij   $  Bij   Bji
C    (Bij is Fij for view factor data)
C
     -1,      CBAY.1,           SPACE.999,        0.28249  $     0.088278
     -2,      CBAY.2,           SPACE.999,        0.61932  $      0.19354
     -3,      CBAY.3,           SPACE.999,        0.61982  $      0.19369
     -4,      CBAY.4,           SPACE.999,        0.61687  $      0.19277
     -5,      CBAY.5,           SPACE.999,        0.62300  $      0.19469
     -6,      SATT.11,          SPACE.999,        0.64904  $      0.81130
     -7,      SATT.12,          SPACE.999,       0.066508  $     0.083135
     -8,      SATT.13,          SPACE.999,       0.067021  $     0.083777
     -9,      SATT.14,          SPACE.999,       0.066850  $     0.083563
    -10,      SATT.15,          SPACE.999,       0.067927  $     0.084909
    -11,      SATT.16,          SPACE.999,      0.0095085  $     0.011886
    -12,       CBAY.1,             CBAY.2,        0.49292  $      0.15404,    0.15404
    -13,       CBAY.1,             CBAY.3,        0.49455  $      0.15455,    0.15455
    -14,       CBAY.1,             CBAY.4,        0.49356  $      0.15424,    0.15424
    -15,       CBAY.1,             CBAY.5,        0.49418  $      0.15443,    0.15443
    -16,       CBAY.1,            SATT.11,     0.00099867  $   0.00031209,  0.0012483
    -17,       CBAY.1,            SATT.12,       0.053134  $     0.016605,   0.066418
    -18,       CBAY.1,            SATT.13,       0.053475  $     0.016711,   0.066844
    -19,       CBAY.1,            SATT.14,       0.053576  $     0.016742,   0.066970
    -20,       CBAY.1,            SATT.15,       0.053339  $     0.016668,   0.066674
    -21,       CBAY.1,            SATT.16,        0.52934  $      0.16542,    0.66167
    -22,       CBAY.2,             CBAY.3,        0.48610  $      0.15191,    0.15191
    -23,       CBAY.2,             CBAY.4,        0.21867  $     0.068335,   0.068335
    -24,       CBAY.2,             CBAY.5,        0.48286  $      0.15089,    0.15089
    -25,       CBAY.2,            SATT.11,       0.036413  $     0.011379,   0.045516
    -26,       CBAY.2,            SATT.12,        0.52576  $      0.16430,    0.65719
    -27,       CBAY.2,            SATT.13,       0.052554  $     0.016423,   0.065693
    -28,       CBAY.2,            SATT.14,      0.0070383  $    0.0021995,  0.0087978
    -29,       CBAY.2,            SATT.15,       0.052657  $     0.016455,   0.065821
    -30,       CBAY.2,            SATT.16,       0.053933  $     0.016854,   0.067417
    -31,       CBAY.3,             CBAY.4,        0.48699  $      0.15219,    0.15219
    -32,       CBAY.3,             CBAY.5,        0.21848  $     0.068276,   0.068276
    -33,       CBAY.3,            SATT.11,       0.036331  $     0.011354,   0.045414
    -34,       CBAY.3,            SATT.12,       0.052323  $     0.016351,   0.065403
    -35,       CBAY.3,            SATT.13,        0.52585  $      0.16433,    0.65731
    -36,       CBAY.3,            SATT.14,       0.052700  $     0.016469,   0.065875
    -37,       CBAY.3,            SATT.15,      0.0069238  $    0.0021637,  0.0086548
    -38,       CBAY.3,            SATT.16,       0.053933  $     0.016854,   0.067416
    -39,       CBAY.4,             CBAY.5,        0.48520  $      0.15163,    0.15163
    -40,       CBAY.4,            SATT.11,       0.035907  $     0.011221,   0.044884
    -41,       CBAY.4,            SATT.12,      0.0070410  $    0.0022003,  0.0088013
    -42,       CBAY.4,            SATT.13,       0.052757  $     0.016487,   0.065946
    -43,       CBAY.4,            SATT.14,        0.52487  $      0.16402,    0.65609
    -44,       CBAY.4,            SATT.15,       0.053002  $     0.016563,   0.066252
    -45,       CBAY.4,            SATT.16,       0.054214  $     0.016942,   0.067768
```

```
   -46,         CBAY.5,            SATT.11,      0.035652  $    0.011141,  0.044565
   -47,         CBAY.5,            SATT.12,      0.052848  $    0.016515,  0.066060
   -48,         CBAY.5,            SATT.13,     0.0069434  $   0.0021698, 0.0086792
   -49,         CBAY.5,            SATT.14,      0.053016  $    0.016567,  0.066269
   -50,         CBAY.5,            SATT.15,        0.52486  $     0.16402,   0.65607
   -51,         CBAY.5,            SATT.16,      0.054594  $    0.017061,  0.068243
   -52,        SATT.11,            SATT.12,    0.00089299  $   0.0011162, 0.0011162
   -53,        SATT.11,            SATT.13,    0.00083830  $   0.0010479, 0.0010479
   -54,        SATT.11,            SATT.14,    0.00089525  $   0.0011191, 0.0011191
   -55,        SATT.11,            SATT.15,    0.00083622  $   0.0010453, 0.0010453
    -56,     SATT.11,          SATT.16,    4.0876e-005  $  5.1095e-005,5.1095e-005
    -57,      SATT.12,          SATT.13,      0.0023657  $   0.0029572,  0.0029572
   -58,        SATT.12,           SATT.14,     0.00022904  $  0.00028630,0.00028630
   -59,        SATT.12,           SATT.15,      0.0023746  $   0.0029682, 0.0029682
   -60,        SATT.12,           SATT.16,      0.0024888  $   0.0031110, 0.0031110
   -61,        SATT.13,           SATT.14,      0.0024088  $   0.0030111, 0.0030111
   -62,        SATT.13,           SATT.15,     0.00022597  $  0.00028246,0.00028246
   -63,        SATT.13,           SATT.16,      0.0024119  $   0.0030149, 0.0030149
   -64,        SATT.14,           SATT.15,      0.0023453  $   0.0029316, 0.0029316
   -65,        SATT.14,           SATT.16,      0.0024784  $   0.0030980, 0.0030980
   -66,        SATT.15,           SATT.16,      0.0024605  $   0.0030756, 0.0030756
C
C Summary data for nodes with bij sums < 1.0000 or > 1.0000
C
C Summary data for position 1
C       node            area          rays      emiss        bij     bij     bij
C                                                            sum     self    inact
C           CBAY.1       4.0000     100000    0.80000    0.99949    0.062
C           CBAY.2       4.0000     100000    0.80000    0.99962    0.053
C           CBAY.3       4.0000     100000    0.80000     1.0014    0.053
C           CBAY.4       4.0000     100000    0.80000    0.99984    0.053
C           CBAY.5       4.0000     100000    0.80000     1.0008    0.053
C          SATT.11       1.0000     100000    0.80000    0.99975    0.002
C          SATT.12       1.0000     100000    0.80000    0.99944    0.042
C          SATT.13       1.0000     100000    0.80000     1.0004    0.042
C          SATT.14       1.0000     100000    0.80000    0.99959    0.042
C          SATT.15       1.0000     100000    0.80000     1.0006    0.042
C          SATT.16       1.0000     100000    0.80000    0.99980    0.043

C CONTENTS OF CBAY.HRA =============================================
C SINDA/FLUINT data created with RadCAD Thermal Desktop 3.0 Beta 4
C
C     Generated on              Thu Jun 25 10:15:22 1998
C     Generated from database   BASE-sinsanp-RcOptics.rch
C     Solar flux                429.239 BTU/hr/ft^2
C     Albedo                    0.35
C     Planet flux               70.2139 BTU/hr/ft^2
C     Time units                sec
C
HEADER ARRAY DATA, CBAY
C Time Array
 1=0.000000e+000,1.913750e-001,3.827500e-001,4.628962e-001,4.638148e-001
         5.741251e-001,7.655000e-001
C   Solar, arrays for node CBAY.1
      2= 3.866803e+002,6.186134e+001,  0.0,   0.0,   0.0,   0.0,   0.0
C   Solar, arrays for node CBAY.2
      3= 1.173343e+002,6.801181e+001,  0.0,   0.0,   0.0,   0.0,   0.0
C   Solar, arrays for node CBAY.3
      4= 1.158302e+002,2.512501e+002,  0.0,   0.0,   0.0,   0.0,   0.0
```

```
C   Solar, arrays for node CBAY.4
      5= 1.167593e+002,6.829151e+001,  0.0,  0.0,  0.0,  0.0,  0.0
C   Solar, arrays for node CBAY.5
      6= 1.161674e+002,4.292244e+001,  0.0,  0.0,  0.0,  0.0,  0.0
C   Solar, arrays for node SATT.11
      7= 8.835480e+001,6.563374e+001,  0.0,  0.0,  0.0,  0.0,  0.0
C   Solar, arrays for node SATT.12
      8= 2.432099e+001,1.522803e+001,  0.0,  0.0,  0.0,  0.0,  0.0
C   Solar, arrays for node SATT.13
      9= 2.373689e+001,4.075434e+001,  0.0,  0.0,  0.0,  0.0,  0.0
C   Solar, arrays for node SATT.14
     10= 2.379765e+001,1.434728e+001,  0.0,  0.0,  0.0,  0.0,  0.0
C   Solar, arrays for node SATT.15
     11= 2.434319e+001,7.005503e+00,  0.0,  0.0,  0.0,  0.0,  0.0
C   Solar, arrays for node SATT.16
     12= 5.467846e+001,1.283601e+001,  0.0,  0.0,  0.0,  0.0,  0.0
C
C CONTENTS OF CBAY.HRL ============================================
HEADER VARIABLES 0, CBAY
C
C The variable NSOL is set by the solution routines
C Its value is 1 or -1 if stdstl or fastic have been called.
C
C Note that sides 3,5 and 13,15 are averaged because these
C fluxes were calculated for an asymmetric orbit
C
      IF(NSOL .GT. 1) THEN
          CALL D11MDA(TIMEM,A1,A2,1.,CBAY.Q1)
          CALL D11MDA(TIMEM,A1,A3,1.,CBAY.Q2)
          CALL D11MDA(TIMEM,A1,A4,1.,CBAY.Q3)
          CALL D11MDA(TIMEM,A1,A5,1.,CBAY.Q4)
          CALL D11MDA(TIMEM,A1,A6,1.,CBAY.Q5)
          CALL D11MDA(TIMEM,A1,A7,1.,SATT.Q11)
          CALL D11MDA(TIMEM,A1,A8,1.,SATT.Q12)
          CALL D11MDA(TIMEM,A1,A9,1.,SATT.Q13)
          CALL D11MDA(TIMEM,A1,A10,1.,SATT.Q14)
          CALL D11MDA(TIMEM,A1,A11,1.,SATT.Q15)
          CALL D11MDA(TIMEM,A1,A12,1.,SATT.Q16)
      ELSE
C   Average heating rates - solar albedo planet
          CBAY.Q1 = 6.380037e+001
          CBAY.Q2 = 3.166973e+001
          CBAY.Q3 = 7.729131e+001
          CBAY.Q4 = 3.166780e+001
          CBAY.Q5 = 2.525154e+001
          ATEST = (CBAY.Q3+CBAY.Q5)*.5
          CBAY.Q3 = ATEST
          CBAY.Q5 = ATEST
          SATT.Q11 = 2.745278e+001
          SATT.Q12 = 6.847129e+000
          SATT.Q13 = 1.315570e+001
          SATT.Q14 = 6.561526e+000
          SATT.Q15 = 4.794274e+000
          SATT.Q16 = 1.004381e+001
          ATEST = (SATT.Q13+SATT.Q15)*.5
          SATT.Q13 = ATEST
          SATT.Q15 = ATEST
      ENDIF
```

```
C CONTENTS OF DEPLOY.HRA ==============================================
C SINDA/FLUINT data created with RadCAD Thermal Desktop 3.0 Beta 4
C
C     Generated on             Thu Jun 25 12:49:35 1998
C     Generated from database  BASE-sinsanp-RcOptics.rch
C     Solar flux               429.239 BTU/hr/ft^2
C     Albedo                   0.35
C     Planet flux              70.2139 BTU/hr/ft^2
C     Time units               sec
C
HEADER ARRAY DATA, DEPLOY
C Time Array
      1= 7.655000e-001,9.568750e-001,1.067185e+000,1.068104e+000,1.148250e+000
         1.339625e+000,1.531000e+000
C   Albedo, Planetary arrays for node SATT.11
      2=           0.0,2.105797e+000,9.181647e+000,9.181647e+000,1.670099e+001
         5.113816e+001,7.698719e+001
C   Albedo, Planetary arrays for node SATT.12
      3= 1.663198e+001,1.660682e+001,1.679658e+001,1.679658e+001,1.694666e+001
         2.303428e+001,2.557895e+001
C   Albedo, Planetary arrays for node SATT.13
      4= 1.661427e+001,2.071449e+000,          0.0,          0.0,          0.0
         2.785763e+000,2.545740e+001
C   Albedo, Planetary arrays for node SATT.14
      5= 1.679688e+001,1.661840e+001,1.672988e+001,1.672988e+001,1.691685e+001
         2.292814e+001,2.560221e+001
C   Albedo, Planetary arrays for node SATT.15
      6= 1.666788e+001,3.761446e+001,4.756657e+001,4.756657e+001,5.084436e+001
         5.232275e+001,2.554244e+001
C   Solar, Albedo, Planetary arrays for node SATT.16
      7= 5.021540e+001,3.758260e+001,2.550934e+001,1.113571e+002,1.032532e+002
         8.882850e+001,8.584780e+001
C
C CONTENTS OF DEPLOY.HRA ==============================================
HEADER VARIABLES 0, DEPLOY
C
C The variable NSOL is set by the solution routines
C Its value is 1 or -1 if stdstl or fastic have been called.
C
      IF(NSOL .GT. 1) THEN
          CALL D11MDA(TIMEM,A1,A2,1.,SATT.Q11)
          CALL D11MDA(TIMEM,A1,A3,1.,SATT.Q12)
          CALL D11MDA(TIMEM,A1,A4,1.,SATT.Q13)
          CALL D11MDA(TIMEM,A1,A5,1.,SATT.Q14)
          CALL D11MDA(TIMEM,A1,A6,1.,SATT.Q15)
          CALL D11MDA(TIMEM,A1,A7,1.,SATT.Q16)
      ELSE
C   Average heating rates - solar albedo planet
          SATT.Q11 = 2.693814e+001
          SATT.Q12 = 1.942243e+001
          SATT.Q13 = 6.364202e+000
          SATT.Q14 = 1.940807e+001
          SATT.Q15 = 4.075850e+001
          SATT.Q16 = 7.268327e+001
          ATEST = (SATT.Q13+SATT.Q15)*.5
          SATT.Q13 = ATEST
          SATT.Q15 = ATEST
      ENDIF
```

Input File: Second Run (Parametric using a Simplified Model)

```
HEADER OPTIONS DATA
TITLE SINDA SAMPLE PROBLEM DEMONSTRATING SUBMODELS, PART TWO
         OUTPUT   = sinsamp2.out
         USER1    = sinsamp2.usr
C        USER2    = sinsamp2.qsr
         qmap     = sinsamp2.map
C
HEADER CONTROL DATA,GLOBAL
         ABSZRO   = -459.67         $ DEGREES F USED
         SIGMA    = sbcon           $ STEFAN BOLTZMANN (english units)
         NLOOPS   = 200             $ 200 MAX STEADY STATE ITERATIONS
C
HEADER REGISTER DATA
C DEFINE THE EMISSIVITY FOR INTERNAL SURFACES
         EMISSin  = 0.8
C DEFINE THE EMISSIVITY FOR EXTERNAL SURFACES
         EMISSout= 0.8
C Density times Density times Cp of Aluminum
         RhoCpAl  = 169.*0.214
C
C Panel thickness (1/8″ in feet)
C
         thick    = 0.125/12.0
C
C Cube Volume (1 cu in), and surface area (6 cu in)
C
         CubeVol  = (1.0/12.0)^3
         CubeArea= 6*1.0/12.^2
C
```

```
HEADER OPERATIONS
C
DEFMOD SATT
         WRITE(NUSER1,1)’TEMPERATURES’,’  EMIS’
1        FORMAT(‘  SUMMARY TABLE OF SINDA SAMPLE PROBLEM: SIMPLIFIED’,
     .   ‘ SATELLITE DEPLOYMENT  ++ ‘,A,’ ++’//
     .    A,T12,’CUBE’,8X,’OUTSIDE’,5X,
     .   ‘INSIDE’,6X,’OTHER SIDE PANELS’,29(‘-’),5X,’STATUS SUMMARY’//)
C
C FIRST HALF OF ORBIT: START WITH ORBITAL AVERAGES
C
BUILD WHOLE,SATT,TSINK
         UCA1     = ‘COMPARISON WITH FULL MODEL’
         CALL STEADY
         call nodmap(‘satt’,11,1)
         call nodmap(‘satt’,99,1)
         write(nuser1,*)’ ‘
C
C NOW DO PARAMETRIC SWEEP OF EMISSin: 0.1, 0.2, ... 1.0
C
         UCA1     = ‘ORBITAL AVERAGE IN CARGO BAY’
         CALL PSWEEP(‘EMISSin’,0.1,1.0,10,’steady’)
C
HEADER OUTPUT CALLS,SATT
         IF(NSOL .LE. 1 .AND. LOOPCT .EQ. 0)RETURN
         CALL TPRINT(‘ALL’)
C
C PARAMETRIC
C
         CALL GPRINT(‘ALL’)
         CALL REGTAB
         WRITE(NUSER1,100)EMISSin,T20,T11,T16,T12,T14,T13,T15,UCA1(1:30)
100      FORMAT(1X,F6.3,T10,1P,7G12.5,5X,A)
C
HEADER CARRAY DATA,SATT
         1=OUTPUT STATUS LINE
```

```
HEADER NODE DATA,SATT
C        11       "OUTSIDE" INITIALLY SUNFACING, FACES SPACE AFTER DEPLOY
C        16       "INSIDE" OPPOSITE 11, FACES SUN AFTER DEPLOY
C        12-15    OTHER SIDES, 12 OPPOSITE 14, 13 OPPOSITE 15
C        20       ENCLOSED 1 INCH CUBE
C        99       ENCLOSURE EFFECTIVE RADIATION NODE
C
         GEN 11,6,1,70.0,RhoCpAl*thick       $ PANELS (1 NODE EACH)
         20,70.0,RhoCpAl*cubeVol             $ 1 INCH CUBE (1 NODE)
         99,70.0,-1.0                        $ ERN NODE
HEADER CONDUCTOR DATA,SATT
         GEN -11,6,1,11,1,99,0,EMISSin*1.0   $ PANELS TO ERN
         -20,20,99,EMISSin*CubeArea          $ ERN TO CUBE
C
C GET RADCAD-GENERATED AND TSINK-GENERATED FILES:
C
INSERT cbay2.k
INSERT sinsampTs.inc
INSERT sinsampGs.inc
```

```
C CONTENTS OF CBAY2.K ==============================================
HEADER CONDUCTOR DATA, SATT
C
C         SATT to SATT connections only
C
C     SINDA/FLUINT data created with Thermal Desktop 3.0 Beta 4
C     Generated on Thu Jun 25 09:50:33 1998
C
C         Generated from database BASE-RcOptics.rck
C         Bij/Bji cutoff factor   0.00000
C         Conductor units are: ft^2
C         (more information at end of file)
C
C   format:
C   cond_id    node_1     node_2     area*Bij   $  Bij   Bji
C   (Bij is Fij for view factor data)
   -52,          SATT.11,         SATT.12,    0.00089299  $  0.0011162, 0.0011162
   -53,          SATT.11,         SATT.13,    0.00083830  $  0.0010479, 0.0010479
   -54,          SATT.11,         SATT.14,    0.00089525  $  0.0011191, 0.0011191
   -55,          SATT.11,         SATT.15,    0.00083622  $  0.0010453, 0.0010453
   -56,         SATT.11,         SATT.16,   4.0876e-005  $ 5.1095e-005,5.1095e-005
   -57,          SATT.12,         SATT.13,     0.0023657  $  0.0029572, 0.0029572
   -58,          SATT.12,         SATT.14,    0.00022904  $ 0.00028630,0.00028630
   -59,          SATT.12,         SATT.15,     0.0023746  $  0.0029682, 0.0029682
   -60,          SATT.12,         SATT.16,     0.0024888  $  0.0031110, 0.0031110
   -61,          SATT.13,         SATT.14,     0.0024088  $  0.0030111, 0.0030111
   -62,          SATT.13,         SATT.15,    0.00022597  $ 0.00028246,0.00028246
   -63,          SATT.13,         SATT.16,     0.0024119  $  0.0030149, 0.0030149
   -64,          SATT.14,         SATT.15,     0.0023453  $  0.0029316, 0.0029316
   -65,          SATT.14,         SATT.16,     0.0024784  $  0.0030980, 0.0030980
   -66,          SATT.15,         SATT.16,     0.0024605  $  0.0030756, 0.0030756


C CONTENTS OF sinsampTs.inc ==============================================
CHEADER CONTROL DATA, GLOBAL
C      ABSZRO =  -459.67
HEADER NODE DATA, TSINK
       -11,  -47.04501    , -1.0
       -12,   10.47195    , -1.0
       -13,   18.50525    , -1.0
       -14,   9.950348    , -1.0
       -15,   18.28595    , -1.0
       -16,   38.66858    , -1.0
   -999999,   9.874207    , -1.0


C CONTENTS OF sinsampGs.inc ==============================================
CHEADER CONTROL DATA, GLOBAL
C      SIGMA =   1.71200E-09
HEADER CONDUCTOR DATA, TSINK
       -11,SATT    .      11,      11,  0.7943417
       -12,SATT    .      12,      12,  0.7576140
       -13,SATT    .      13,      13,  0.7586004
       -14,SATT    .      14,      14,  0.7580503
       -15,SATT    .      15,      15,  0.7587088
       -16,SATT    .      16,      16,  0.7555225
```

Processor Output

```
SUMMARY TABLE OF SINDA SAMPLE PROBLEM: SIMPLIFIED SATELLITE DEPLOYMENT  ++ TEMPERATURES ++

TIME     CUBE        OUTSIDE     INSIDE      OTHER SIDE PANELS-----------------------------     STATUS SUMMARY


0.000    10.073      -15.570     24.519      10.290      10.037      14.224      14.115        ORBITAL AVERAGE IN CARGO BAY
0.000    10.073      -15.570     24.519      10.290      10.037      14.224      14.115        HALF ORBIT IN CARGO BAY
0.077    10.793      -2.1548     48.202      24.637      24.332      29.536      27.029        HALF ORBIT IN CARGO BAY
0.153    12.655       8.2662     59.873      34.754      34.392      44.048      34.832        HALF ORBIT IN CARGO BAY
0.230    15.162       15.115     61.932      40.481      40.070      55.773      37.904        HALF ORBIT IN CARGO BAY
0.306    17.741       15.745     58.744      40.934      40.533      57.932      37.170        HALF ORBIT IN CARGO BAY
0.383    19.798       10.255     51.014      36.148      35.809      50.867      32.598        HALF ORBIT IN CARGO BAY
0.459    20.946       2.1776     41.440      28.864      28.596      40.216      26.025        HALF ORBIT IN CARGO BAY
0.536    21.257      -5.3335     32.715      21.844      21.630      30.713      19.549        HALF ORBIT IN CARGO BAY
0.612    20.883      -12.348     24.691      15.110      14.937      22.120      13.236        HALF ORBIT IN CARGO BAY
0.689    19.952      -18.924     17.256      8.6668      8.5256      14.265      7.1209        HALF ORBIT IN CARGO BAY
0.766    18.570      -25.111     10.325      2.5095      2.3928      7.0222      1.2216        HALF ORBIT IN CARGO BAY
0.766    18.570      -25.111     10.325      2.5095      2.3928      7.0222      1.2216        HALF ORBIT AFTER DEPLOYED
0.842    16.748      -32.205     5.4254     -6.4963     -6.5662     -3.4141     -6.7352        HALF ORBIT AFTER DEPLOYED
0.919    14.521      -38.728   -0.11414     -14.525     -14.568     -13.634     -12.371        HALF ORBIT AFTER DEPLOYED
0.995    11.995      -44.621    -6.1946     -21.736     -21.770     -23.604     -16.094        HALF ORBIT AFTER DEPLOYED
1.072    9.2575      -49.359    -12.440     -28.233     -28.269     -32.792     -18.389        HALF ORBIT AFTER DEPLOYED
1.148    6.4866      -52.598    -4.2290     -33.967     -34.007     -40.961     -19.739        HALF ORBIT AFTER DEPLOYED
1.225    3.8082      -53.563     1.0328     -38.718     -38.760     -47.958     -20.685        HALF ORBIT AFTER DEPLOYED
1.301    1.2457      -51.920     4.0926     -42.409     -42.459     -53.863     -21.483        HALF ORBIT AFTER DEPLOYED
1.378   -1.1816      -48.080     5.5228     -45.211     -45.272     -58.628     -22.397        HALF ORBIT AFTER DEPLOYED
1.454   -3.4636      -42.827     6.3003     -47.434     -47.495     -61.271     -24.950        HALF ORBIT AFTER DEPLOYED
1.531   -5.5959      -36.448     6.6743     -49.174     -49.228     -61.879     -29.097        HALF ORBIT AFTER DEPLOYED
1.531   -72.017      -78.427    -18.662     -91.459     -91.485     -84.115     -84.115        ORBITAL AVERAGE AFTER DEPLOYED
```

```
SUMMARY TABLE OF SINDA SAMPLE PROBLEM: SIMPLIFIED SATELLITE DEPLOYMENT  ++ HEAT RATES ++

TIME     CUBE        OUTSIDE     INSIDE      OTHER SIDE PANELS-----------------------------     STATUS SUMMARY


0.000    0.0000      27.453      10.044      6.8471      6.5615      8.9750      8.9750        ORBITAL AVERAGE IN CARGO BAY
0.000    0.0000      88.355      54.678      24.321      23.798      23.737      24.343        HALF ORBIT IN CARGO BAY
0.077    0.0000      79.425      38.234      20.747      20.084      30.425      17.529        HALF ORBIT IN CARGO BAY
0.153    0.0000      70.360      21.539      17.119      16.313      37.215      10.612        HALF ORBIT IN CARGO BAY
0.230    0.0000      53.032      10.371      12.304      11.593      32.930      5.6604        HALF ORBIT IN CARGO BAY
0.306    0.0000      26.779      5.2371      6.2130      5.8537      16.628      2.8582        HALF ORBIT IN CARGO BAY
0.383    0.0000     0.52507     0.10269     0.12182     0.11478     0.32604     5.60442E-02    HALF ORBIT IN CARGO BAY
0.459    0.0000      0.0000      0.0000      0.0000      0.0000      0.0000      0.0000        HALF ORBIT IN CARGO BAY
0.536    0.0000      0.0000      0.0000      0.0000      0.0000      0.0000      0.0000        HALF ORBIT IN CARGO BAY
0.612    0.0000      0.0000      0.0000      0.0000      0.0000      0.0000      0.0000        HALF ORBIT IN CARGO BAY
0.689    0.0000      0.0000      0.0000      0.0000      0.0000      0.0000      0.0000        HALF ORBIT IN CARGO BAY
0.766    0.0000      0.0000      0.0000      0.0000      0.0000      0.0000      0.0000        HALF ORBIT IN CARGO BAY
0.766    0.0000      0.0000      50.215      16.632      16.797      16.614      16.668        HALF ORBIT AFTER DEPLOYED
0.842    0.0000     0.82968      45.238      16.622      16.727      10.884      24.921        HALF ORBIT AFTER DEPLOYED
0.919    0.0000      1.6678      40.210      16.612      16.656      5.0964      33.258        HALF ORBIT AFTER DEPLOYED
0.995    0.0000      4.4627      33.561      16.670      16.656      1.3815      40.929        HALF ORBIT AFTER DEPLOYED
1.072    0.0000      9.3754      111.15      16.800      16.735      0.0000      47.651        HALF ORBIT AFTER DEPLOYED
1.148    0.0000      16.557      103.41      16.944      16.913      0.0000      50.782        HALF ORBIT AFTER DEPLOYED
1.225    0.0000      30.200      97.599      19.333      19.273      1.0920      51.424        HALF ORBIT AFTER DEPLOYED
1.301    0.0000      43.975      91.829      21.768      21.678      2.2063      52.015        HALF ORBIT AFTER DEPLOYED
1.378    0.0000      56.101      88.256      23.523      23.442      7.1387      47.181        HALF ORBIT AFTER DEPLOYED
1.454    0.0000      66.441      87.064      24.541      24.511      16.207      36.469        HALF ORBIT AFTER DEPLOYED
1.531    0.0000      76.780      85.872      25.559      25.276      25.628      25.757        HALF ORBIT AFTER DEPLOYED
1.531    0.0000      26.938      72.683      19.422      19.408      23.561      23.561        ORBITAL AVERAGE AFTER DEPLOYED
```

```
                           SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR          PAGE     2

MODEL = SINDA                        SINDA SAMPLE PROBLEM DEMONSTRATING SUBMODELS
  FASTIC


 SUBMODEL NAME = SATT


                                      CALCULATED                               ALLOWED
        MAX DIFF DELTA T PER ITER     DRLXCC(SATT        13)=-1.749140E-03 VS. DRLXCA= 1.000000E-02
        MAX ARITH DELTA T PER ITER    ARLXCC(SATT        99)=-7.985776E-04 VS. ARLXCA= 1.000000E-02
        MAX SYSTEM ENERGY BALANCE     EBALSC                =-8.946990E-03 VS. EBALSA * ESUMIS       = 0.688552
                                                                               EBALSA= 1.000000E-02
        ENERGY INTO AND OUT OF SYS    ESUMIS                =  68.8552         ESUMOS=  0.00000
        MAX NODAL ENERGY BALANCE      EBALNC(SATT        99)=-4.563989E-03 VS. EBALNA=  0.00000
        NUMBER OF ITERATIONS          LOOPCT                =      24      VS. NLOOPS=     200
        PROBLEM TIME                  TIMEN                 =  0.00000     VS. TIMEND=  0.00000

                                    DIFFUSION NODES IN INPUT NODE NUMBER ORDER
  T    11= -15.570     T    12=  10.290     T    13=  14.224     T    14=  10.037     T    15=  14.115     T    16=  24.519
  T    20=  10.073
                                    ARITHMETIC NODES IN INPUT NODE NUMBER ORDER

  T    99=  10.073
                                    HEATER NODES IN INPUT NODE NUMBER ORDER
                                                       ++NONE++
                                    BOUNDARY NODES IN INPUT NODE NUMBER ORDER
                                                       ++NONE++

 SUBMODEL NAME = CBAY


                                      CALCULATED                               ALLOWED
        MAX DIFF DELTA T PER ITER     DRLXCC(             0)=  0.00000     VS. DRLXCA= 1.000000E-02
        MAX ARITH DELTA T PER ITER    ARLXCC(CBAY         4)=-1.888597E-03 VS. ARLXCA= 1.000000E-02
        MAX SYSTEM ENERGY BALANCE     EBALSC                =-4.858403E-03 VS. EBALSA * ESUMIS       =  2.29681
                                                                               EBALSA= 1.000000E-02
        ENERGY INTO AND OUT OF SYS    ESUMIS                =  229.681         ESUMOS=  0.00000
        MAX NODAL ENERGY BALANCE      EBALNC(CBAY         5)=-1.932515E-03 VS. EBALNA=  0.00000
        NUMBER OF ITERATIONS          LOOPCT                =      24      VS. NLOOPS=     200
        PROBLEM TIME                  TIMEN                 =  0.00000     VS. TIMEND=  0.00000

                                    DIFFUSION NODES IN INPUT NODE NUMBER ORDER
                                                       ++NONE++
                                    ARITHMETIC NODES IN INPUT NODE NUMBER ORDER
  T     1=  29.528     T     2=  4.5808     T     3=  12.414     T     4=  4.6442     T     5=  12.298
```

```


MODEL = SINDA                        SINDA SAMPLE PROBLEM DEMONSTRATING SUBMODELS
  FWDBCK


 SUBMODEL NAME = SATT


                                      CALCULATED                               ALLOWED
        MAX DIFF DELTA T PER ITER     DRLXCC(SATT        13)=-6.479022E-06 VS. DRLXCA= 1.000000E-02
        MAX ARITH DELTA T PER ITER    ARLXCC(SATT        99)=-6.433543E-06 VS. ARLXCA= 1.000000E-02
        MAX DIFF DEL T PER TIME STEP  DTMPCC(SATT        11)= 0.274301     VS. DTMPCA= 1.000000E+30
        MAX ARITH DEL T PER TIME STEP ATMPCC(SATT        99)=-3.804698E-03 VS. ATMPCA= 1.000000E+30
        MIN STABILITY CRITERIA        CSGMIN(SATT        16)= 0.602679
        MAX STABILITY CRITERIA        CSGMAX(SATT        20)=  1.07815
        NUMBER OF ITERATIONS          LOOPCT                =       2      VS. NLOOPT=     100
        PROBLEM TIME                  TIMEN                 =  1.53100     VS. TIMEND=  1.53100
        MEAN PROBLEM TIME             TIMEM                 =  1.52947
        AVERAGE TIME STEP USED SINCE LAST OUTPUT            = 3.062000E-03 VS. DTIMEI=  0.00000

                                    DIFFUSION NODES IN INPUT NODE NUMBER ORDER
  T    11= -36.448     T    12= -49.174     T    13= -61.879     T    14= -49.228     T    15= -29.097     T    16=  6.6743
  T    20= -5.5959
                                    ARITHMETIC NODES IN INPUT NODE NUMBER ORDER

  T    99= -34.550
                                    HEATER NODES IN INPUT NODE NUMBER ORDER
                                                       ++NONE++
                                    BOUNDARY NODES IN INPUT NODE NUMBER ORDER
                                                       ++NONE++
```

```
MODEL = SINDA                         SINDA SAMPLE PROBLEM DEMONSTRATING SUBMODELS
  FASTIC

 SUBMODEL NAME = SATT


                                       CALCULATED                               ALLOWED
        MAX DIFF DELTA T PER ITER      DRLXCC(SATT        11)=-1.231005E-04 VS. DRLXCA= 1.000000E-02
        MAX ARITH DELTA T PER ITER     ARLXCC(SATT        99)= 3.116015E-04 VS. ARLXCA= 1.000000E-02
        MAX SYSTEM ENERGY BALANCE      EBALSC                = 3.333868E-04 VS. EBALSA * ESUMIS       =  1.85575
                                                                                EBALSA= 1.000000E-02
        ENERGY INTO AND OUT OF SYS     ESUMIS                =  185.575         ESUMOS=  0.00000
        MAX NODAL ENERGY BALANCE       EBALNC(SATT        15)= 9.944486E-05 VS. EBALNA=  0.00000
        NUMBER OF ITERATIONS           LOOPCT                =        7     VS. NLOOPS=      200
        PROBLEM TIME                   TIMEN                 =  1.53100     VS. TIMEND=  1.53100

                                     DIFFUSION NODES IN INPUT NODE NUMBER ORDER
  T    11= -78.427     T    12= -91.459     T    13= -84.115     T    14= -91.485     T    15= -84.115     T    16= -18.662
  T    20= -72.017
                                     ARITHMETIC NODES IN INPUT NODE NUMBER ORDER
  T    99= -72.017
                                     HEATER NODES IN INPUT NODE NUMBER ORDER
                                                       ++NONE++
                                     BOUNDARY NODES IN INPUT NODE NUMBER ORDER
                                                       ++NONE++
```

RESULTS OF SECOND (REDUCED, PARAMETRIC RUN)

```
SUMMARY TABLE OF SINDA SAMPLE PROBLEM: SIMPLIFIED SATELLITE DEPLOYMENT  ++ TEMPERATURES ++

EMIS     CUBE        OUTSIDE     INSIDE      OTHER SIDE PANELS-----------------------------      STATUS SUMMARY


0.800    10.065      -15.575     24.516      10.286      10.033      14.219      14.111         COMPARISON WITH FULL MODEL

0.100    10.221      -39.145     35.355      10.516      10.059      17.530      17.338         ORBITAL AVERAGE IN CARGO BAY
0.200    10.186      -33.388     32.916      10.471      10.062      16.779      16.606         ORBITAL AVERAGE IN CARGO BAY
0.300    10.161      -28.851     30.905      10.432      10.061      16.163      16.006         ORBITAL AVERAGE IN CARGO BAY
0.400    10.138      -25.183     29.217      10.397      10.058      15.648      15.504         ORBITAL AVERAGE IN CARGO BAY
0.500    10.118      -22.153     27.780      10.365      10.053      15.211      15.078         ORBITAL AVERAGE IN CARGO BAY
0.600    10.107      -19.605     26.545      10.340      10.050      14.838      14.714         ORBITAL AVERAGE IN CARGO BAY
0.700    10.093      -17.436     25.468      10.315      10.045      14.512      14.397         ORBITAL AVERAGE IN CARGO BAY
0.800    10.079      -15.566     24.522      10.293      10.040      14.226      14.118         ORBITAL AVERAGE IN CARGO BAY
0.900    10.068      -13.936     23.684      10.272      10.035      13.974      13.872         ORBITAL AVERAGE IN CARGO BAY
1.000    10.057      -12.504     22.937      10.253      10.029      13.749      13.652         ORBITAL AVERAGE IN CARGO BAY
```

NODE SATT.11: FIRST VS. SECOND RUN

```
                                                       NODE SATT          11

A QMAP OF INPUT DIFF   NODE SATT          11 (INTERNAL      1)

THE PARAMETERS OF NODE SATT          11 ARE:    TEMPERATURE      =  -15.5698     (DEG.)
                                                CAPACITANCE      =  0.376729     (ENERGY/DEG)
                                                NET SOURCE/SINK  =   27.4528     (ENERGY/TIME, INCLUDES TIES)
                                                CAP./SUM OF COND.=  0.525280     (TIME, INCLUDES TIES)


                                        THE ADJOINING NODES TO NODE SATT          11 ARE:

NODE                      CONDUCTOR                      CONDUCTOR     % OF  % OF    HEAT TRANSFER RATE     TEMPERATURE OF
INPUT          (INTERNAL) INPUT    (INTERNAL)    TYPE     VALUE         TYPE  TOTAL   (ENERGY/TIME)          ADJOINING NODE
------------------------- ------------------ --------- ------------- ----- ----- ---------------------- --------------
SATT           99 (      8)       11 (      1)  RADIAT    0.800000      50.1  72.9       13.4116              10.0727
SPACE         999 (      9)        6 (     19)  RADIAT    0.649040      40.6  13.6      -43.2214             -459.670
CBAY            1 (     10)       16 (     29)  RADIAT    9.986700E-04   0.1   0.1      3.141442E-02          29.5284
CBAY            2 (     11)       25 (     38)  RADIAT    3.641300E-02   2.3   3.3      0.470969              4.58081
CBAY            3 (     12)       33 (     46)  RADIAT    3.633100E-02   2.3   3.3      0.669901              12.4140
CBAY            4 (     13)       40 (     53)  RADIAT    3.590700E-02   2.2   3.2      0.465985              4.64423
CBAY            5 (     14)       46 (     59)  RADIAT    3.565200E-02   2.2   3.3      0.654402              12.2980
SATT           12 (      2)       52 (     65)  RADIAT    8.929900E-04   0.1   0.1      1.510820E-02          10.2898
SATT           13 (      3)       53 (     66)  RADIAT    8.383000E-04   0.1   0.1      1.655650E-02          14.2236
SATT           14 (      4)       54 (     67)  RADIAT    8.952500E-04   0.1   0.1      1.498595E-02          10.0374
SATT           15 (      5)       55 (     68)  RADIAT    8.362200E-04   0.1   0.1      1.644952E-02          14.1154
SATT           16 (      6)       56 (     69)  RADIAT    4.087600E-05   0.0   0.0      1.124164E-03          24.5195


                                             THE TOTALS ON NODE SATT          11 ARE:

                    LINEAR HEAT TRANSFER (CONDUCTION/CONVECTION)...   0.00000
                    RADIATION HEAT TRANSFER........................  -27.4530
                    HEAT SOURCE/SINKS APPLIED......................   27.4528
                                                                ---------------
                                                                 -1.811981E-04  (ENERGY/TIME)
                    EFFECTIVE ERN TEMPERATURE......................  -47.4952
```

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                                                      NODE SATT          11

A QMAP OF INPUT DIFF   NODE SATT          11 (INTERNAL      1)

THE PARAMETERS OF NODE SATT          11 ARE:    TEMPERATURE      =  -15.5746     (DEG.)
                                                CAPACITANCE      =  0.376729     (ENERGY/DEG)
                                                NET SOURCE/SINK  =   0.00000     (ENERGY/TIME, INCLUDES TIES)
                                                CAP./SUM OF COND.=  0.395122     (TIME, INCLUDES TIES)


                                        THE ADJOINING NODES TO NODE SATT          11 ARE:

NODE                      CONDUCTOR                      CONDUCTOR     % OF  % OF    HEAT TRANSFER RATE     TEMPERATURE OF
INPUT          (INTERNAL) INPUT    (INTERNAL)    TYPE     VALUE         TYPE  TOTAL   (ENERGY/TIME)          ADJOINING NODE
------------------------- ------------------ --------- ------------- ----- ----- ---------------------- --------------
SATT           99 (      8)       11 (      1)  RADIAT    0.800000      50.1  54.9       13.4105              10.0667
SATT           12 (      2)       52 (      8)  RADIAT    8.929900E-04   0.1   0.1      1.510840E-02          10.2860
SATT           13 (      3)       53 (      9)  RADIAT    8.383000E-04   0.1   0.1      1.655609E-02          14.2189
SATT           14 (      4)       54 (     10)  RADIAT    8.952500E-04   0.1   0.1      1.498609E-02          10.0335
SATT           15 (      5)       55 (     11)  RADIAT    8.362200E-04   0.1   0.1      1.644908E-02          14.1107
SATT           16 (      6)       56 (     12)  RADIAT    4.087600E-05   0.0   0.0      1.124171E-03          24.5159
TSINK          11 (      9)       11 (     23)  RADIAT    0.794342      49.7  44.9      -13.4737             -47.0450


                                             THE TOTALS ON NODE SATT          11 ARE:

                    LINEAR HEAT TRANSFER (CONDUCTION/CONVECTION)...   0.00000
                    RADIATION HEAT TRANSFER........................  1.045227E-03
                    HEAT SOURCE/SINKS APPLIED......................   0.00000
                                                                ---------------
                                                                 1.045227E-03  (ENERGY/TIME)
                    EFFECTIVE ERN TEMPERATURE......................  -15.5735
```

NODE SATT.199: FIRST VS. SECOND RUN

```
                                                         NODE SATT          99

A QMAP OF INPUT ARITH  NODE SATT          99 (INTERNAL      8)

THE PARAMETERS OF NODE SATT          99 ARE:    TEMPERATURE      =   10.0727     (DEG.)
                                                CAPACITANCE      =   0.00000     (ENERGY/DEG)
                                                NET SOURCE/SINK  =   0.00000     (ENERGY/TIME, INCLUDES TIES)
                                                CAP./SUM OF COND.=   0.00000     (TIME, INCLUDES TIES)


                                         THE ADJOINING NODES TO NODE SATT          99 ARE:

NODE                      CONDUCTOR                        CONDUCTOR     % OF  % OF    HEAT TRANSFER RATE     TEMPERATURE OF
INPUT           (INTERNAL) INPUT    (INTERNAL)   TYPE      VALUE         TYPE  TOTAL    (ENERGY/TIME)         ADJOINING NODE
------------------------- ------------------ --------- ------------- ----- ----- ---------------------- --------------
SATT           11 (     1)        11 (      1)  RADIAT    0.800000      16.6  15.3       -13.4116              -15.5698
SATT           12 (     2)        12 (      2)  RADIAT    0.800000      16.6  16.6       0.123337               10.2898
SATT           13 (     3)        13 (      3)  RADIAT    0.800000      16.6  16.8        2.38848               14.2236
SATT           14 (     4)        14 (      4)  RADIAT    0.800000      16.6  16.6      -2.007087E-02           10.0374
SATT           15 (     5)        15 (      5)  RADIAT    0.800000      16.6  16.8        2.32543               14.1154
SATT           16 (     6)        16 (      6)  RADIAT    0.800000      16.6  17.3        8.58986               24.5195
SATT           20 (     7)        20 (      7)  RADIAT    3.333334E-02   0.7   0.7        0.00000               10.0727


                                              THE TOTALS ON NODE SATT          99 ARE:

                    LINEAR HEAT TRANSFER (CONDUCTION/CONVECTION)...   0.00000
                    RADIATION HEAT TRANSFER........................ -4.564285E-03
                    HEAT SOURCE/SINKS APPLIED......................   0.00000
                                                                   ---------------
                                                                    -4.564285E-03   (ENERGY/TIME)
                    EFFECTIVE ERN TEMPERATURE......................   10.0714
```

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                                                         NODE SATT          99

A QMAP OF INPUT ARITH  NODE SATT          99 (INTERNAL      8)

THE PARAMETERS OF NODE SATT          99 ARE:    TEMPERATURE      =   10.0667     (DEG.)
                                                CAPACITANCE      =   0.00000     (ENERGY/DEG)
                                                NET SOURCE/SINK  =   0.00000     (ENERGY/TIME, INCLUDES TIES)
                                                CAP./SUM OF COND.=   0.00000     (TIME, INCLUDES TIES)


                                         THE ADJOINING NODES TO NODE SATT          99 ARE:

NODE                      CONDUCTOR                        CONDUCTOR     % OF  % OF    HEAT TRANSFER RATE     TEMPERATURE OF
INPUT           (INTERNAL) INPUT    (INTERNAL)   TYPE      VALUE         TYPE  TOTAL    (ENERGY/TIME)         ADJOINING NODE
------------------------- ------------------ --------- ------------- ----- ----- ---------------------- --------------
SATT           11 (     1)        11 (      1)  RADIAT    0.800000      16.6  15.3       -13.4105              -15.5746
SATT           12 (     2)        12 (      2)  RADIAT    0.800000      16.6  16.6       0.124620               10.2860
SATT           13 (     3)        13 (      3)  RADIAT    0.800000      16.6  16.8        2.38919               14.2189
SATT           14 (     4)        14 (      4)  RADIAT    0.800000      16.6  16.6      -1.885153E-02           10.0335
SATT           15 (     5)        15 (      5)  RADIAT    0.800000      16.6  16.8        2.32611               14.1107
SATT           16 (     6)        16 (      6)  RADIAT    0.800000      16.6  17.3        8.59108               24.5159
SATT           20 (     7)        20 (      7)  RADIAT    3.333334E-02   0.7   0.7      -4.341228E-05           10.0648


                                              THE TOTALS ON NODE SATT          99 ARE:

                    LINEAR HEAT TRANSFER (CONDUCTION/CONVECTION)...   0.00000
                    RADIATION HEAT TRANSFER........................  1.612166E-03
                    HEAT SOURCE/SINKS APPLIED......................   0.00000
                                                                   ---------------
                                                                     1.612166E-03   (ENERGY/TIME)
                    EFFECTIVE ERN TEMPERATURE......................   10.0672
```

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                           SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE    52

MODEL = SINDA                   SINDA SAMPLE PROBLEM DEMONSTRATING SUBMODELS, PART TWO
  FASTIC (IN PSWEEP)


 SUBMODEL NAME = SATT


                                      CALCULATED                               ALLOWED
        MAX DIFF DELTA T PER ITER     DRLXCC(SATT        20)=-5.891027E-03 VS. DRLXCA= 1.000000E-02
        MAX ARITH DELTA T PER ITER    ARLXCC(SATT        99)=-4.289800E-03 VS. ARLXCA= 1.000000E-02
        MAX SYSTEM ENERGY BALANCE     EBALSC                =-1.846181E-02 VS. EBALSA * ESUMIS       =  0.00000
                                                                               EBALSA= 1.000000E-02
        ENERGY INTO AND OUT OF SYS    ESUMIS                =  0.00000         ESUMOS=  0.00000
        MAX NODAL ENERGY BALANCE      EBALNC(SATT        12)=-3.066382E-03 VS. EBALNA=  0.00000
        NUMBER OF ITERATIONS          LOOPCT                =       2      VS. NLOOPS=     200
        PROBLEM TIME                  TIMEN                 =  0.00000     VS. TIMEND=  0.00000

                                    DIFFUSION NODES IN INPUT NODE NUMBER ORDER
  T    11= -12.504     T    12=  10.253     T    13=  13.749     T    14=  10.029     T    15=  13.652     T    16=  22.937
  T    20=  10.057
                                    ARITHMETIC NODES IN INPUT NODE NUMBER ORDER
  T    99=  10.053
                                    HEATER NODES IN INPUT NODE NUMBER ORDER
                                                       ++NONE++
                                    BOUNDARY NODES IN INPUT NODE NUMBER ORDER
                                                       ++NONE++





                                    NAMED CALCULATOR REGISTER TABULATION

 NAME        VALUE       EXPRESSION ......

EMISSIN       1.0000        1.0000000
EMISSOUT     0.80000      0.8
RHOCPAL       36.166      169.*0.214
THICK        1.04167E-02  0.125/12.0
CUBEVOL      5.78704E-04  (1.0/12.0)^3
CUBEAREA     4.16667E-02  6*1.0/12.^2
```

PROBLEM A: FILLING TOY BALLOONS

This problem simulates the simultaneous filling of three toy balloons using a pressurized air tank. This problem was chosen to demonstrate the following FLUINT features:

1. the properties of gas-filled tanks
2. the use of compliances (albeit in an extreme case)
3. duplication options
4. user logic for specialized output
5. user logic for customized solutions
6. user-defined gases
7. choked valves
8. the use of registers, conditional expressions, and processor variable references in input
9. the broad range of application of the FLUINT code

A.1 Problem Description

Three identical balloons are to be filled from one air tank (see Figure A-1). There is a hose leading from the supply tank to a tee. Three hand valves are attached to the tee, one for each balloon. The tank is fully charged to 22 atmospheres gauge, the balloons are resting at atmospheric pressure, and the entire system is at room temperature (70°F). At time zero, the hand valves are opened simultaneously and the balloons begin to fill. The simulation ends when each balloon has reached a volume of 1 ft^3. The entire system is assumed adiabatic. The relevant characteristics are:

Balloon:		
	Number of balloons	3
	Initial balloon diameter (spherical)	2 in.
	Final balloon volume	1 ft^3
	Initial thickness	0.005 in.
	Modulus	1500 psi
Tank:		
	Volume	3 ft^3
	Initial pressure	22 atm.
Valve:		
	Open flow area	0.002 sq. in.
	Head loss K-factor	25.0
Hose:		
	Diameter (inner)	1/8 in.
	Length	5 ft

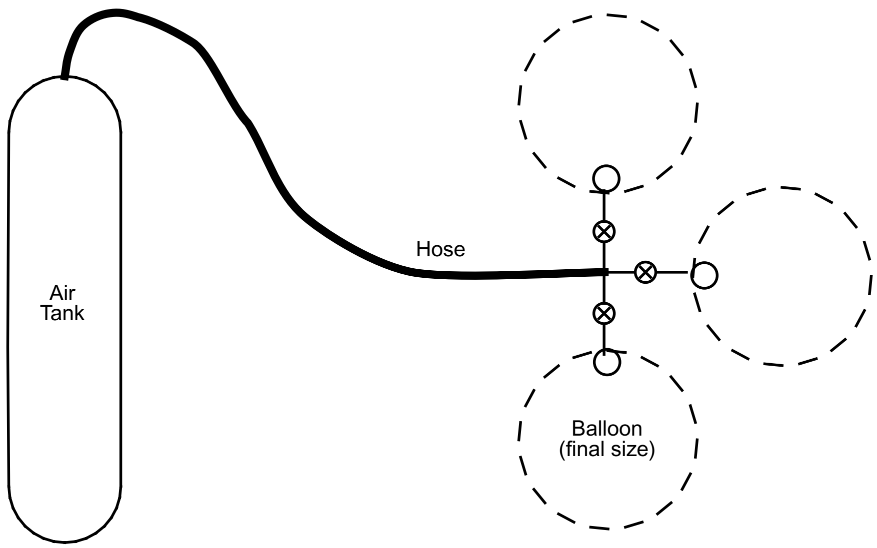


Figure A-1 Toy Balloons Filled from a Tank

A.2 A FLUINT Model

Most modeling choices are clear. Logically, a rigid FLUINT "tank" will be used to model the supply tank. Compliant tanks will be used to model the balloons; this is stretching the intended use of the compliance factor, but is still perfectly valid. Both tanks will be designated as "stagnant" since they represent low-velocity dead-ends. Because hydrodynamic inertia is usually negligible in a gas, an STUBE connector will be used to include the pressure drop in the hose.

The symmetry in the system is obvious. An upstream duplication factor (DUPI) of 3.0 (or register *NumBalon*) applied to a valve will simulate the effects on the tank of filling three balloons, while only one valve and one balloon need be input and analyzed.

The modeling choice for the valve itself is less clear. At first, it might seem desirable to use a CTLVLV connector that is initially closed (negative FK), and then opened at time zero. The user would then use a positive FK value of 25.0 when the valve is open. However, since the value is never actually closed (the problem starts just as the valve opens), a simple LOSS connector will be used.

The large pressure difference between the supply tank (whose pressure should not diminish significantly during the fill) and the balloons (whose pressure will remain near atmospheric) means that the valve is almost certainly choked—the Mach number in the valve throat cannot be greater than unity. For these reasons, the value of the AFTH (throat area) of the LOSS element will be critical. This throat area is often smaller than the smallest physical opening in the device, and is independent of the flow area basis for the K-factor: AF.

Choosing a correct value for the balloon compliance requires some thought. For the purposes of this example, the compliance of the balloon will be estimated roughly. Note that the thickness and the modulus noted above are rough estimates for a rubber balloon. Assuming the modulus remains constant (which it doesn't), the compliance should scale similarly to a flexible line: D/(Et). Note that as the balloon stretches, the thickness decreases in approximate proportion to the inverse of the diameter squared. This means that the compliance can be set to be proportional to the volume. A factor of ten (10D/(Et)) was applied after an initial run showed the compliance to be too low by an order of magnitude; the final balloon pressure was too high by at least an order of magnitude.

A.3 The Input File

The input file is listed immediately following the last section.

OPTIONS DATA—Note that a user file (USER1) is named. This file will contain a summary listing of the transient event.

CONTROL DATA—English units are chosen, with units of °F and psig. The value of TIMEND, the problem end time, is not known in advance. Therefore, TIMEND is set to be initially large (10 hours), but when the balloon volume (the volume of tank 3 in submodel FILLIT -- see FLOW DATA below) exceeds 1 cubic foot, TIMEND is reset to the current problem time, TIMEN ("time now"). Setting TIMEND=TIMEN terminates the run.

The value of OUTPTF, the fluid submodel output interval during a transient defaults to 0.01*TIMEND, which in this case means it will be 0.01*10=0.1 hours: the event will be over before the first output interval is met! Instead, output is desired while the balloon fills: at intervals of approximately 5% (0.05 ft^3). Once again this value is not known in advance, and furthermore, the time interval will vary during the solution.

The expression defining OUTPTF therefore sets the interval as a function of the incoming volumetric flowrate (FR20/DL3: the mass flowrate of path 20 divided by the density of balloon: lump 3).

```
OUTPTF = 0.05*FILLIT.DL3/FILLIT.FR20    $ This wouldn't work!
```

Unfortunately, this above value is undefined initially since FR20 is initialized to zero. Therefore, a minimum value of 0.25 seconds (0.25/3600 hours) is used until FR20 becomes nonzero. Unfortunately, the conditional expression "(FILLIT.FR20 == 0)?" does not prevent the expression evaluator from evaluating "0.05*FILLIT.DL3/FILLIT.FR20" and aborting from a divide by zero. Therefore, a little tolerance is added to avoid arithmetic faults: "0.05*FILLIT.DL3/(FILLIT.FR20+1.0E-10)." The full expression is therefore:

```
OUTPTF = MIN(0.25/3600, 0.05*FILLIT.DL3/(FILLIT.FR20+1.0E-10))
```

REGISTER DATA—A total of eight registers are defined. The initial values and descriptions are listed below:

Register Name	Description	Initial Value	Units
TOTMAS	Total mass in system	unknown	lbm
CVINIT	Initial comp/vol product	unknown	1/(ft^3-psi)
HoseDia	hose diameter	0.125/12	ft.
HoseLen	hose length	5	-
NumBalon	number of balloons	3	ft.
TankPi	supply tank initial pressure	22	atm.
BalonVol	balloon volume	pi*4/3*(BalonDia/2)^2/1728	ft^3
BalonDia	balloon diameter	2	in.

The registers are listed in the same order here as they appeared in the input file. Note that the balloon diameter (BalonDia) is defined after it has been used to calculate the volume (BalonVol). The initial COMP/VOL product is input. Note that multiplying CVINIT times the balloon volume yields the compliance -- see FLOW DATA.

FLOW DATA—Only one submodel is used: a fluid submodel named FILLIT. The working fluid is “8000,” meaning a user-defined gas described elsewhere in the input. The default state is given as the tank temperature and pressure, the balloon initial conditions will override this pressure. The default initial flowrate is zero.

The names and types of the elements are as follows:

TANK 1 . . . . . . supply tank (designated stagnant)
STUBE 10 . . . . hose
JUNC 2 . . . . . . tee between hose and valves
LOSS 20 . . . . . a valve
TANK 3 . . . . . . a single balloon (designated stagnant)

The DUPI for the LOSS connector is 3.0 (NumBalon). The initial balloon compliance will be immediately overridden by user logic in FLOGIC 0, as described next.

FPROP DATA—This data block defines air as perfect gas number 8000. All properties are assumed constant, and are input in SI units (conversions are automatic).

OUTPUT CALLS—This logic block defines the output to be produced at each output interval. Note that a compressed line of important data is written to the user file USER1.

OPERATIONS—Even though there is only one submodel, the configuration must be built faithfully. Also, the default model name is set to avoid extra input. As a check on the conservation of total mass, the initial and final masses (the register *TOTMAS*) are written out. A header for the user summary file is also written here. Prior to performing the analysis, REGTAB is called to write out the all register data. The only analysis operation is a transient using FORWRD, which is identical to the more commonly used FWDBCK (“Transient”) at least when only fluid submodels are active. No steady-state solution is needed. Finally, the endpoint conditions including final mass are written to the user summary file.

A.4 Output Description

The user summary file and selected printings from the OUTPUT file are listed following the input file.

With regard to the output formats and the program response, note that the time step was limited by the volume change of the balloon. Over a volume increase of more than 400 times, the number of time steps required was approximately 100. Note that the total system mass was conserved to better than 5 decimal places throughout the integration of the equations over hundreds of time intervals.

With regard to the physical response of the system, note that almost all of the pressure rise in the balloon occurs within the first few microseconds of the event. The temperature across the valve does not change significantly (there is no Joule-Thomson effect for a perfect gas); the temperature drop in the balloon is due to the temperature drop in the supply tank as its pressure drops. In fact, inspection of the full OUTPUT file reveals that the balloon temperature initially rose by a few tenths of a degree before starting to descend. This was caused by the compression of the gas against the higher compliance of the small balloon. The total fill time was about 6.8 seconds; this seems a little slow—the valve throat area may be too small.

Although this response seems intuitively correct, no experimental data was available. A more comprehensive discussion of this subject can be found in Jearl Walker's Amateur Scientist column in the December 1989 issue of *Scientific American*. This column contains more complete references to other work on toy balloons, and points out the importance of a constant pressure source versus a constant mass flowrate source. Because of choking, this particular sample problem represents the latter rather than the former even though a large supply bottle is used. Walker suggests that the pressure should actually peak in such constant flowrate cases, and then decrease as the radius of curvature increases. Decreasing pressure with increasing volume implies negative compliances in the FLUINT model. Negative compliances are legal although not often used, and can cause instabilities if not used carefully. Unfortunately, this column did not present enough specific information to update the membrane flexibility model used in this sample problem. Fortunately, an accurate model is unnecessary for demonstration purposes.

Input File

```
HEADER OPTIONS DATA
TITLE FLUINT SAMPLE PROBLEM 1 - FILLING AIR BALLOONS
         MODEL    = BALLOON
         USER1    = balloon.usr
         OUTPUT   = balloon.out
C
HEADER CONTROL DATA,GLOBAL
         UID      = ENG
         ABSZRO   = -460.0
         PATMOS   = -14.7
C
C IF VOL OF TANK #3 EXCEEDS 1.0, END RUN, ELSE SET TIMEND LARGE:
C
        TIMEND  = (FILLIT.VOL3 >= 1.0)? TIMEN : 10.0
C
C THIS LOGIC ADJUSTS THE OUTPUT INTERVAL FOR ABOUT EVERY 0.05 CUFT.
C BUT CARE WITH INITIAL CONDITIONS WHERE FR20 = 0.0: USE 1/4 SECOND
C
 OUTPTF=(FILLIT.FR20==0)?0.25/3600:0.05*FILLIT.DL3/(FILLIT.FR20+1.0E-10)
C
C
HEADER REGISTER DATA
C
C TOTAL SYSTEM MASS: (NO DEFAULT MODEL: MUST USE FILLIT PREFIX)
C COULD HAVE USED CALLS TO SUMDFLO FOR MORE COMPLICATED SYSTEMS
C
 TOTMAS  = fillit.VOL1*fillit.DL1 + fillit.DUPI20*fillit.VOL3*fillit.DL3
C
C DIA = 2", THK = 5 MILS, MODULUS = 1500 PSI, INIT VOL = 0.002424
C 10.0 IS A FUDGE FACTOR FOUND BY TRIAL RUNS TO
C BRING PRESSURES INTO AN INTUITIVE RANGE FOR BALLOONS
C
        CVINIT = 10.0*BalonDia/(1500.0*0.005*BalonVol)  $ COMP/VOL INIT
C
C HOSE DIAMETER
         HoseDia  = 0.125/12.0
C HOSE LENGTH
         HoseLen  = 5.0
C NUMBER OF BALLOONS USED IN DEFINING DUPI FOR PATH 20
         NumBalon = 3.0
C SUPPLY TANK INITIAL PRESSURE
         TankPi   = 22.0
C BALLOON INITIAL VOLUME AND DIAMETER
         BalonVol = pi*4/3*(BalonDia/2)^3/1728
         BalonDia = 2.0
```

```
HEADER FLOW DATA,FILLIT,FID=8000    $ SUBMODEL DEFINITION
C
C DEFAULT CONDITIONS (THOSE OF SUPPLY TANK)
C
LU DEF, PL = TankPi*14.7, TL = 70.0, XL = 1.0
PA DEF, FR = 0.0,DH = HoseDia       $ 1/8” DIA
C
LU TANK,1, VOL    = 3.0, LSTAT = STAG$ SUPPLY TANK
PA CONN,10,1,2,DEV= STUBE           $ HOSE
         TLEN     = HoseLen         $ 5’ LONG
LU JUNC,2                           $ TEE TO BALLOONS
PA CONN,20,2,3, DUPI = NumBalon     $ VALVE TO 3 BALLOONS
         DEV      = LOSS
         FK       = 25.0            $ K-FACTOR, UNCHOKED
         AFTH     = 0.002/144.0     $ THROAT AREA
LU TANK,3, VOL    = BalonVol, LSTAT = STAG$ A BALLOON, 2” DIA
         PL       = 0.0             $ AT ATMOSPHERIC PRESS.
C
C THIS LOGIC CHANGES BALLOON COMPLIANCE AS IT FILLS
C PROPORTIONAL TO D/t, t PROPORTIONAL TO 1/D**2, SO
C COMPLIANCE PROPORTIONAL TO VOLUME (DV/DP = CONSTANT)
C
         COMP = CVINIT*VOL#THIS     $ VOL#THIS = VOL OF THIS TANK
C
HEADER FPROP DATA, 8000, SI, 0.0    $ DESCRIBE AIR
         RGAS     = 8314.34/28.97
         CP       = 1002.0
         K        = 7.4E-3
         V        = 5.38E-6
C
HEADER OUTPUT CALLS, FILLIT         $ OUTPUT OPERATIONS
         CALL LMPTAB(’FILLIT’)      $ TEMPS & PRESS
         CALL LMXTAB(’FILLIT’)      $ VOLS & COMPS
         CALL PTHTAB(’FILLIT’)      $ FLOWRATES
C
C NOW, THE CONDENSED TABLE OF PARAMETERS ON USER FILE
C
         WRITE(NUSER1,10) 3600.0*TIMEN,PL(1),FR(20)
     .            ,PL(3),VOL(3),COMP(3)
F10      FORMAT(1X,6(1PG13.5,7X))

HEADER OPERATIONS                   $ LIST OPERATIONS
BUILDF CONFIG,FILLIT
C
DEFMOD FILLIT
         WRITE(NUSER1,10) TOTMAS
C
         CALL REGTAB                $ ECHO REGISTERS
         CALL FORWRD                $ START TRANSIENT
```

```
C
          WRITE(NUSER1,20) TOTMAS,TL1,TL3
100       CONTINUE
FSTART
10        FORMAT(’ THE INITIAL SYSTEM MASS IS:’,T40,1PG13.5///
     .    ’   TIME (SEC)’,T25,’P SUPPLY’,T45,’FLOWRATE’,
     .    T65,’P BALLOON’,T85,’V BALLOON’,T105,’COMPLIANCE’/)
20        FORMAT(//’ THE FINAL SYSTEM MASS IS:’,T40,1PG13.5/
     .    ’ THE FINAL SUPPLY TEMPERATURE IS:’,T40,G13.5/
     .    ’ THE FINAL BALLOON TEMPERATURE IS:’,T40,G13.5)
FSTOP
C
END OF DATA
```

Processor Output

```
THE INITIAL SYSTEM MASS IS:              5.1737


  TIME (SEC)           P SUPPLY           FLOWRATE           P BALLOON          V BALLOON           COMPLIANCE

   0.0000              323.40             0.0000              0.0000            2.42407E-03         2.6667
  0.32180              322.35             42.883             0.34709            5.24409E-02         56.529
  0.64495              321.29             42.765             0.35456            0.10242             109.98
  0.96926              320.24             42.647             0.35687            0.15238             164.12
   1.2947              319.18             42.528             0.35793            0.20233             217.45
   1.6212              318.13             42.410             0.35849            0.25225             271.61
   1.9488              317.08             42.291             0.35882            0.30216             327.02
   2.2774              316.03             42.173             0.35902            0.35204             380.66
   2.6071              314.97             42.055             0.35914            0.40188             432.61
   2.9378              313.92             41.937             0.35922            0.45168             482.93
   3.2697              312.87             41.818             0.35926            0.50147             539.37
   3.6027              311.82             41.699             0.35928            0.55125             595.80
   3.9366              310.77             41.583             0.35929            0.60096             642.82
   4.2717              309.72             41.464             0.35929            0.65066             698.32
   4.6079              308.68             41.345             0.35928            0.70034             753.80
   4.9453              307.63             41.226             0.35926            0.74999             809.26
   5.2838              306.58             41.108             0.35924            0.79963             864.69
   5.6235              305.53             40.989             0.35922            0.84925             920.10
   5.9640              304.49             40.873             0.35919            0.89878             961.46
   6.3057              303.44             40.756             0.35917            0.94828             1015.9
   6.6486              302.40             40.637             0.35914            0.99777             1070.4
   6.8203              301.88             40.578             0.35913             1.0225             1124.8


THE FINAL SYSTEM MASS IS:                5.1737
THE FINAL SUPPLY TEMPERATURE IS:         60.106
THE FINAL BALLOON TEMPERATURE IS:        64.873
```

```
                           SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE     2

MODEL = BALLOON                         FLUINT SAMPLE PROBLEM 1 - FILLING AIR BALLOONS


                                        NAMED CALCULATOR REGISTER TABULATION

 NAME         VALUE       EXPRESSION ......

TOTMAS        5.1737      FILLIT.VOL1*FILLIT.DL1 + FILLIT.DUPI20*FILLIT.VOL3*FILLIT.DL3
CVINIT        1100.1      10.0*BALONDIA/(1500.0*0.005*BALONVOL)
HOSEDIA      1.04167E-02  0.125/12.0
HOSELEN       5.0000      5.0
NUMBALON      3.0000      3.0
TANKPI        22.000      22.0
BALONVOL     2.42407E-03  PI*4/3*(BALONDIA/2)^3/1728
BALONDIA      2.0000      2.0
```

```
                           SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE     3

MODEL = BALLOON                     FLUINT SAMPLE PROBLEM 1 - FILLING AIR BALLOONS
  FORWRD


 FLUID SUBMODEL NAME = FILLIT  ; FLUID NO. = 8000


        MAX TIME STEP =        0.     ; LIMITING MESSAGE = (NO SOLUTION STEP TAKEN YET)
        LAST TIME STEP =        0.     VS. DTMAXF/DTMINF =  1.000000E+30 /        0.    ;   AVERAGE TIME STEP =        0.
        PROBLEM TIME                  TIMEN  =       0.     VS. TIMEND  =  10.0000


                                    LUMP PARAMETER TABULATION FOR SUBMODEL FILLIT

  LUMP  TYPE     TEMP       PRESSURE     QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

     1  TANK    70.00      323.4        1.000        1.000        1.724        126.8           0.           0.           0.
     3  TANK    70.00         0.        1.000        1.000       7.4973E-02    126.8           0.           0.           0.
     2  JUNC    70.00      323.4        1.000        1.000        1.724        126.8           0.           0.           0.
```

```
                           SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE     4

MODEL = BALLOON                     FLUINT SAMPLE PROBLEM 1 - FILLING AIR BALLOONS
  FORWRD


 FLUID SUBMODEL NAME = FILLIT  ; FLUID NO. = 8000


        MAX TIME STEP =        0.     ; LIMITING MESSAGE = (NO SOLUTION STEP TAKEN YET)
        LAST TIME STEP =        0.     VS. DTMAXF/DTMINF =  1.000000E+30 /        0.    ;   AVERAGE TIME STEP =        0.
        PROBLEM TIME                  TIMEN  =       0.     VS. TIMEND  =  10.0000


                                    LUMP EXTRA PARAMETER TABULATION FOR SUBMODEL FILLIT
                                    BODY FORCE ACCELERATION COMPONENTS (X,Y,Z):         0.     ,       0.     ,       0.

  LUMP  TYPE      CX            CY            CZ      NO. PATHS     HOLDS      MASS         VOLUME     COMPLIANCE   VOLUME RATE

     1  TANK       0.            0.            0.            1        NONE     5.173        3.000           0.            0.
     3  TANK       0.            0.            0.            1        NONE    1.8174E-04   2.4241E-03    2.667           0.
     2  JUNC       0.            0.            0.            2        NONE
```

```
                          SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE     5

MODEL = BALLOON                        FLUINT SAMPLE PROBLEM 1 - FILLING AIR BALLOONS
  FORWRD


 FLUID SUBMODEL NAME = FILLIT  ; FLUID NO. = 8000


        MAX TIME STEP =   0.00000      ; LIMITING MESSAGE = (NO SOLUTION STEP TAKEN YET)
        LAST TIME STEP =   0.00000      VS. DTMAXF/DTMINF =  1.000000E+30 /   0.00000     ;   AVERAGE TIME STEP =   0.00000
        PROBLEM TIME                  TIMEN  =  0.00000      VS. TIMEND  =  10.0000


                                   PATH PARAMETER TABULATION FOR SUBMODEL FILLIT

   PATH  TYPE    LMP 1   LMP 2   DUP I      DUP J     STAT   XL UPSTRM    FLOWRATE     DELTA PRES    REYNOLDS     MACH    REGIME

    10   STUBE       1       2   1.0         1.0      NORM     1.000        0.000        0.000        0.000       0.000x  1 PHASE
    20   LOSS        2       3   3.0         1.0      NORM     1.000        0.000        323.4                    0.000*
```

```
                          SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE    66

MODEL = BALLOON                        FLUINT SAMPLE PROBLEM 1 - FILLING AIR BALLOONS
  FORWRD

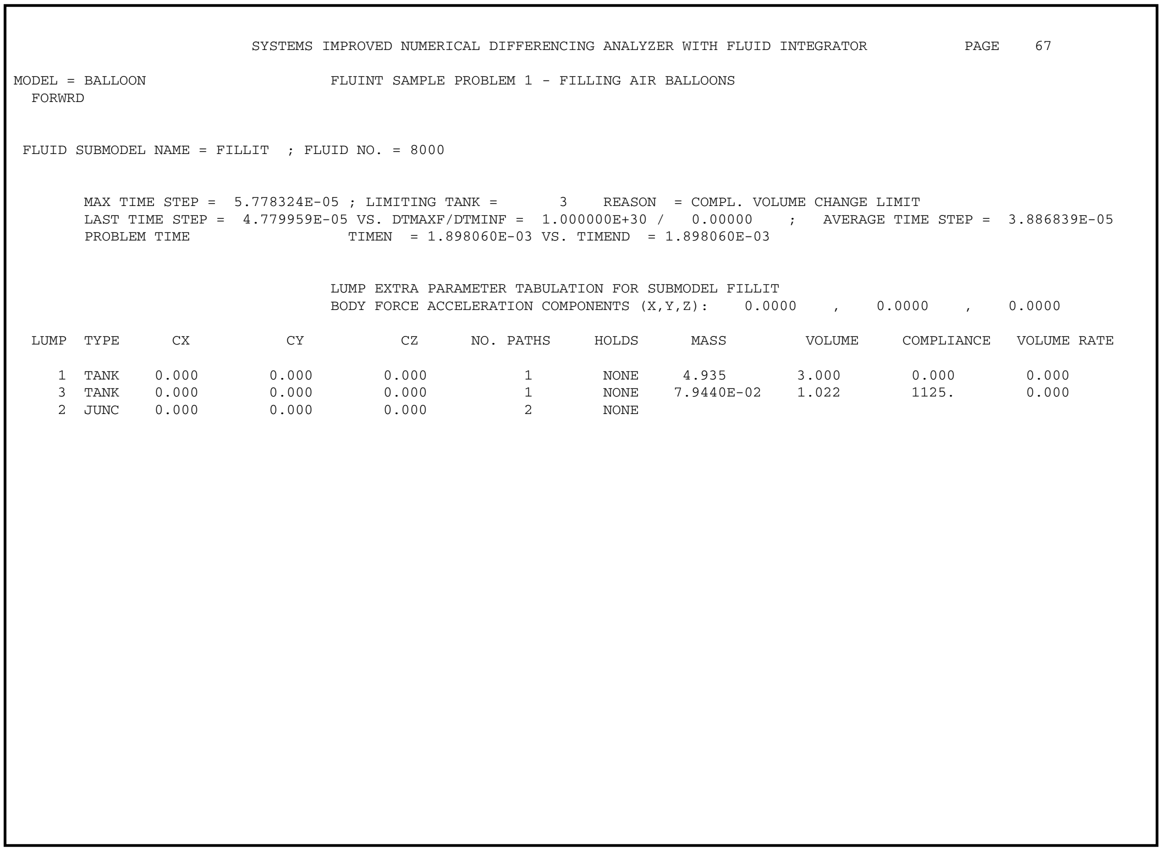

 FLUID SUBMODEL NAME = FILLIT  ; FLUID NO. = 8000


        MAX TIME STEP =  5.778324E-05 ; LIMITING TANK =       3    REASON  = COMPL. VOLUME CHANGE LIMIT
        LAST TIME STEP =  4.779959E-05 VS. DTMAXF/DTMINF =  1.000000E+30 /   0.00000     ;   AVERAGE TIME STEP =  3.886839E-05
        PROBLEM TIME                  TIMEN  = 1.898060E-03 VS. TIMEND  = 1.898060E-03


                                   LUMP PARAMETER TABULATION FOR SUBMODEL FILLIT

  LUMP  TYPE     TEMP        PRESSURE      QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

     1  TANK    60.11         301.8         1.000        1.000        1.645        124.5        0.000       -121.7      -1.5150E+04
     3  TANK    64.87        0.3890         1.000        1.000       7.7708E-02    125.6        0.000        40.57        5050.
     2  JUNC    59.18         226.7         1.000        1.000        1.257        124.2        0.000        0.000        0.000
```



```
                           SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE    67

MODEL = BALLOON                     FLUINT SAMPLE PROBLEM 1 - FILLING AIR BALLOONS
  FORWRD

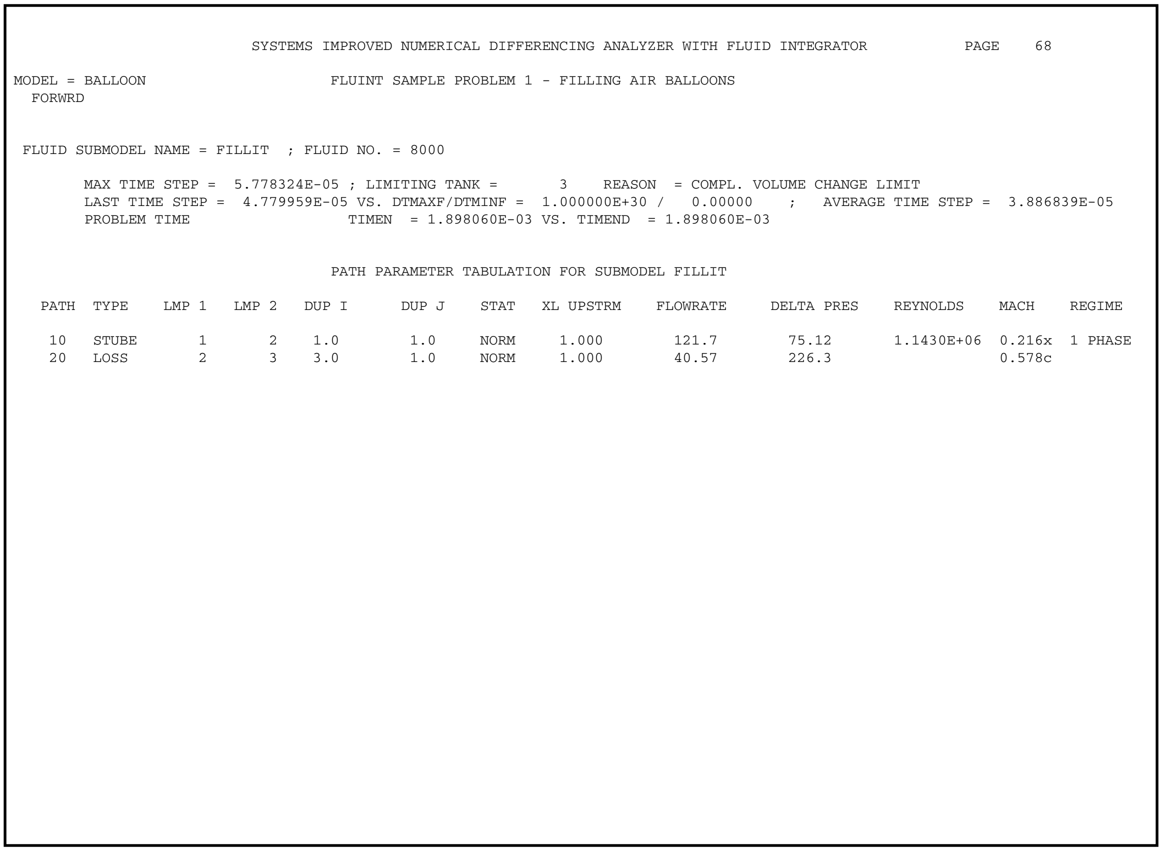

 FLUID SUBMODEL NAME = FILLIT   ; FLUID NO. = 8000


        MAX TIME STEP =  5.778324E-05 ; LIMITING TANK =       3    REASON  = COMPL. VOLUME CHANGE LIMIT
        LAST TIME STEP =  4.779959E-05 VS. DTMAXF/DTMINF =  1.000000E+30 /   0.00000    ;   AVERAGE TIME STEP =  3.886839E-05
        PROBLEM TIME                  TIMEN  = 1.898060E-03 VS. TIMEND  = 1.898060E-03


                                    LUMP EXTRA PARAMETER TABULATION FOR SUBMODEL FILLIT
                                    BODY FORCE ACCELERATION COMPONENTS (X,Y,Z):    0.0000    ,    0.0000    ,    0.0000

  LUMP  TYPE      CX           CY           CZ       NO. PATHS     HOLDS      MASS          VOLUME     COMPLIANCE    VOLUME RATE

     1  TANK    0.000        0.000        0.000           1        NONE     4.935        3.000        0.000         0.000
     3  TANK    0.000        0.000        0.000           1        NONE    7.9440E-02    1.022        1125.         0.000
     2  JUNC    0.000        0.000        0.000           2        NONE
```



```
                           SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE    68

MODEL = BALLOON                     FLUINT SAMPLE PROBLEM 1 - FILLING AIR BALLOONS
  FORWRD


 FLUID SUBMODEL NAME = FILLIT   ; FLUID NO. = 8000

        MAX TIME STEP =  5.778324E-05 ; LIMITING TANK =       3    REASON  = COMPL. VOLUME CHANGE LIMIT
        LAST TIME STEP =  4.779959E-05 VS. DTMAXF/DTMINF =  1.000000E+30 /   0.00000    ;   AVERAGE TIME STEP =  3.886839E-05
        PROBLEM TIME                  TIMEN  = 1.898060E-03 VS. TIMEND  = 1.898060E-03


                                    PATH PARAMETER TABULATION FOR SUBMODEL FILLIT

   PATH  TYPE    LMP 1   LMP 2   DUP I      DUP J    STAT   XL UPSTRM    FLOWRATE     DELTA PRES    REYNOLDS    MACH    REGIME

    10   STUBE       1       2    1.0        1.0     NORM    1.000        121.7        75.12       1.1430E+06  0.216x  1 PHASE
    20   LOSS        2       3    3.0        1.0     NORM    1.000        40.57        226.3                   0.578c
```

PROBLEM B: SIPHON IN A ROMAN AQUEDUCT

When the Romans built aqueducts to supply European cities with continuous water, they used for the most part open channels with slight hydraulic gradients. Unfortunately, this meant having to build now-famous bridges to span small valleys. The height limit on these masonry bridges was approximately 50m. When a valley was deeper than this limit, the Roman engineers used an ingenious but less-famous alternate: an inverted (U shaped) siphon. In the more common siphon, the difference in gravitational head between the inlet and outlet of a duct is used to drive the flow over a higher intermediate section, requiring a starter pump. In the inverted version, the outlet is lower than the inlet, but the intermediate section is lower still. Thus, the Romans used huge siphons along the bottom of deep valleys instead of tall bridges.*

In order to contain the large pressures at the bottoms of the siphons, the ducts were made out of thick lead that was rolled into a pear-shaped pipe and hammered or soldered shut. To carry the necessary flowrates and because of manufacturing limits on the pipe size, siphons typically used several such pipes. At the bottoms of the valleys, a relatively small bridge was used to limit the maximum pressure of the water by carrying the pipes above the lowest point. The siphons began and ended with open channel headers that connected to the rest of the aqueduct. The specific numbers used in this example are composites based on information available for several siphons.

This problem was chosen to demonstrate the following FLUINT features:

1. the properties of liquid-filled tanks
2. the use of body force options
3. the differences between tanks and junctions
4. the differences between tubes and STUBE connectors
5. heat transfer options; ties to thermal nodes
6. user-defined liquids
7. non-circular cross-sections
8. internal restarts (reusing initial conditions)
9. LINE and HX macros
10. Multiple fluid and thermal submodels
11. INSERT options
12. use of dynamic registers to reduce user logic
13. again, the flexibility of the code

---

* All information in this example comes from: “Siphons in Roman Aqueducts,” A. Trevor Hodge, *Scientific American,* June 1985, pp. 114-119.

B.1 Problem Description

A 1.2 kilometer siphon has eight 26 cm O.D. pipes (see Figure B-1 and Figure B-2). The difference in the free surface height of the headers is 9m, and the bridge at the bottom of the valley is 93m below the inlet header. The fluid temperature is initially at room temperature (20°C). The total flowrate of the aqueduct and the pressure profile is desired. The relevant characteristics are:

Siphon (Figure B-1):	
Total piping length	1.2 km
Hydraulic gradient	9 m
Bridge length	400 m
Bridge depth	93 m
Number of pipes in parallel	8
Pipe X-Section (Figure B-2):	
Inner diameter	18 cm
Perimeter	60.4 cm
Flow area	272 cm^2
Hydraulic diameter	18 cm
Lead wall:	
Wall thickness	4 cm
Cross-sectional area	295 cm^2
Density	11340 kg/m^3
Specific heat	129 J/kg-K
Thermal conductivity	35.3 W/m-K

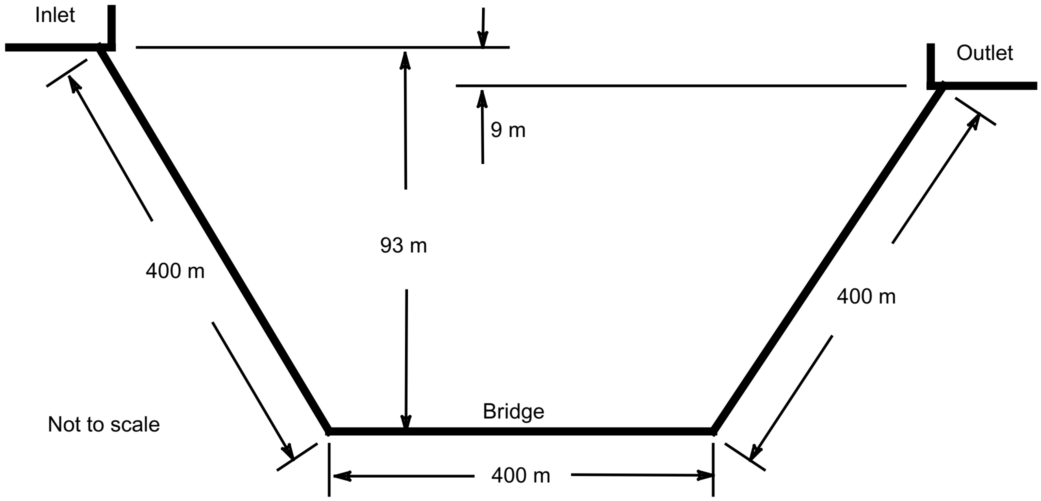


Figure B-1 Profile of the Aqueduct

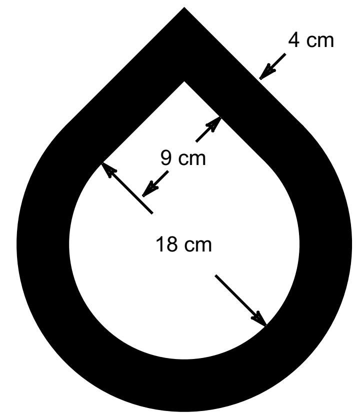


Figure B-2 Idealized Pipe Cross-Section

Two transient events are analyzed. These events are chosen to demonstrate program usage and are therefore somewhat whimsical. In the first event, a sudden snow melt causes the inlet temperature to drop linearly with time to 1°C over a 10 minute interval. The desired output is the transient thermal response of the pipes. The pipes are embedded in masonry, and hence are assumed to be adiabatic at the outside diameter.

The second event uses the same initial conditions as the first event. In this case, however, an earthquake strikes at time zero, springing identical leaks in each pipe in the middle of the bridge. Each leak has a flow area of 10 cm^2, and the surrounding bridge is assumed to not inhibit the leakage flow. The desired output is the transient hydrodynamic response of the pipes. The effect of the flow changes on the liquid level in the headers is assumed negligible.

B.2 A FLUINT Model

Clearly, body forces will play an important role in this model,[*] and only one dimension is needed: the elevation from the bottom of the siphon. Also, flow losses need to be accurately modeled since the driving force is constant—the flowrate will depend on the losses in the pipes.

The modeling choice for the headers should be clear; the ducts will be bounded by two plena of different height but with the same initial temperature and pressure (atmospheric). These plena might be designated as low-velocity stagnant states (LSTAT=STAG), which would include inlet accelerational losses equivalent to a K-factor of one. However, their pressures will instead be interpreted as the pressure at the top free surface of an already moving stream of water (LSTAT=NORM, the default).[†] This choice generates some cautions in the output file, since plena are normally stagnant states.

The temperature of the inlet plenum, “TUP,” can be changed for the snow melt transient.

The leakages for the earthquake transient can be modeled as CTLVLVs that are closed until that event. These paths dump into a third plenum that is at the same height as the leak, but is still at atmospheric pressure. The FK is assumed to be 1.0.[‡]

---

[*] FLUINT currently neglects kinetic energy terms; this analysis would have been invalid if the actual flowrates were limited by inviscid energy constraints and not by frictional losses.

[†] In other words, the choice of LSTAT=STAG or LSTAT=NORM is one of relative volume of the inlet plena. If they are large, velocities will be low and LSTAT=STAG should be used. If they are small, then the fluid is assumed to already be moving at approximately the same velocity as that of the pipes. Otherwise, no velocity can be attributed to a lump, only to a path: the main effect of LSTAT is on paths downstream of any lump. Therefore, the designation at the exit plena is of no consequence.

In order to investigate modeling choices for the ducts themselves, each pipe will be modeled using a different combination. This will allow comparisons of the thermal and hydraulic transient response of each pipe model. The basic combinations will be as follows:

Pipe 1: Junctions and STUBE connectors, 29 segments, adiabatic
Pipe 2: Junctions and tubes, 29 segments, adiabatic
Pipe 3: Tanks and STUBE connectors, 29 segments, adiabatic
Pipe 4: Tanks and tubes, 29 segments, adiabatic
Pipe 5: Junctions and STUBE connectors, 29 segments, wall model included
Pipe 6: Tanks and tubes, 29 segments, wall model included
Pipe 7: Junctions and STUBE connectors, 15 segments, wall model included
Pipe 8: Tanks and tubes, 15 segments, wall model included

Note that these combinations will illustrate changes in spatial and temporal resolution. The input and the model is greatly complicated by this investigation; in a normal model the input and execution would be greatly simplified by using one duct model duplicated 8 times.

The wall roughness of the pipes can be expected to be very high considering the available manufacturing methods. A value of WRF=0.01 is assumed, meaning that the size of the roughness is on the order of 0.18 cm. (The pipes were constructed by joining sections that were 3m long; this roughness ratio will take into account frequent rough joints as well.)

As is evident in Figure B-2, the pipes are not circular. DH must then be specified as the hydraulic diameter (four times the flow area divided by the wetted perimeter). However, the user has the choice of whether to let the effective diameter DEFF default to this same value (18cm in this case), or whether it should be different. At the risk of oversimplifying, DEFF will be used for pressure drop calculations, but DH will be used for heat transfer calculations. In extreme cases that depart strongly from near-circular such as star-shaped passages or thin rectangular slots, the hydraulic diameter approximation is inaccurate for pressure drop calculations. (It is still needed for heat transfer not only because it enables the code to calculate the wetted perimeter, but also because most heat transfer correlations are based on the hydraulic diameter instead of the effective diameter as a characteristic length.) In this case, however, no handbook value of DEFF is available, and a laminar solution (whether closed form or CFD) is not worth the trouble since the cross-section *is* nearly circular. Therefore, DEFF will be allowed to default to DH.

With respect to heat transfer between the fluid and the wall for those diabatic ducts, one node is used per lump to represent the pipe. This is equivalent to assuming that the circumferential gradients in the pipe are negligible; this assumption can be lifted by adding more ties as needed. Axial gradients will be nonnegligible, and axial conductances will be added even though the axial heat transport along the pipe is negligible compared to the fluid transport. Diffusion nodes will be used throughout to characterize the substantial thermal capacitance of the thick lead pipes. Also, although the pipes were probably heavily encrusted, they are assumed to have been recently cleaned in this example; no fouling resistance will be taken into account in the heat transfer model.[*]

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‡ This choice should not be confused with the assignment of an "exit loss" of unity. In FLUINT, with static pressures being the default, exit losses are not equal to one dynamic head. Rather, entrance losses (or, more appropriately, "accelerations") *are* applicable and are automatically applied if the inlet is designated as stagnant.

[*] The tie UAM factor, which defaults to unity, is a convenient tool for modeling such fouling otherwise.

In order to fully demonstrate the LINE and HX macros, the first downhill segment will be downstream discretized, the center section will be center discretized, and the uphill section will be upstream discretized.* This is displayed in Figure B-3 along with the naming conventions for all pipes. Because some pipes have fewer elements, they exclude the elements shown in parentheses. This does not mean that tank 10 for a 29 segment model corresponds exactly to tank 10 in a 15 segment model since the latter tank has twice the volume of the former.

Inlet and bend losses need also be taken into account. (K-factors of unity, on the other hand, *shouldn't* be applied in FLUINT.) An FK value of 0.5 is typical for a sharp inlet. The bends at either end of the bridge were slight but could be expected to be manufactured crudely; a value of 0.2 is attributed to each of them. These bend losses can be added into the entrance and exit losses for the purposes of all expected analyses. To interface with the duct models, an extra junction is inserted along with each LOSS connector.

Alternatively (and more efficiently), these losses could have been superimposed on the entrance and exit paths of the ducts. In that case, the FK factors would be added in OPERATIONS since specifying them within duct macros would apply them to all generated tubes or STUBE connectors. Sinaps*Plus*® and FloCAD®, on the other hand, allow such customizing of individual macro elements once the macro (or *pipe*, in FloCAD) has been created on the screen.

B.3 The Input File

The input file is listed immediately following the last section.

In order to demonstrate important submodel concepts, each pipe has been input as a separate fluid submodel, and each pipe wall has been input as a separate thermal submodel. Normally, a fluid system cannot be divided into submodels. However, in this case each pipe is completely independent of the other pipes because they all begin and end at plena. By subdividing the model into eight fluid submodels, intricate naming schemes can be avoided, and the same lump/path/node designators can be reused in each submodel in the corresponding location. The penalty that is paid is the need to repeat the common inputs describing the plena, the leaks, and the LOSS connectors and associated junctions. This work was minimized by writing this data once in a separate file, and then using the INSERT command to bring that data into each pipe submodel. The INSERT file contents are listed at the last page of the input file after the END OF DATA command.

Actually, there is a much more important but subtle reason to separate the pipes into submodels: the simulation will run much faster with 8 submodels having some 30 lumps each than will a model built with one 240-lump submodel. The reasons have to do with internal matrix operations whose cost scales approximately with the number of lumps squared, as discussed in the manual under Modeling Tips for Efficient Use. In other words, $8*(30^2) < 240^2$. Therefore, although most fluid submodels cannot be subdivided, it is well worth the user's time to subdivide them where possible.

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* Use of centered macros is encouraged over use of up or downstream macros. Centered macros are more "general purpose" and work better with two-phase flows and other complicated analyses.

OPTIONS DATA—Like the previous balloon example, user files will be opened to contain summary tables of important data during each transient. The reader will note the use of these summary files throughout this appendix. SINDA/FLUINT output routines are necessarily general and complete, but a full dump of data can be cumbersome. Thus, a little simple Fortran programming allows the user to summarize the data that is really important. This is an important tool for scanning results to make sure that both the system and the model of that system are adequate. Another relevant tool is EZ-XY and its Excel templates, which can be used to interrogate SAVE or RESAVE (RSO) files *after* an analysis has been completed, providing the user with the freedom to change his mind regarding which data are important enough to print or plot.

FPROP DATA—A full description of liquid water is provided in this section, and is named fluid 9718. It is more complete than the analysis warrants having been taking from the author's library of single-phase fluids. Deletion or simplification would speed the program, but is probably not worth the user's time. However, it is well worth the user's time to use an FPROP data block instead of relying on the complete internal description of water since the siphon is and will always be single-phase. This eliminates the substantial overhead involved in calculating liquid properties that are consistent with the vapor phase.

For analyses of fluid systems in which the working fluid is a standard FLUINT library fluid, the RAPPR program* can be used to create customized single- and two-phase descriptions similar to the one provided above, which was instead taken from ASHRAE handbook data. This ASHRAE description will differ slightly from the RAPPR-produced description. Using RAPPR to generate a 9000 series (incompressible liquid) description of water allows the user to tailor the description to his accuracy requirements: more array points are used to comply with tighter error tolerance specifications. The reader is encouraged to repeat this analysis using a RAPPR description, but is cautioned against requesting very low error tolerances (less than 3%) because of the increased solution cost required by such a complete description.

NODE and CONDUCTOR DATA—These blocks contain the thermal network descriptions for the four thermal submodels used to represent the walls of pipes #5 through #8. They are named WALL5 through WALL8. GEN options are used to generate each segment of the duct corresponding to the LINE and HX macros in the relevant FLOW DATA blocks. Registers were used to define dimensions and property values. Calculations for capacitance and conductors are performed in the NODE and CONDUCTOR blocks. These calculations could of been performed in REGISTER DATA, and a single register variable could have been used to define capacitance and coadjutor values.

FLOW DATA—The eight submodel blocks corresponding to the eight pipe models are input here and named PIPE1 through PIPE8. Note that data common to all submodels is written once and inserted. The INSERT file, which includes the defaults, is listed at the end of the input list. All fluid submodels refer to the same working fluid (9718) that was described in the FPROP DATA block. The elevation of each lump with respect to the bottom is input as the Z coordinate. Again registers are used to define some of dimensional parameters.

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* RAPPR is effectively obsolete since many of the fluids in the standard library are ozone depleting, and more accurate descriptions are available at www.crtech.com.

Figure B-3 displays the naming conventions for each pipe submodel. The FLOW DATA sections contain three macros each for each leg of the aqueduct pipe. LINE macros are used to input nodeless models; HX macros are used to input models with ties to nodes. Note that the default values for LUINC, PAINC, and NINC are one, and that the diameter and flow area must be input explicitly as DHS and AFS. CZINC is used to increment the elevation along each duct. Each tie is named after the lump on which it operates.

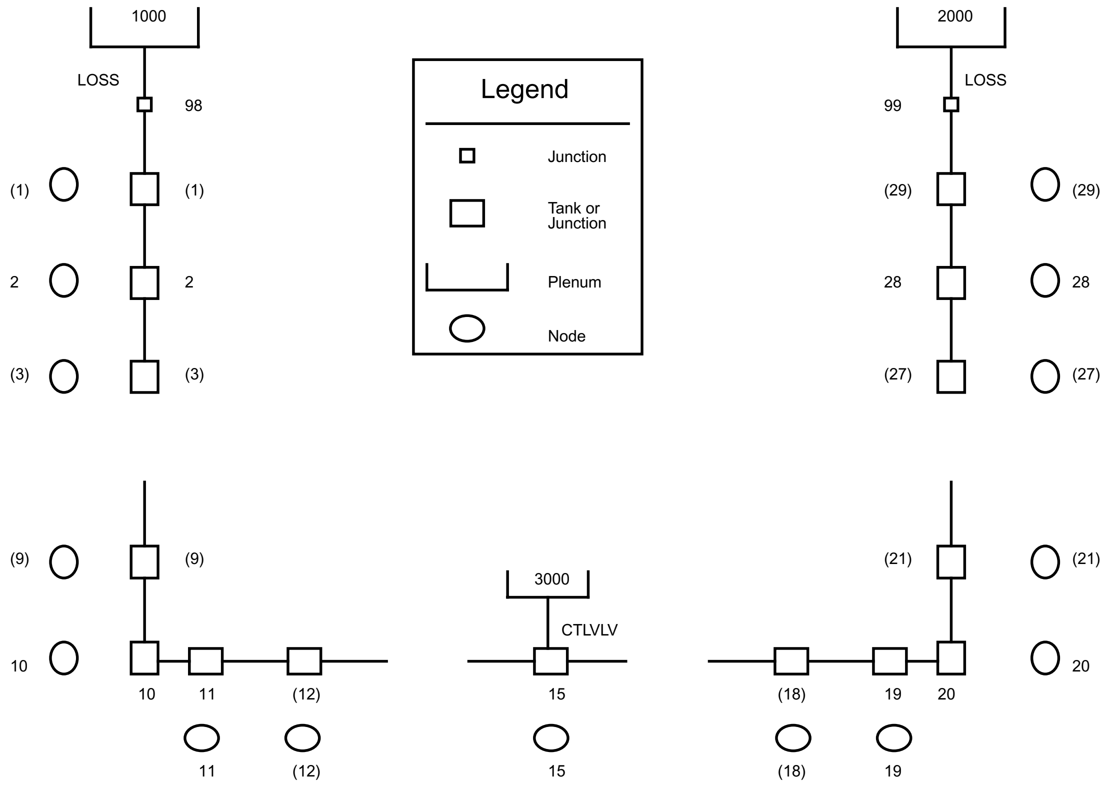

Figure B-3 Naming Conventions for Each Pipe Submodel

CONTROL DATA—SI units are chosen, with temperature in units of °C, and pressure is relative to atmospheric. The acceleration of gravity in the Z direction is given in the appropriate units. (If the model had been in English units, the acceleration would have to be in units of ft/hr^2, or 32.174*3600.0*3600.0, available as the built-in constant *grav*. The constant *gravsi* is available for SI units of m/s^2.) Also, the temperature changes in the thermal models have been limited by the constants EXTLIM and DTMPCA as preventative measures. EBALSA is set to zero to turn off the thermal energy balance check, which if active would encumber the convergence because there is no net energy flow through the thermal system at steady-state: the *relative* energy balance error would otherwise be compared against a diminishingly small *absolute* number.

USER DATA—The variables to be used in logic blocks are declared here. Note that the constant ITRAN is used to help the logic blocks distinguish between the snow melt transient (ITRAN=1) and the earthquake transient (ITRAN=2). Initially, ITRAN is zero. Registers could have been used equivalently for these variables.

REGISTER DATA—Eleven registers are defined. The initial values and descriptions are listed below:

Register Name	Description	Initial Value
TUP	inlet temperature	20
PIPECP	pipe specific heat	129
PIPEDEN	pipe density	11340
PIPECOND	pipe thermal conductivity	35.3
PIPEAX	pipe cross sectional area	295.0/100.0^2
PIPEAF	pipe flow area	272.0/100.0^2
PIPEDH	pipe hydraulic diameter	18.0/100.0
DOWNLEN	down hill length	400
BRIDGELEN	bridge length	400
UPLEN	up hill length	400
KLOSLEAK	K factor for leak	-1.0

These registers are employed extensively in FLOW DATA, NODE DATA, and CONDUCTOR DATA blocks, among others.

Some of these registers will be changed during the course of the run as needed to simulate the snowmelt transient (in which case TUP will be varied with time) and the earthquake event (in which case KLOSKEAK will be changed).

OPERATIONS—First, all submodels are built into one configuration. A steady-state analysis is run to find initial conditions such as the pressure profile along each pipe. Note that the call to STDSTL is actually redundant in this instance, but is it is normally a good practice to call this routine after calling FASTIC to make sure. The results of the steady-state run are saved for future use by calling SAVPAR, and pressures and flowrates are printed to the output file.

The snow melt transient is then run, with a large value of TIMEND being used because it will be overwritten in the FLOGIC 2 block. A "snapshot" of the end state after the snow melt transient is then taken, focusing on temperatures and heat rates. Note that the changing inlet plenum temperature is handled in the FLOGIC 0 block.

The earthquake (pipe break) transient is then run. First, the network steady-state solution is retrieved as initial conditions for the pipe break transient. Note that all control constant and variable changes occur *after* this retrieval; the control constants and variables themselves are stored and retrieved as part of the restart operation. The valves (leaks) are opened for all pipes before the run, and the pressures and flowrates are printed out after the run is completed.

FLOGIC 0—One FLOGIC 0 block is used to update values in all fluid submodels. The only operation required here is the update of the inlet temperatures during the snow melt transient. Since the inlet temperature was defined as a register (TUP) changing TUP changes all inlet (plena) temperatures in all eight submodels. Note that the output interval OUTPTF assures that the program stops at exactly 600 seconds (10 minutes).

FLOGIC 2—Again, only one FLOGIC 2 block is used instead of eight. This logic alters the output interval depending on the transient event. During the pipe break transient, output is requested each time step instead of at regular intervals. The logic stops the simulation during the snow melt transient when the outlet temperature of PIPE6 falls below 5.0 °C, and it stops the pipe break transient when the network has relaxed enough to take a one second time step. Note that DTIMUF is the time step just taken; in FLOGIC 0 and 1, DTIMUF represents the time step taken in the *previous* solution step.

OUTPUT CALLS—This block writes one line of summary data for each event. Note that calls to generalized output routines are not made here; these are contained in the OPERATIONS block to reduce the volume of output.

B.4 Output Description

The user summary files and selected parts of the OUTPUT file are listed following the input file. The results of each run are discussed separately.

Warnings are produced because LSTAT=NORM plena have been input, and this is unusual but purposeful as was explained above. A single warning ("ILLEGAL OPERATION IN PROPERTY ROUTINE --- MISSING ENTROPY, SOUND SPEED, COMP. LIQUID, ETC. CHOKED FLOW DISABLED IN THIS SUBMODEL ; FLUID: 9718, TYPE: INCOMPRESSIBLE LIQUID") is produced because the compliance (compressibility) data is missing from the fluid description (FPROP DATA)::, and therefore automatic choking calculations are disabled. Choking is rarely a concern in a liquid-only model such as this, so this warning can also be safely ignored.

STEADY-STATE—As should be the case, the flowrates are the same in each pipe: about 22.5 kg/s. Although no specific data is available for any one aqueduct, this flowrate is within 20% of values estimated for typical aqueducts. It may be a bit low, indicating that a roughness ratio of 0.01 may be too high; the Romans might be given more credit for smoother pipes, joints, and fittings.

The pressure profiles indicate a maximum pressure of 8.6 atmospheres. This is by no means the deepest siphon ever found; experiments indicate pipes built in modern times by ancient methods could withstand 18 atmospheres.

The pressure of the inlet junction (#98) is subatmospheric because it is at the same height as the inlet but experiences a loss due to connector #98. This is important to note because the model is valid even though no pressures are below atmospheric in a real siphon; the FLUINT model imitates the real system mathematically, not analogously. Junctions and connectors are artificial constructs useful as modeling tools; they do not necessarily have to correspond to a device on a schematic.

SNOW MELT EVENT—The temperature histories at the outlet of each pipe are plotted in Figure B-4. These profiles illustrate the important differences in modeling ducts.

First, note that there is no difference between using tubes and STUBE connectors. This event is a thermal transient that happens over the course of minutes and hours. Tubes are only needed to distinguish the more rapid hydraulic transients that happen over the course of seconds and microseconds. Thus, tubes are rarely needed in most thermal management systems.

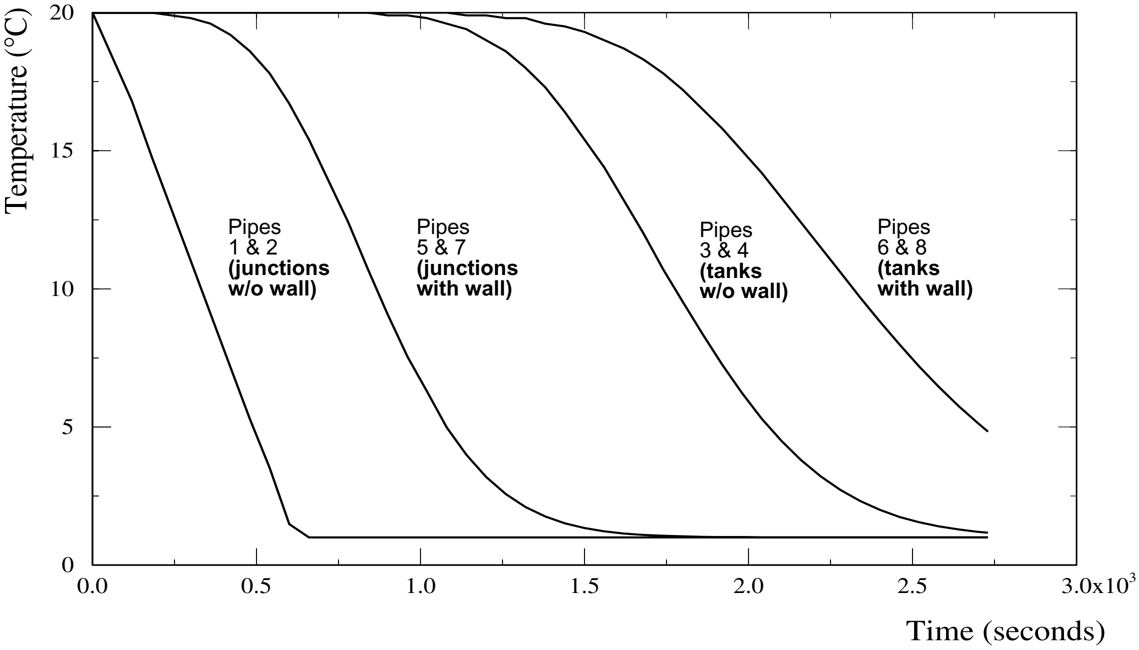

Figure B-4 Outlet Temperature Histories for Snow Melt Event

Second, note that there is no lag time associated with junctions (pipes 1 and 2). Inlet changes are passed through instantaneously such that changes in the inlet plenum are reflected at the duct outlet immediately. This is obviously an inappropriate assumption for this event, but it is usually adequate in many real analyses and should be made whenever possible. Note that the inlet temperature was actually changed in a stair-step fashion rather than linearly, causing some artificial differences between the inlet and outlet temperatures.

In models with tanks in place of junctions (pipes 3 and 4), the lag time associated with moving fluid is included, causing a delay between the inlet and the outlet. Note that the answers that result here differ slightly from the answers that would result if the fluid front were viewed as flat front that progresses at constant velocity through the length of the pipe. FLUINT uses a control volume approach instead. This means that the problem can be thought of as the transient cooling of the fluid in the middle of the pipe. *Neither assumption is completely correct.* FLUINT uses the control volume approach because of greater flexibility and modeling power; this approach has been shown to be acceptable in systems with temperature control valves where the lag effects are critical to the simulated response. Also, note that the ducts built with tanks do not respond for the first 20 to 25 minutes, which is equal to the amount of time required for the first cold front to reach the outlet.

When nodes are added to the model, the fluid is no longer considered adiabatic and the lag associated with transiently cooling the extensive amount of lead is included. The effect of thermal inertia on junctions can be seen in the response of pipes 5 and 7; the corresponding effect on tanks is seen in the response of pipes 6 and 8. Pipes 6 and 8 have the most accurate response since they contain the fewest simplifying assumptions. *This does not mean that tanks and diffusion nodes should always be used.* Simplifying assumptions should always be sought in any analyses.

Note that there is a negligibly small difference between the use of 29 lumps versus 15 (pipe 5 vs. 7, pipe 6 vs. 8). Clearly, acceptable answers can be found using coarse spatial resolution for liquids. Pipe 8 is then the best choice for this particular problem. However, the user should be warned that greater spatial resolution is required in two-phase ducts because of the large property gradients inherent in such systems. The user should also note that two-phase ducts modeled with tanks might be prohibitively expensive because of the resolution of fast time scale events, forcing the use of small time steps.

EARTHQUAKE (PIPE BREAK) EVENT—Figure B-5 contains the outlet flowrate histories for the pipes during the pipe break event. The responses illustrate the differences between tubes and STUBE connectors. In those pipes built with tubes, the flowrate slows, reverses, and gradually approaches the steady-state value of -7.4 kg/s after about 15 seconds. The significant inertia of the moving liquid means that the leak starts slowly and builds to its full value as the flow is decelerated in the outlet and accelerated in the inlet. In those ducts built with STUBE connectors, the flowrates changes almost instantly to the final value. (There is some negligible delay: internal damping causes the flowrate to take two to three solution steps to arrive at the final answer.) Meanwhile, the inlet flowrate increases to 33 kg/s, and the leakage flowrate approaches 40 kg/s, the sum of the incoming flow.

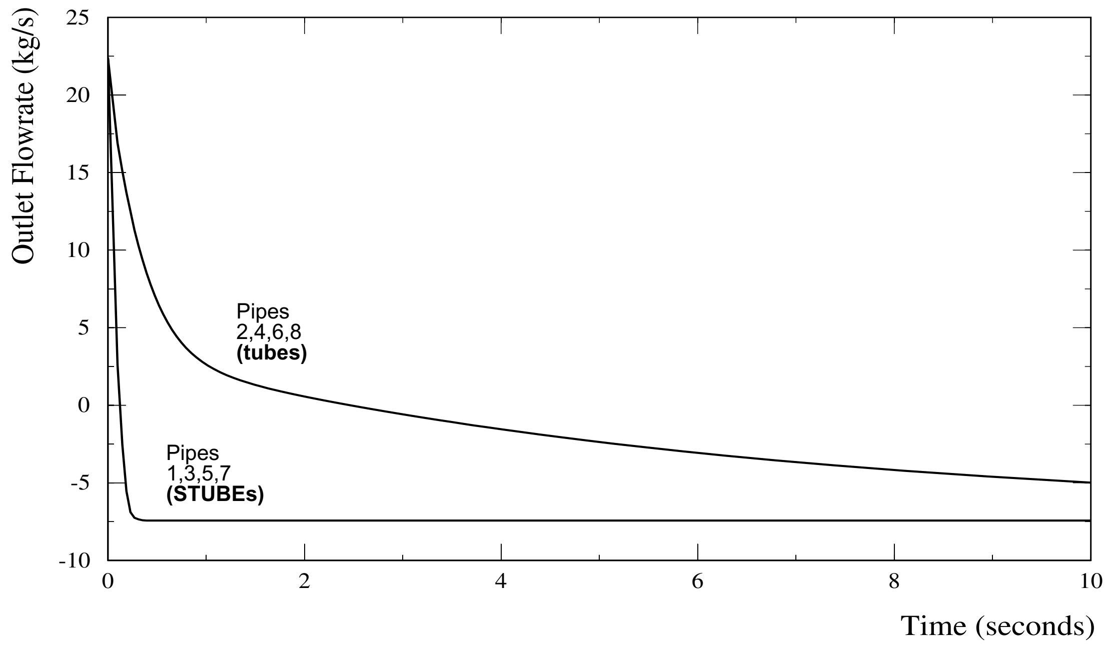

Figure B-5 Outlet Flowrate Histories for the Earthquake Event

The responses of the pipes are independent of whether they contain tanks or junctions. This is true only for noncompliant single-phase liquid systems, where pressures can propagate instantly due to the assumption of incompressibility. If the tanks were compliant (COMP > 0.0) or if any vapor were present, the responses would have differed.

In examining the output file, note that the time step is controlled to attempt to keep the tube flowrate percent change to DTSIZF. An important point to notice is that the time step decreases to capture a percentage change in a smaller flowrate as the flowrate reverses. Although tubes with negligibly small flowrates (<1% of model average) are ignored, tubes should be avoided in modeling ducts with small or zero flowrates, or where the flowrate reverses often.

As a point of interest, preliminary analyses found that the aqueduct would still transport 20 kg/s to the outlet even with a hole as large as 1 cm^2. Thus, the aqueducts would continue to function with minor leaks, which were probably common. The same is not true for the more familiar siphon having a raised center section.

Input File

```
HEADER OPTIONS DATA
TITLE FLUINT SAMPLE PROBLEM 2 - SIPHON IN A ROMAN AQUEDUCT
         OUTPUT   = aqueduct.out
         USER1    = snowmelt.out
         USER2    = earthquake.out
C
HEADER FPROP DATA,9718,ENG,-460.0
C
C MOST COMPLETE LIQUID WATER DESCRIPTION
C
         TMIN     = 32.0,  TMAX     = 706.
AT,V,    32.0,4.28,40.0,3.69,50.0,3.12,60.0,2.68,
         70.0,2.32,80.0,2.03,90.0,1.79,100.0,1.6,
         120.0,1.30,140.0,1.093,160.0,0.938,180.0,0.813,
         200.0,0.717,220.0,0.638,240.0,0.574,260.0,0.521,
         280.0,0.476,300.0,0.439,320.0,0.406,340.0,0.379,
         360.0,0.355,400.0,0.315,500.0,0.251,600.0,0.200,
         700.0,0.121,706.0,0.101
AT,K,    32.0,0.329,50.0,0.339,70.0,0.35,90.0,0.359,
         120.0,0.371,180.0,0.388,220.0,0.395,260.0,0.398
         280.0,0.398,320.0,0.396,360.0,0.391,400.0,0.383
         500.0,0.349,600.0,0.296,700.0,0.188,706.0,0.139
AT,CP,   32.0,1.007,60.0,1.001,90.0,0.998,120.0,0.998,
         160.0,1.001,180.0,1.003,220.0,1.009,240.0,1.013
         260.0,1.017,280.0,1.022,300.0,1.029,320.0,1.040
         360.0,1.066,400.0,1.085,500.0,1.18,600.0,1.528
AT,D,    33.0,1.0/0.01602,50.0,1.0/0.01602
         60.0,1.0/0.01603,80.0,1.0/0.01607
         120.0,1.0/0.01620,170.0,1.0/0.01645
         190.0,1.0/0.01657,212.0,1.0/0.01671,
         220.0,1.0/0.016772,240.0,1.0/0.01692
         260.0,1.0/0.017084,280.0,1.0/0.017259
         300.0,1.0/0.017448,340.0,1.0/0.017872
         380.0,1.0/0.018363,420.0,1.0/0.018936
         460.0,1.0/0.019614,500.0,1.0/0.02043
C
```

```
HEADER NODE DATA,WALL5
C PIPE 5
   GEN 1,10,1,20.0,DOWNLEN*PIPEAX*PIPECP*PIPEDEN/10.0$ DOWN
   GEN 20,10,1,20.0,UPLEN*PIPEAX*PIPECP*PIPEDEN/10.0$ UP
   GEN 11,9,1,20.0,BRIDGLEN*PIPEAX*PIPECP*PIPEDEN/9.0$ BRIDGE
C
HEADER NODE DATA,WALL6
C PIPE 6
   GEN 1,10,1,20.0,DOWNLEN*PIPEAX*PIPECP*PIPEDEN/10.0$ DOWN
   GEN 20,10,1,20.0,UPLEN*PIPEAX*PIPECP*PIPEDEN/10.0$ UP
   GEN 11,9,1,20.0,BRIDGLEN*PIPEAX*PIPECP*PIPEDEN/9.0$ BRIDGE
C
HEADER NODE DATA,WALL7
C PIPE 7
   GEN 2,5,2,20.0,DOWNLEN*PIPEAX*PIPECP*PIPEDEN/5.0$ DOWN
   GEN 20,5,2,20.0,UPLEN*PIPEAX*PIPECP*PIPEDEN/5.0$ UP
   GEN 11,5,2,20.0,BRIDGLEN*PIPEAX*PIPECP*PIPEDEN/5.0$ BRIDGE
C
HEADER NODE DATA,WALL8
C PIPE 8
   GEN 2,5,2,20.0,DOWNLEN*PIPEAX*PIPECP*PIPEDEN/5.0$ DOWN
   GEN 20,5,2,20.0,UPLEN*PIPEAX*PIPECP*PIPEDEN/5.0$ UP
   GEN 11,5,2,20.0,BRIDGLEN*PIPEAX*PIPECP*PIPEDEN/5.0$ BRIDGE
```

```
HEADER CONDUCTOR DATA,WALL5
C PIPE 5
   GEN 1,9,1,1,1,2,1,PIPECOND*PIPEAX*10.0/DOWNLEN              $ DOWN
   GEN 20,9,1,20,1,21,1,PIPECOND*PIPEAX*10.0/UPLEN             $ UP
   GEN 11,8,1,11,1,12,1,PIPECOND*PIPEAX*9.0/BRIDGLEN           $ BRIDGE
   10,10,11,0.5*PIPECOND*PIPEAX*9.0/BRIDGLEN                   $ BEND 1
   19,19,20,0.5*PIPECOND*PIPEAX*9.0/BRIDGLEN                   $ BEND 2
C
HEADER CONDUCTOR DATA,WALL6
C PIPE 6
   GEN 1,9,1,1,1,2,1,PIPECOND*PIPEAX*10.0/DOWNLEN              $ DOWN
   GEN 20,9,1,20,1,21,1,PIPECOND*PIPEAX*10.0/UPLEN             $ UP
   GEN 11,8,1,11,1,12,1,PIPECOND*PIPEAX*9.0/BRIDGLEN           $ BRIDGE
   10,10,11,0.5*PIPECOND*PIPEAX*9.0/BRIDGLEN                   $ BEND 1
   19,19,20,0.5*PIPECOND*PIPEAX*9.0/BRIDGLEN                   $ BEND 2
C
HEADER CONDUCTOR DATA,WALL7
C PIPE 7
   GEN 2,4,2,2,2,4,2,PIPECOND*PIPEAX*5.0/DOWNLEN               $ DOWN
   GEN 20,4,2,20,2,22,2,PIPECOND*PIPEAX*5.0/UPLEN              $ UP
   GEN 11,4,2,11,2,13,2,PIPECOND*PIPEAX*5.0/BRIDGLEN           $ BRIDGE
   10,10,11,0.5*PIPECOND*PIPEAX*5.0/BRIDGLEN                   $ BEND 1
   19,19,20,0.5*PIPECOND*PIPEAX*5.0/BRIDGLEN                   $ BEND 2
C
HEADER CONDUCTOR DATA,WALL8
C PIPE 8
   GEN 2,4,2,2,2,4,2,PIPECOND*PIPEAX*5.0/DOWNLEN               $ DOWN
   GEN 20,4,2,20,2,22,2,PIPECOND*PIPEAX*5.0/UPLEN              $ UP
   GEN 11,4,2,11,2,13,2,PIPECOND*PIPEAX*5.0/BRIDGLEN           $ BRIDGE
   10,10,11,0.5*PIPECOND*PIPEAX*5.0/BRIDGLEN                   $ BEND 1
   19,19,20,0.5*PIPECOND*PIPEAX*5.0/BRIDGLEN                   $ BEND 2
C
```

```
HEADER FLOW DATA,PIPE1,FID=9718              $ START DESCR OF PIPE1
C
C INSERT BASIC INFO (SAME FOR ALL PIPES)
INSERT aqueduct.inc
C
C DOWNHILL LINE
M LINE,1,D,1,1,98,NSEG = 10,UPF = 0.0
         LU = JUNC,PA = STUBE,CZ = 0.9*93.0
         CZINC = -9.3,TLENT = DOWNLEN,DHS = PIPEDH,AFS = PIPEAF
C ACROSS BRIDGE
M LINE,2,C,11,11,10,20,NSEG = 9,UPF = 0.5
         LU = JUNC,PA = STUBE,CZ = 0.0
         CZINC = 0.0,TLENT = BRIDGLEN,DHS = PIPEDH,AFS = PIPEAF
C UPHILL LINE
M LINE,3,U,20,21,99,NSEG = 10,UPF = 1.0
         LU = JUNC,PA = STUBE,CZ = 0.0
         CZINC = 8.4,TLENT = UPLEN,DHS = PIPEDH,AFS = PIPEAF
C
HEADER FLOW DATA,PIPE2,FID=9718$ START DESCR OF PIPE2
C
C INSERT BASIC INFO (SAME FOR ALL PIPES)
INSERT AQUEDUCT.INC
C
C DOWNHILL LINE
M LINE,1,D,1,1,98,NSEG = 10,UPF = 0.0
         LU = JUNC,PA = TUBE,CZ = 0.9*93.0
         CZINC = -9.3,TLENT = DOWNLEN,DHS = PIPEDH,AFS = PIPEAF
C ACROSS BRIDGE
M LINE,2,C,11,11,10,20,NSEG = 9,UPF = 0.5
         LU = JUNC,PA = TUBE,CZ = 0.0
         CZINC = 0.0,TLENT = BRIDGLEN,DHS = PIPEDH,AFS = PIPEAF
C UPHILL LINE
M LINE,3,U,20,21,99,NSEG = 10,UPF = 1.0
         LU = JUNC,PA = TUBE,CZ = 0.0
         CZINC = 8.4,TLENT = UPLEN,DHS = PIPEDH,AFS = PIPEAF
C
```

```
HEADER FLOW DATA,PIPE3,FID=9718$ START DESCR OF PIPE3
C
C INSERT BASIC INFO (SAME FOR ALL PIPES)
INSERT AQUEDUCT.INC
C
C DOWNHILL LINE
M LINE,1,D,1,1,98,NSEG = 10,UPF = 0.0
         LU = TANK,PA = STUBE,CZ = 0.9*93.0
         CZINC = -9.3,TLENT = DOWNLEN,DHS = PIPEDH,AFS = PIPEAF
C ACROSS BRIDGE
M LINE,2,C,11,11,10,20,NSEG = 9,UPF = 0.5
         LU = TANK,PA = STUBE,CZ = 0.0
         CZINC = 0.0,TLENT = BRIDGLEN,DHS = PIPEDH,AFS = PIPEAF
C UPHILL LINE
M LINE,3,U,20,21,99,NSEG = 10,UPF = 1.0
         LU = TANK,PA = STUBE,CZ = 0.0
         CZINC = 8.4,TLENT = UPLEN,DHS = PIPEDH,AFS = PIPEAF
C
HEADER FLOW DATA,PIPE4,FID=9718$ START DESCR OF PIPE4
C
C INSERT BASIC INFO (SAME FOR ALL PIPES)
INSERT AQUEDUCT.INC
C
C DOWNHILL LINE
M LINE,1,D,1,1,98,NSEG = 10,UPF = 0.0
         LU = TANK,PA = TUBE,CZ = 0.9*93.0
         CZINC = -9.3,TLENT = DOWNLEN,DHS = PIPEDH,AFS = PIPEAF
C ACROSS BRIDGE
M LINE,2,C,11,11,10,20,NSEG = 9,UPF = 0.5
         LU = TANK,PA = TUBE,CZ = 0.0
         CZINC = 0.0,TLENT = BRIDGLEN,DHS = PIPEDH,AFS = PIPEAF
C UPHILL LINE
M LINE,3,U,20,21,99,NSEG = 10,UPF = 1.0
         LU = TANK,PA = TUBE,CZ = 0.0
         CZINC = 8.4,TLENT = UPLEN,DHS = PIPEDH,AFS = PIPEAF
C
```

```
HEADER FLOW DATA,PIPE5,FID=9718              $ START DESCR OF PIPE5
C
C INSERT BASIC INFO (SAME FOR ALL PIPES)
INSERT aqueduct.inc
C
C DOWNHILL LINE
M HX,1,D,1,1,1,WALL5.1,98,NSEG = 10,UPF = 0.0
         LU = JUNC,PA = STUBE,CZ = 0.9*93.0
         CZINC = -9.3,TLENT = DOWNLEN,DHS = PIPEDH,AFS = PIPEAF
C ACROSS BRIDGE
M HX,2,C,11,11,11,WALL5.11,10,20,NSEG = 9,UPF = 0.5
         LU = JUNC,PA = STUBE,CZ = 0.0
         CZINC = 0.0,TLENT = BRIDGLEN,DHS = PIPEDH,AFS = PIPEAF
C UPHILL LINE
M HX,3,U,20,21,20,WALL5.20,99,NSEG = 10,UPF = 1.0
         LU = JUNC,PA = STUBE,CZ = 0.0
         CZINC = 8.4,TLENT = UPLEN,DHS = PIPEDH,AFS = PIPEAF
C
HEADER FLOW DATA,PIPE6,FID=9718$ START DESCR OF PIPE6
C
C INSERT BASIC INFO (SAME FOR ALL PIPES)
INSERT AQUEDUCT.INC
C
C DOWNHILL LINE
M HX,1,D,1,1,1,WALL6.1,98,NSEG = 10,UPF = 0.0
         LU = TANK,PA = TUBE,CZ = 0.9*93.0
         CZINC = -9.3,TLENT = DOWNLEN,DHS = PIPEDH,AFS = PIPEAF
C ACROSS BRIDGE
M HX,2,C,11,11,11,WALL6.11,10,20,NSEG = 9,UPF = 0.5
         LU = TANK,PA = TUBE,CZ = 0.0
         CZINC = 0.0,TLENT = BRIDGLEN,DHS = PIPEDH,AFS = PIPEAF
C UPHILL LINE
M HX,3,U,20,21,20,WALL6.20,99,NSEG = 10,UPF = 1.0
         LU = TANK,PA = TUBE,CZ = 0.0
         CZINC = 8.4,TLENT = UPLEN,DHS = PIPEDH,AFS = PIPEAF
C
```

```
HEADER FLOW DATA,PIPE7,FID=9718              $ START DESCR OF PIPE7
C
C INSERT BASIC INFO (SAME FOR ALL PIPES)
INSERT AQUEDUCT.INC
C
C DOWNHILL LINE
M HX,1,D,2,2,2,WALL7.2,98,NSEG = 5,UPF = 0.0
         LU = JUNC,PA = STUBE,CZ = 0.8*93.0
         LUINC = 2,PAINC = 2,NINC = 2,TIINC  = 2
         CZINC = -18.6,TLENT = DOWNLEN,DHS = PIPEDH,AFS = PIPEAF
C ACROSS BRIDGE
M HX,2,C,11,11,11,WALL7.11,10,20,NSEG = 5,UPF = 0.5
         LU = JUNC,PA = STUBE,CZ = 0.0
         LUINC = 2,PAINC = 2,NINC = 2,TIINC  = 2
         CZINC = 0.0,TLENT = BRIDGLEN,DHS = PIPEDH,AFS = PIPEAF
C UPHILL LINE
M HX,3,U,20,22,20,WALL7.20,99,NSEG = 5,UPF = 1.0
         LU = JUNC,PA = STUBE,CZ = 0.0
         LUINC = 2,PAINC = 2,NINC = 2,TIINC  = 2
         CZINC = 16.8,TLENT = UPLEN,DHS = PIPEDH,AFS = PIPEAF
C
HEADER FLOW DATA,PIPE8,FID=9718$ START DESCR OF PIPE8
C
C INSERT BASIC INFO (SAME FOR ALL PIPES)
INSERT AQUEDUCT.INC
C
C DOWNHILL LINE
M HX,1,D,2,2,2,WALL8.2,98,NSEG = 5,UPF = 0.0
         LU = TANK,PA = TUBE,CZ = 0.8*93.0
         LUINC = 2,PAINC = 2,NINC = 2,TIINC  = 2
         CZINC = -18.6,TLENT = DOWNLEN,DHS = PIPEDH,AFS = PIPEAF
C ACROSS BRIDGE
M HX,2,C,11,11,11,WALL8.11,10,20,NSEG = 5,UPF = 0.5
         LU = TANK,PA = TUBE,CZ = 0.0
         LUINC = 2,PAINC = 2,NINC = 2,TIINC  = 2
         CZINC = 0.0,TLENT = BRIDGLEN,DHS = PIPEDH,AFS = PIPEAF
C UPHILL LINE
M HX,3,U,20,22,20,WALL8.20,99,NSEG = 5,UPF = 1.0
         LU = TANK,PA = TUBE,CZ = 0.0
         LUINC = 2,PAINC = 2,NINC = 2,TIINC  = 2
         CZINC = 16.8,TLENT = UPLEN,DHS = PIPEDH,AFS = PIPEAF
C
```

```
HEADER CONTROL DATA,GLOBAL
         NLOOPS   = 100              $ MAX OF 100 SS ITERATIONS
         OUTPUT   = 1000.0           $ LARGE FAKE OUTPUT INTERVAL
         OUTPTF   = 1000.0           $ LARGE FAKE OUTPUT INTERVAL
         EXTLIM   = 5.0              $ LIMIT THERMAL EXTRAPOLATIONS
         DTMPCA   = 2.0              $ LIMIT THERMAL CHANGES TO 10%
         EBALSA   = 0.0              $ NO NET ENERGY FLOW IN THERMAL
C
         UID      = SI               $ METRIC UNITS
         ABSZRO   = -273.16          $ DEGREES C
         PATMOS   = -101325.0        $ GAUGE PRESSURE
C
         ACCELZ   = 9.81             $ ACCEL OF GRAVITY. Same as "gravsi"
C
HEADER USER DATA,GLOBAL
         NREC     = 0                $ PARAMETRIC RECORD NUMBER
         ITRAN    = 0                $ RUN FLAG FOR EVENTS
         I        = 0                $ USED IN OPERATIONS
C
HEADER REGISTER DATA
C
C TEMPERATURE OF INLET
         TUP               = 20.0
C
C PIPE MATERIAL THERMAL DATA: SPECIFIC HEAT, DENSITY, CONDUCTIVITY
         PIPECP            = 129.0
         PIPEDEN           = 11340.0
         PIPECOND          = 35.3
C
C PIPE PHYSICAL DIMENSIONS
C        PIPE MATERIAL CROSS SECTIONAL AREA
         PIPEAX            = 295.0/100.0^2
C        PIPE FLOW AREA
         PIPEAF            = 272.0/100.0^2
C        PIPE HYDRAULIC DIAMETER
         PIPEDH            = 18.0/100.0
C        DOWN HILL LENGTH
         DOWNLEN           = 400.0
C        BRIDGE LENGTH
         BRIDGLEN          = 400.0
C        UP HILL LENGTH
         UPLEN             = 400.0
C
C K FACTOR FOR THE LEAK DURING THE ERATHQUAKE TRANSIENT DURING
C THE SNOW MELT TRANSIENT KLOSLEAK IS NEGATIVE TO SIMULATE A CLOSED VALVE
         KLOSLEAK = -1.0
C
```

```
HEADER OPERATIONS
BUILD ALL
BUILDF ALL
C
         CALL FASTIC                         $ SMOOTH INIT COND
         CALL SAVPAR(NREC)                   $ SAVE FOR FUTURE USE
C
C OUTPUT STEADY STATE FLOWRATES AND PRESSURES
C
         CALL LMPTAB(’ALL’)
         CALL PTHTAB(’ALL’)
C
C SET UP AND RUN SNOWMELT TRANSIENT
C
         WRITE(NUSER1,10)(I,I=1,8)
10      FORMAT(’ SNOWMELT TRANSIENT SUMMARY: OUTLET TEMPERATURE’//
     .   ’   TIME (SEC)’,T15,8(4X,’PIPE’,I2,2X)/)
C
         ITRAN             = 1
         TIMEND            = 10000.0         $ LARGE ARTIFICIAL TIMEND
         CALL FORWRD
C
C TAKE SNAPSHOT AT END OF SNOWMELT TRANSIENT
C
         CALL LMPTAB(’ALL’)
         CALL PTHTAB(’ALL’)
         CALL TIETAB(’ALL’)
         CALL TPRINT(’ALL’)
C
C SET UP AND RUN PIPE BREAK (EARTHQUAKE) TRANSIENT
C
         WRITE(NUSER2,20)(I,I=1,8)
20      FORMAT(’ EARTHQUAKE TRANSIENT SUMMARY: OUTLET FLOWRATE’//
     .   ’   TIME (SEC)’,T15,8(4X,’PIPE’,I2,2X)/)
C
         CALL RESPAR(NREC) $ RETRIEVE STEADY STATE
         ITRAN             = 2      $ CHANGE AFTER RESPAR
         TIMEO             = 0.0    $ RESET TIME ZERO
         KLOSLEAK          = 1.0    $ OPEN LEAKS AT TIME ZERO
         TIMEND            = 100.0  $ LARGE ARTIFICIAL TIMEND
         CALL FORWRD
C
C TAKE SNAPSHOT AT END OF EARTHQUAKE TRANSIENT
C
         CALL LMPTAB(’ALL’)
         CALL PTHTAB(’ALL’)
DEFMOD PIPE1
         WRITE(NUSER2,30) FR98, FR3000
30       FORMAT(//’ FINAL INLET FLOWRATE:’,T30,1PG12.3/
```

```
     .              ' FINAL LEAKAGE FLOWRATE:',T30,G12.3)
C
HEADER FLOGIC 0,PIPE1                           $ LOGIC FOR ALL PIPES
C
C
C THE FOLLOWING LOGIC ADJUSTS THE INLET TEMPERATURE TO DECREASE
C LINEARLY WITH TIME FOR THE SNOWMELT TRANSIENT.
C
         IF(ITRAN .EQ. 1 .AND. TIMEN .LE. 610.0) THEN
                  TUP      = MAX(1.0,20.0-19.0*TIMEN/600.0)
         ENDIF
C
HEADER FLOGIC 2,PIPE1                           $ LOGIC FOR ALL PIPES
C
C THE FOLLOWING LOGIC SELECTS AN APPROPRIATE OUTPUT INTERVAL
C AND AN APPROPRIATE END TIME
C
         IF(ITRAN .EQ. 1)THEN
                  OUTPTF            = 60.0
                  IF(PIPE6.TL99 .LE. 5.0) TIMEND= MAX(TIMEN,600.0)
         ELSEIF(ITRAN .EQ. 2)THEN
                  OUTPTF            = 1000.0
                  OPITRF            = 1.0       $ OUTPUT EACH STEP
                  IF(PIPE6.DTIMUF .GT. 1.0) TIMEND = TIMEN
         ENDIF
C
HEADER OUTPUT CALLS, PIPE1
C
         IF(ITRAN .EQ. 1)THEN
                  WRITE(NUSER1,10)TIMEN,TL99,PIPE2.TL99,PIPE3.TL99,
     .            PIPE4.TL99,PIPE5.TL99,PIPE6.TL99,PIPE7.TL99,PIPE8.TL99
         ELSEIF(ITRAN .EQ. 2)THEN
                  WRITE(NUSER2,10)TIMEN,FR99,PIPE2.FR99,PIPE3.FR99,
     .            PIPE4.FR99,PIPE5.FR99,PIPE6.FR99,PIPE7.FR99,PIPE8.FR99
         ENDIF
10       FORMAT(1X,1PG13.6,8G12.3)
END OF DATA
C
C THIS IS THE INSERT FILE FOR ALL AQUEDUCT PIPE SUBMODELS
C
LU DEF, TL = 20.0, PL = 0.0, XL = 0.0
PA DEF, FR = 25.0, WRF = 0.01                      $ ~20000 m3/day/aqueduct
            DH = PIPEDH, AF = PIPEAF
C
LU PLEN,1000,TL = TUP,  CZ = 93.0                  $ INLET
LU PLEN,2000,CZ = 84.0                             $ OUTLET
LU PLEN,3000,CZ = 0.0                              $ EXIT
PA CONN,98,1000,98,DEV = LOSS,FK = 0.7             $ ENTRANCE, BEND
PA CONN,99,99,2000,DEV = LOSS,FK = 0.2             $ EXIT, BEND
LU JUNC,98, CZ = 93.0                              $ ENTRANCE
```

```
LU JUNC,99, CZ = 84.0                             $ EXIT
PA CONN,3000,15,3000,DEV = CTLVLV,FK = KLOSLEAK $ LEAK
                        AF = 10.0E-4
```

Processor Output

```
SNOWMELT TRANSIENT SUMMARY: OUTLET TEMPERATURE

  TIME (SEC)      PIPE 1      PIPE 2      PIPE 3      PIPE 4      PIPE 5      PIPE 6      PIPE 7      PIPE 8

  0.00000         20.0        20.0        20.0        20.0        20.0        20.0        20.0        20.0
  60.0000         18.3        18.3        20.0        20.0        20.0        20.0        20.0        20.0
  120.000         16.5        16.5        20.0        20.0        20.0        20.0        20.0        20.0
  180.000         14.8        14.8        20.0        20.0        20.0        20.0        20.0        20.0
  240.000         12.9        12.9        20.0        20.0        19.9        20.0        19.9        20.0
  300.000         11.0        11.0        20.0        20.0        19.9        20.0        19.8        20.0
  360.000         9.14        9.14        20.0        20.0        19.8        20.0        19.6        20.0
  420.000         7.29        7.29        20.0        20.0        19.5        20.0        19.3        20.0
  480.000         5.31        5.31        20.0        20.0        18.9        20.0        18.6        20.0
  540.000         3.41        3.41        20.0        20.0        18.1        20.0        17.8        20.0
  600.000         1.51        1.51        20.0        20.0        17.0        20.0        16.7        20.0
  660.000         1.02        1.02        20.0        20.0        15.7        20.0        15.4        20.0
  720.000         1.02        1.02        20.0        20.0        14.2        20.0        13.9        20.0
  780.000         1.02        1.02        20.0        20.0        12.5        20.0        12.4        20.0
  840.000         1.02        1.02        20.0        20.0        10.8        20.0        10.7        20.0
  900.000         1.02        1.02        20.0        20.0        9.12        20.0        9.08        20.0
  960.000         1.02        1.02        19.9        19.9        7.48        20.0        7.55        20.0
  1020.00         1.02        1.02        19.8        19.8        6.13        20.0        6.27        19.9
  1080.00         1.02        1.02        19.7        19.7        4.77        20.0        4.98        19.9
  1140.00         1.02        1.02        19.4        19.4        3.73        20.0        3.98        19.8
  1200.00         1.02        1.02        19.1        19.1        2.93        19.9        3.19        19.7
  1260.00         1.02        1.02        18.7        18.7        2.32        19.9        2.57        19.6
  1320.00         1.02        1.02        18.1        18.1        1.88        19.8        2.10        19.4
  1380.00         1.02        1.02        17.4        17.4        1.57        19.7        1.76        19.2
  1440.00         1.02        1.02        16.5        16.5        1.37        19.5        1.52        18.9
  1500.00         1.02        1.02        15.5        15.6        1.24        19.3        1.35        18.6
  1560.00         1.02        1.02        14.4        14.4        1.15        19.1        1.24        18.2
  1620.00         1.02        1.02        13.2        13.3        1.09        18.7        1.16        17.8
  1680.00         1.02        1.02        12.0        12.0        1.06        18.3        1.10        17.3
  1740.00         1.02        1.02        10.7        10.7        1.04        17.8        1.07        16.8
  1800.00         1.02        1.02        9.49        9.49        1.03        17.3        1.06        16.2
```

```
  1860.00         1.02        1.02        8.30        8.31        1.03        16.6        1.04        15.5
  1920.00         1.02        1.02        7.19        7.20        1.02        15.9        1.03        14.8
  1980.00         1.02        1.02        6.17        6.18        1.02        15.1        1.02        14.1
  2040.00         1.02        1.02        5.25        5.26        1.02        14.2        1.02        13.4
  2100.00         1.02        1.02        4.44        4.45        1.02        13.4        1.02        12.6
  2160.00         1.02        1.02        3.75        3.76        1.02        12.5        1.02        11.9
  2220.00         1.02        1.02        3.17        3.17        1.02        11.5        1.02        11.1
  2280.00         1.02        1.02        2.69        2.69        1.02        10.6        1.02        10.3
  2340.00         1.02        1.02        2.30        2.30        1.02        9.67        1.02        9.58
  2400.00         1.02        1.02        1.98        1.99        1.02        8.79        1.02        8.87
  2460.00         1.02        1.02        1.74        1.74        1.02        7.95        1.02        8.18
  2520.00         1.02        1.02        1.55        1.55        1.02        7.15        1.02        7.52
  2580.00         1.02        1.02        1.40        1.41        1.02        6.41        1.02        6.90
  2640.00         1.02        1.02        1.30        1.30        1.02        5.72        1.02        6.31
  2700.00         1.02        1.02        1.22        1.22        1.02        5.09        1.02        5.76
  2730.00         1.02        1.02        1.18        1.19        1.02        4.80        1.02        5.50
```

```
EARTHQUAKE TRANSIENT SUMMARY: OUTLET FLOWRATE

  TIME (SEC)     PIPE 1      PIPE 2      PIPE 3      PIPE 4      PIPE 5      PIPE 6      PIPE 7      PIPE 8

  0.00000        22.5        22.5        22.5        22.5        22.5        22.5        22.5        22.5
 2.776187E-02    2.58        20.5        2.58        20.5        2.58        20.5        2.58        20.5
 5.672976E-02   -3.08        19.2       -3.08        19.2       -3.08        19.2       -3.19        19.2
 9.955715E-02   -6.02        17.8       -6.02        17.8       -6.02        17.8       -6.05        17.8
 0.152086       -7.01        16.1       -7.01        16.1       -7.01        16.1       -7.09        16.1
 0.200974       -7.26        14.5       -7.27        14.5       -7.26        14.5       -7.33        14.5
 0.247096       -7.37        13.1       -7.38        13.1       -7.37        13.1       -7.39        13.1
 0.291301       -7.42        11.9       -7.42        11.9       -7.42        11.9       -7.42        11.9
 0.334200       -7.43        10.8       -7.43        10.8       -7.43        10.8       -7.43        10.8
 0.376414       -7.43        9.83       -7.43        9.83       -7.43        9.83       -7.43        9.83
 0.418298       -7.44        8.93       -7.44        8.93       -7.43        8.93       -7.43        8.93
 0.460188       -7.44        8.13       -7.44        8.13       -7.43        8.13       -7.43        8.13
 0.502364       -7.44        7.39       -7.44        7.39       -7.43        7.39       -7.43        7.39
 0.544974       -7.44        6.73       -7.44        6.73       -7.43        6.73       -7.43        6.73
 0.588143       -7.44        6.13       -7.44        6.13       -7.43        6.13       -7.43        6.13
 0.632166       -7.44        5.58       -7.44        5.58       -7.43        5.58       -7.43        5.58
 0.677196       -7.44        5.09       -7.44        5.09       -7.43        5.09       -7.43        5.09
 0.723445       -7.44        4.64       -7.44        4.64       -7.43        4.64       -7.43        4.64
 0.771136       -7.44        4.23       -7.44        4.23       -7.43        4.23       -7.43        4.23
 0.820496       -7.44        3.86       -7.44        3.86       -7.43        3.86       -7.43        3.86
 0.871751       -7.44        3.52       -7.44        3.52       -7.43        3.52       -7.43        3.52
 0.925139       -7.44        3.21       -7.44        3.21       -7.43        3.21       -7.43        3.21
 0.980878       -7.44        2.93       -7.44        2.93       -7.43        2.93       -7.43        2.93
  1.03914       -7.44        2.68       -7.44        2.68       -7.43        2.68       -7.43        2.68
  1.10007       -7.44        2.44       -7.44        2.44       -7.43        2.44       -7.43        2.44
  1.16369       -7.44        2.23       -7.44        2.23       -7.43        2.23       -7.43        2.23
  1.22997       -7.44        2.03       -7.44        2.03       -7.43        2.03       -7.43        2.03
  1.29860       -7.44        1.85       -7.44        1.85       -7.43        1.85       -7.43        1.85
  1.36920       -7.44        1.69       -7.44        1.69       -7.43        1.69       -7.43        1.69
  1.44107       -7.44        1.53       -7.44        1.53       -7.43        1.53       -7.43        1.53
  1.51338       -7.44        1.39       -7.44        1.39       -7.43        1.39       -7.43        1.39
  1.58536       -7.44        1.27       -7.44        1.27       -7.43        1.27       -7.43        1.27
  1.65605       -7.44        1.15       -7.44        1.15       -7.43        1.15       -7.43        1.15
  1.72456       -7.44        1.04       -7.44        1.04       -7.43        1.04       -7.43        1.04
  1.79024       -7.44       0.940       -7.44       0.940       -7.43       0.940       -7.43       0.940
  1.85256       -7.44       0.850       -7.44       0.850       -7.43       0.850       -7.43       0.849
  1.91108       -7.44       0.768       -7.44       0.767       -7.43       0.767       -7.43       0.767
  1.96579       -7.44       0.693       -7.44       0.693       -7.43       0.693       -7.43       0.693
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  2.01659       -7.44       0.625       -7.44       0.625       -7.43       0.625       -7.43       0.625
  2.06346       -7.44       0.564       -7.44       0.564       -7.43       0.564       -7.43       0.564
  2.10660       -7.44       0.509       -7.44       0.508       -7.43       0.508       -7.43       0.508
  2.14611       -7.44       0.458       -7.44       0.458       -7.43       0.458       -7.43       0.458
  2.18226       -7.44       0.413       -7.44       0.413       -7.43       0.413       -7.43       0.413
  2.21519       -7.44       0.372       -7.44       0.372       -7.43       0.372       -7.43       0.372
  2.24519       -7.44       0.335       -7.44       0.335       -7.43       0.335       -7.43       0.335
  2.27248       -7.44       0.302       -7.44       0.302       -7.43       0.302       -7.43       0.302
  2.29725       -7.44       0.272       -7.44       0.272       -7.43       0.272       -7.43       0.272
  2.31971       -7.44       0.245       -7.44       0.245       -7.43       0.245       -7.43       0.245
  2.34006       -7.44       0.221       -7.44       0.221       -7.43       0.221       -7.43       0.221
  2.35848       -7.44       0.199       -7.44       0.199       -7.43       0.199       -7.43       0.199
  2.37587       -7.44       0.178       -7.44       0.178       -7.43       0.178       -7.43       0.178
  2.39331       -7.44       0.157       -7.44       0.157       -7.43       0.158       -7.43       0.157
  2.41080       -7.44       0.137       -7.44       0.137       -7.43       0.137       -7.43       0.137
  2.42835       -7.44       0.116       -7.44       0.116       -7.43       0.116       -7.43       0.116
  2.44596       -7.44       9.572E-02   -7.44       9.578E-02   -7.43       9.581E-02   -7.43       9.568E-02
  2.46362       -7.44       7.516E-02   -7.44       7.524E-02   -7.43       7.527E-02   -7.43       7.514E-02
  2.48133       -7.44       5.463E-02   -7.44       5.473E-02   -7.43       5.475E-02   -7.43       5.461E-02
  2.49910       -7.44       3.410E-02   -7.44       3.423E-02   -7.43       3.425E-02   -7.43       3.411E-02
  2.51691       -7.44       1.360E-02   -7.44       1.376E-02   -7.43       1.377E-02   -7.43       1.363E-02
  2.53477       -7.44      -6.886E-03   -7.44      -6.738E-03   -7.43      -6.685E-03   -7.43      -6.833E-03
  2.55268       -7.44      -2.733E-02   -7.44      -2.721E-02   -7.43      -2.712E-02   -7.43      -2.731E-02
  2.57067       -7.44      -4.778E-02   -7.44      -4.768E-02   -7.43      -4.761E-02   -7.43      -4.779E-02
  2.58871       -7.44      -6.823E-02   -7.44      -6.814E-02   -7.43      -6.808E-02   -7.43      -6.826E-02
  2.60682       -7.44      -8.869E-02   -7.44      -8.860E-02   -7.43      -8.856E-02   -7.43      -8.873E-02
  2.62500       -7.44      -0.109       -7.44      -0.109       -7.43      -0.109       -7.43      -0.109
  2.64324       -7.44      -0.130       -7.44      -0.130       -7.43      -0.130       -7.43      -0.130
  2.66154       -7.44      -0.150       -7.44      -0.150       -7.43      -0.150       -7.43      -0.150
  2.67991       -7.44      -0.171       -7.44      -0.171       -7.43      -0.170       -7.43      -0.171
  2.69834       -7.44      -0.191       -7.44      -0.191       -7.43      -0.191       -7.43      -0.191
  2.71683       -7.44      -0.212       -7.44      -0.211       -7.43      -0.211       -7.43      -0.212
  2.73593       -7.44      -0.233       -7.44      -0.233       -7.43      -0.233       -7.43      -0.233
  2.75700       -7.44      -0.256       -7.44      -0.256       -7.43      -0.256       -7.43      -0.256
  2.78023       -7.44      -0.281       -7.44      -0.281       -7.43      -0.281       -7.43      -0.281
  2.80588       -7.44      -0.309       -7.44      -0.309       -7.43      -0.309       -7.43      -0.309
  2.83422       -7.44      -0.340       -7.44      -0.340       -7.43      -0.340       -7.43      -0.340
  2.86553       -7.44      -0.374       -7.44      -0.374       -7.43      -0.374       -7.43      -0.374
  2.90014       -7.44      -0.411       -7.44      -0.411       -7.43      -0.411       -7.43      -0.411
  2.93835       -7.44      -0.452       -7.44      -0.452       -7.43      -0.452       -7.43      -0.452
  2.98065       -7.44      -0.496       -7.44      -0.497       -7.43      -0.497       -7.43      -0.497
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  3.02747       -7.44      -0.546       -7.44      -0.546       -7.43      -0.546       -7.43      -0.546
  3.07933       -7.44      -0.600       -7.44      -0.600       -7.43      -0.600       -7.43      -0.600
  3.13683       -7.44      -0.659       -7.44      -0.659       -7.43      -0.659       -7.43      -0.659
  3.20054       -7.44      -0.724       -7.44      -0.725       -7.43      -0.725       -7.43      -0.725
  3.27113       -7.44      -0.796       -7.44      -0.796       -7.43      -0.796       -7.43      -0.796
  3.34969       -7.44      -0.875       -7.44      -0.875       -7.43      -0.875       -7.43      -0.875
  3.43710       -7.44      -0.961       -7.44      -0.961       -7.43      -0.961       -7.43      -0.961
  3.53439       -7.44       -1.06       -7.44       -1.06       -7.43       -1.06       -7.43       -1.06
  3.64279       -7.44       -1.16       -7.44       -1.16       -7.43       -1.16       -7.43       -1.16
  3.76390       -7.44       -1.27       -7.44       -1.27       -7.43       -1.27       -7.43       -1.27
  3.89933       -7.44       -1.40       -7.44       -1.40       -7.43       -1.40       -7.43       -1.40
  4.05109       -7.44       -1.53       -7.44       -1.53       -7.43       -1.53       -7.43       -1.53
  4.22140       -7.44       -1.68       -7.44       -1.68       -7.43       -1.68       -7.43       -1.68
  4.41304       -7.44       -1.85       -7.44       -1.85       -7.43       -1.85       -7.43       -1.85
  4.62959       -7.44       -2.03       -7.44       -2.03       -7.43       -2.03       -7.43       -2.03
  4.87482       -7.44       -2.22       -7.44       -2.22       -7.43       -2.22       -7.43       -2.22
  5.15367       -7.44       -2.43       -7.44       -2.43       -7.43       -2.43       -7.43       -2.43
  5.47198       -7.44       -2.67       -7.44       -2.67       -7.43       -2.67       -7.43       -2.67
  5.83768       -7.44       -2.92       -7.44       -2.92       -7.43       -2.92       -7.43       -2.92
  6.26011       -7.44       -3.19       -7.44       -3.19       -7.43       -3.19       -7.43       -3.19
  6.75178       -7.44       -3.49       -7.44       -3.49       -7.43       -3.49       -7.43       -3.49
  7.32933       -7.44       -3.81       -7.44       -3.81       -7.43       -3.81       -7.43       -3.81
  8.01517       -7.44       -4.15       -7.44       -4.15       -7.43       -4.15       -7.43       -4.15
  8.84091       -7.44       -4.52       -7.44       -4.52       -7.43       -4.52       -7.43       -4.52
  9.85267       -7.44       -4.91       -7.44       -4.91       -7.43       -4.91       -7.43       -4.91


FINAL INLET FLOWRATE:           33.0
FINAL LEAKAGE FLOWRATE:         40.4
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 FLUID SUBMODEL NAME = PIPE1   ; FLUID NO. = 9718


        LOOPCT =    13
        CONVERGENCE STATUS = SUBMODEL CONVERGED AS OF      10 ITERATIONS


                                   LUMP PARAMETER TABULATION FOR SUBMODEL PIPE1

  LUMP  TYPE     TEMP       PRESSURE     QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

    98  JUNC    20.00       -239.7        0.000        0.000        998.3       1.2962E+06    0.000        0.000        0.000
    99  JUNC    20.02        68.49        0.000        0.000        998.3       1.2963E+06    0.000        0.000        0.000
     1  JUNC    20.00       8.7913E+04    0.000        0.000        998.3       1.2963E+06    0.000        0.000        0.000
     2  JUNC    20.00       1.7606E+05    0.000        0.000        998.3       1.2964E+06    0.000        0.000        0.000
     3  JUNC    20.00       2.6422E+05    0.000        0.000        998.3       1.2964E+06    0.000        0.000        0.000
     4  JUNC    20.00       3.5237E+05    0.000        0.000        998.3       1.2965E+06    0.000        0.000        0.000
     5  JUNC    20.00       4.4052E+05    0.000        0.000        998.3       1.2966E+06    0.000        0.000        0.000
     6  JUNC    20.00       5.2867E+05    0.000        0.000        998.3       1.2967E+06    0.000        0.000        0.000
     7  JUNC    20.00       6.1683E+05    0.000        0.000        998.3       1.2968E+06    0.000        0.000        0.000
     8  JUNC    20.01       7.0498E+05    0.000        0.000        998.3       1.2969E+06    0.000        0.000        0.000
     9  JUNC    20.01       7.9313E+05    0.000        0.000        998.3       1.2970E+06    0.000        0.000        0.000
    10  JUNC    20.01       8.8128E+05    0.000        0.000        998.3       1.2971E+06    0.000        0.000        0.000
    11  JUNC    20.01       8.7966E+05    0.000        0.000        998.3       1.2971E+06    0.000        0.000        0.000
    12  JUNC    20.01       8.7640E+05    0.000        0.000        998.3       1.2971E+06    0.000        0.000        0.000
    13  JUNC    20.01       8.7315E+05    0.000        0.000        998.3       1.2971E+06    0.000        0.000        0.000
    14  JUNC    20.01       8.6990E+05    0.000        0.000        998.3       1.2971E+06    0.000        0.000        0.000
    15  JUNC    20.01       8.6664E+05    0.000        0.000        998.3       1.2971E+06    0.000        0.000        0.000
    16  JUNC    20.01       8.6339E+05    0.000        0.000        998.3       1.2971E+06    0.000        0.000        0.000
    17  JUNC    20.01       8.6014E+05    0.000        0.000        998.3       1.2971E+06    0.000        0.000        0.000
    18  JUNC    20.01       8.5688E+05    0.000        0.000        998.3       1.2971E+06    0.000        0.000        0.000
    19  JUNC    20.01       8.5363E+05    0.000        0.000        998.3       1.2971E+06    0.000        0.000        0.000
    20  JUNC    20.01       8.5200E+05    0.000        0.000        998.3       1.2971E+06    0.000        0.000        0.000
    21  JUNC    20.02       7.6681E+05    0.000        0.000        998.3       1.2970E+06    0.000        0.000       -2.000
    22  JUNC    20.02       6.8162E+05    0.000        0.000        998.3       1.2969E+06    0.000        0.000        0.000
    23  JUNC    20.02       5.9642E+05    0.000        0.000        998.3       1.2968E+06    0.000        0.000        0.000
    24  JUNC    20.02       5.1123E+05    0.000        0.000        998.3       1.2968E+06    0.000        0.000        0.000
    25  JUNC    20.02       4.2604E+05    0.000        0.000        998.3       1.2967E+06    0.000        0.000        0.000
    26  JUNC    20.02       3.4084E+05    0.000        0.000        998.3       1.2966E+06    0.000        0.000        0.000
    27  JUNC    20.02       2.5565E+05    0.000        0.000        998.3       1.2965E+06    0.000        0.000        0.000
    28  JUNC    20.02       1.7046E+05    0.000        0.000        998.3       1.2964E+06    0.000        0.000        0.000
    29  JUNC    20.02       8.5262E+04    0.000        0.000        998.3       1.2963E+06    0.000        0.000        0.000
  1000  PLEN    20.00        0.000        0.000        0.000        998.3       1.2962E+06    0.000       -22.49      -2.9152E+07
  2000  PLEN    20.00        0.000        0.000        0.000        998.3       1.2962E+06    0.000        22.49       2.9154E+07
  3000  PLEN    20.00        0.000        0.000        0.000        998.3       1.2962E+06    0.000        0.000        0.000
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FLUID SUBMODEL NAME = PIPE1   ; FLUID NO. = 9718


       LOOPCT =    13
       CONVERGENCE STATUS = SUBMODEL CONVERGED AS OF      10 ITERATIONS


                                   PATH PARAMETER TABULATION FOR SUBMODEL PIPE1

  PATH  TYPE    LMP 1   LMP 2   DUP I      DUP J    STAT   XL UPSTRM    FLOWRATE     DELTA PRES    REYNOLDS     MACH     REGIME

   98   LOSS     1000      98    1.0        1.0     NORM     0.000        22.49        239.7
   99   LOSS       99    2000    1.0        1.0     NORM     0.000        22.49        68.49
 3000   CTLVLV     15    3000    1.0        1.0     NORM     0.000        0.000       8.6664E+05
    1   STUBE      98       1    1.0        1.0     NORM     0.000        22.49      -8.8152E+04   1.4984E+05          1 PHASE
    2   STUBE       1       2    1.0        1.0     NORM     0.000        22.49      -8.8152E+04   1.4984E+05          1 PHASE
    3   STUBE       2       3    1.0        1.0     NORM     0.000        22.49      -8.8152E+04   1.4984E+05          1 PHASE
    4   STUBE       3       4    1.0        1.0     NORM     0.000        22.49      -8.8152E+04   1.4984E+05          1 PHASE
    5   STUBE       4       5    1.0        1.0     NORM     0.000        22.49      -8.8152E+04   1.4985E+05          1 PHASE
    6   STUBE       5       6    1.0        1.0     NORM     0.000        22.49      -8.8152E+04   1.4985E+05          1 PHASE
    7   STUBE       6       7    1.0        1.0     NORM     0.000        22.49      -8.8152E+04   1.4985E+05          1 PHASE
    8   STUBE       7       8    1.0        1.0     NORM     0.000        22.49      -8.8152E+04   1.4986E+05          1 PHASE
    9   STUBE       8       9    1.0        1.0     NORM     0.000        22.49      -8.8152E+04   1.4986E+05          1 PHASE
   10   STUBE       9      10    1.0        1.0     NORM     0.000        22.49      -8.8152E+04   1.4986E+05          1 PHASE
   11   STUBE      10      11    1.0        1.0     NORM     0.000        22.49        1627.       1.4986E+05          1 PHASE
   12   STUBE      11      12    1.0        1.0     NORM     0.000        22.49        3253.       1.4986E+05          1 PHASE
   13   STUBE      12      13    1.0        1.0     NORM     0.000        22.49        3253.       1.4987E+05          1 PHASE
   14   STUBE      13      14    1.0        1.0     NORM     0.000        22.49        3253.       1.4987E+05          1 PHASE
   15   STUBE      14      15    1.0        1.0     NORM     0.000        22.49        3253.       1.4987E+05          1 PHASE
   16   STUBE      15      16    1.0        1.0     NORM     0.000        22.49        3253.       1.4988E+05          1 PHASE
   17   STUBE      16      17    1.0        1.0     NORM     0.000        22.49        3253.       1.4988E+05          1 PHASE
   18   STUBE      17      18    1.0        1.0     NORM     0.000        22.49        3253.       1.4988E+05          1 PHASE
   19   STUBE      18      19    1.0        1.0     NORM     0.000        22.49        3253.       1.4989E+05          1 PHASE
   20   STUBE      19      20    1.0        1.0     NORM     0.000        22.49        1627.       1.4989E+05          1 PHASE
   21   STUBE      20      21    1.0        1.0     NORM     0.000        22.49       8.5194E+04   1.4989E+05          1 PHASE
   22   STUBE      21      22    1.0        1.0     NORM     0.000        22.49       8.5194E+04   1.4989E+05          1 PHASE
   23   STUBE      22      23    1.0        1.0     NORM     0.000        22.49       8.5193E+04   1.4989E+05          1 PHASE
   24   STUBE      23      24    1.0        1.0     NORM     0.000        22.49       8.5193E+04   1.4990E+05          1 PHASE
   25   STUBE      24      25    1.0        1.0     NORM     0.000        22.49       8.5193E+04   1.4990E+05          1 PHASE
   26   STUBE      25      26    1.0        1.0     NORM     0.000        22.49       8.5193E+04   1.4991E+05          1 PHASE
   27   STUBE      26      27    1.0        1.0     NORM     0.000        22.49       8.5193E+04   1.4991E+05          1 PHASE
   28   STUBE      27      28    1.0        1.0     NORM     0.000        22.49       8.5193E+04   1.4991E+05          1 PHASE
   29   STUBE      28      29    1.0        1.0     NORM     0.000        22.49       8.5193E+04   1.4991E+05          1 PHASE
   30   STUBE      29      99    1.0        1.0     NORM     0.000        22.49       8.5193E+04   1.4992E+05          1 PHASE
```

```
FLUID SUBMODEL NAME = PIPE6   ; FLUID NO. = 9718


       MAX TIME STEP =   38.8226     ; LIMITING TIE  =      11    REASON  = NODE TEMPERATURE CHANGE LIMIT
       LAST TIME STEP =   30.0000     VS. DTMAXF/DTMINF =  1.000000E+30 /   0.00000     ;   AVERAGE TIME STEP =   29.0697
       PROBLEM TIME                  TIMEN  =  2730.00     VS. TIMEND  =  2730.00


                                   LUMP PARAMETER TABULATION FOR SUBMODEL PIPE6

 LUMP  TYPE     TEMP       PRESSURE     QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

    1  TANK    1.001       8.8053E+04    0.000        0.000        999.9       1.2165E+06   2.3833E-05    0.000       2.3833E-05
    2  TANK    1.002       1.7634E+05    0.000        0.000        999.9       1.2166E+06  -1.5889E-05    0.000      -1.5889E-05
    3  TANK    1.002       2.6463E+05    0.000        0.000        999.9       1.2166E+06   1.5890E-05    0.000       1.5890E-05
    4  TANK    1.003       3.5292E+05    0.000        0.000        999.9       1.2167E+06  -7.9440E-06    0.000      -7.9440E-06
    5  TANK    1.004       4.4121E+05    0.000        0.000        999.9       1.2168E+06   5.2643E-06    0.000       5.2643E-06
    6  TANK    1.004       5.2950E+05    0.000        0.000        999.9       1.2169E+06  -1.3598E-05    0.000      -1.3598E-05
    7  TANK    1.005       6.1780E+05    0.000        0.000        999.9       1.2170E+06  -3.9869E-03   1.9073E-06  -3.9869E-03
    8  TANK    1.006       7.0609E+05    0.000        0.000        999.9       1.2171E+06    2.202      -1.9073E-06   -3.798
    9  TANK    1.007       7.9438E+05    0.000        0.000        999.9       1.2172E+06    5.993        0.000       -2.007
   10  TANK    1.007       8.8267E+05    0.000        0.000        999.9       1.2173E+06    12.91        0.000       -13.09
   11  TANK    1.008       8.8104E+05    0.000        0.000        999.9       1.2173E+06    15.20        0.000       -40.80
   12  TANK    1.011       8.7778E+05    0.000        0.000        999.9       1.2173E+06    50.46        0.000       -93.54
   13  TANK    1.015       8.7452E+05    0.000        0.000        999.9       1.2173E+06    99.75        0.000       -210.3
   14  TANK    1.022       8.7126E+05    0.000        0.000        999.9       1.2173E+06    202.4        0.000       -415.6
   15  TANK    1.035       8.6800E+05    0.000        0.000        999.9       1.2174E+06    369.5        0.000       -782.5
   16  TANK    1.057       8.6474E+05    0.000        0.000        999.9       1.2175E+06    634.7        0.000       -1383.
   17  TANK    1.094       8.6148E+05    0.000        0.000        999.9       1.2176E+06    1041.        0.000       -2311.
   18  TANK    1.150       8.5822E+05    0.000        0.000        999.9       1.2179E+06    1641.        0.000       -3657.
   19  TANK    1.236       8.5496E+05    0.000        0.000        999.9       1.2182E+06    2459.        0.000       -5529.
   20  TANK    1.342       8.5333E+05    0.000        0.000        999.9       1.2187E+06    3052.        0.000       -6954.
   21  TANK    1.486       7.6800E+05    0.000        0.000        999.9       1.2192E+06    4098.        0.000       -9428.
   22  TANK    1.675       6.8267E+05    0.000        0.000        999.9       1.2199E+06    5342.        0.000      -1.2440E+04
   23  TANK    1.917       5.9734E+05    0.000        0.000        999.9       1.2208E+06    6789.        0.000      -1.5991E+04
   24  TANK    2.219       5.1202E+05    0.000        0.000        999.9       1.2220E+06    8419.        0.000      -2.0053E+04
   25  TANK    2.588       4.2669E+05    0.000        0.000        999.9       1.2235E+06   1.0209E+04    0.000      -2.4563E+04
   26  TANK    3.028       3.4136E+05    0.000        0.000        999.9       1.2253E+06   1.2084E+04    0.000      -2.9422E+04
   27  TANK    3.542       2.5604E+05    0.000        0.000        999.9       1.2273E+06   1.4026E+04    0.000      -3.4508E+04
   28  TANK    4.132       1.7071E+05    0.000        0.000        999.9       1.2297E+06   1.5960E+04    0.000      -3.9650E+04
   29  TANK    4.795       8.5390E+04    0.000        0.000        999.9       1.2324E+06   1.7807E+04    0.000      -4.4667E+04
   98  JUNC    1.000       -237.9        0.000        0.000        999.9       1.2164E+06    0.000        0.000         0.000
   99  JUNC    4.795        67.96        0.000        0.000        999.9       1.2324E+06    0.000        0.000         0.000
 1000  PLEN    1.000        0.000        0.000        0.000        999.9       1.2164E+06    0.000       -22.42      -2.7273E+07
 2000  PLEN    20.00        0.000        0.000        0.000        998.3       1.2962E+06    0.000        22.42       2.7632E+07
 3000  PLEN    20.00        0.000        0.000        0.000        998.3       1.2962E+06    0.000        0.000         0.000
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FLUID SUBMODEL NAME = PIPE6    ; FLUID NO. = 9718


       MAX TIME STEP =    38.8226      ; LIMITING TIE  =       11     REASON   = NODE TEMPERATURE CHANGE LIMIT
       LAST TIME STEP =    30.0000      VS. DTMAXF/DTMINF =  1.000000E+30 /    0.00000     ;    AVERAGE TIME STEP =    29.0697
       PROBLEM TIME                    TIMEN  =  2730.00      VS. TIMEND   =  2730.00


                                    PATH PARAMETER TABULATION FOR SUBMODEL PIPE6

  PATH  TYPE    LMP 1   LMP 2   DUP I      DUP J    STAT   XL UPSTRM    FLOWRATE     DELTA PRES    REYNOLDS    MACH     REGIME

     1  TUBE       98       1   1.0         1.0     NORM     0.000        22.42      -8.8290E+04   8.6084E+04           1 PHASE
     2  TUBE        1       2   1.0         1.0     NORM     0.000        22.42      -8.8290E+04   8.6086E+04           1 PHASE
     3  TUBE        2       3   1.0         1.0     NORM     0.000        22.42      -8.8290E+04   8.6087E+04           1 PHASE
     4  TUBE        3       4   1.0         1.0     NORM     0.000        22.42      -8.8290E+04   8.6090E+04           1 PHASE
     5  TUBE        4       5   1.0         1.0     NORM     0.000        22.42      -8.8290E+04   8.6091E+04           1 PHASE
     6  TUBE        5       6   1.0         1.0     NORM     0.000        22.42      -8.8290E+04   8.6094E+04           1 PHASE
     7  TUBE        6       7   1.0         1.0     NORM     0.000        22.42      -8.8290E+04   8.6095E+04           1 PHASE
     8  TUBE        7       8   1.0         1.0     NORM     0.000        22.42      -8.8290E+04   8.6098E+04           1 PHASE
     9  TUBE        8       9   1.0         1.0     NORM     0.000        22.42      -8.8290E+04   8.6100E+04           1 PHASE
    10  TUBE        9      10   1.0         1.0     NORM     0.000        22.42      -8.8290E+04   8.6102E+04           1 PHASE
    11  TUBE       10      11   1.0         1.0     NORM     0.000        22.42        1630.       8.6102E+04           1 PHASE
    12  TUBE       11      12   1.0         1.0     NORM     0.000        22.42        3260.       8.6105E+04           1 PHASE
    13  TUBE       12      13   1.0         1.0     NORM     0.000        22.42        3260.       8.6111E+04           1 PHASE
    14  TUBE       13      14   1.0         1.0     NORM     0.000        22.42        3260.       8.6122E+04           1 PHASE
    15  TUBE       14      15   1.0         1.0     NORM     0.000        22.42        3260.       8.6143E+04           1 PHASE
    16  TUBE       15      16   1.0         1.0     NORM     0.000        22.42        3260.       8.6178E+04           1 PHASE
    17  TUBE       16      17   1.0         1.0     NORM     0.000        22.42        3260.       8.6239E+04           1 PHASE
    18  TUBE       17      18   1.0         1.0     NORM     0.000        22.42        3260.       8.6339E+04           1 PHASE
    19  TUBE       18      19   1.0         1.0     NORM     0.000        22.42        3259.       8.6496E+04           1 PHASE
    20  TUBE       19      20   1.0         1.0     NORM     0.000        22.42        1630.       8.6732E+04           1 PHASE
    21  TUBE       20      21   1.0         1.0     NORM     0.000        22.42       8.5329E+04   8.7029E+04           1 PHASE
    22  TUBE       21      22   1.0         1.0     NORM     0.000        22.42       8.5329E+04   8.7434E+04           1 PHASE
    23  TUBE       22      23   1.0         1.0     NORM     0.000        22.42       8.5328E+04   8.7971E+04           1 PHASE
    24  TUBE       23      24   1.0         1.0     NORM     0.000        22.42       8.5328E+04   8.8669E+04           1 PHASE
    25  TUBE       24      25   1.0         1.0     NORM     0.000        22.42       8.5327E+04   8.9556E+04           1 PHASE
    26  TUBE       25      26   1.0         1.0     NORM     0.000        22.42       8.5326E+04   9.0663E+04           1 PHASE
    27  TUBE       26      27   1.0         1.0     NORM     0.000        22.42       8.5325E+04   9.2021E+04           1 PHASE
    28  TUBE       27      28   1.0         1.0     NORM     0.000        22.42       8.5324E+04   9.3661E+04           1 PHASE
    29  TUBE       28      29   1.0         1.0     NORM     0.000        22.42       8.5323E+04   9.5615E+04           1 PHASE
    30  TUBE       29      99   1.0         1.0     NORM     0.000        22.42       8.5322E+04   9.7766E+04           1 PHASE
    98  LOSS     1000      98   1.0         1.0     NORM     0.000        22.42         237.9
    99  LOSS       99    2000   1.0         1.0     NORM     0.000        22.42         67.96
  3000  CTLVLV     15    3000   1.0         1.0     NORM     0.000        0.000       8.6800E+05
```

```
FLUID SUBMODEL NAME = PIPE6    ; FLUID NO. = 9718


       MAX TIME STEP =    112.183      ; LIMITING TIE  =       11     REASON   = NODE TEMPERATURE CHANGE LIMIT
       LAST TIME STEP =    30.0000      VS. DTMAXF/DTMINF =  1.000000E+30 /    0.00000     ;    AVERAGE TIME STEP =    29.3129
       PROBLEM TIME                    TIMEN  =  2730.00      VS. TIMEND   =  2730.00


                                    TIE PARAMETER TABULATION FOR SUBMODEL PIPE6

  TIE   TYPE      UA          QTIE          LUMP     TEF          NODE              TEMP.    2P   PATH 1    FRACT   PATH 2    FRACT

     1  HTN    3.8109E+04   1.7700E-05       1     1.001       WALL6.1               1.001            1     1.0000
     2  HTN    3.8110E+04  -4.2550E-02       2     1.001       WALL6.2               1.001            2     1.0000
     3  HTN    3.8110E+04  -3.5387E-05       3     1.002       WALL6.3               1.002            3     1.0000
     4  HTN    3.8111E+04  -2.2281E-03       4     1.003       WALL6.4               1.003            4     1.0000
     5  HTN    3.8111E+04   2.9022E-04       5     1.004       WALL6.5               1.004            5     1.0000
     6  HTN    3.8112E+04   2.2523E-03       6     1.004       WALL6.6               1.004            6     1.0000
     7  HTN    3.8112E+04   0.8655           7     1.005       WALL6.7               1.005            7     1.0000
     8  HTN    4.3281E+04     1.646          8     1.006       WALL6.8               1.006            8     1.0000
     9  HTN    4.3281E+04     3.239          9     1.007       WALL6.9               1.007            9     1.0000
    10  HTN    4.3282E+04     7.037         10     1.007       WALL6.10              1.008           10     1.0000
    11  HTNC   4.8092E+04     19.70         11     1.008       WALL6.11              1.009           11     1.0000    12     0.5000
    12  HTNC   4.8094E+04     47.18         12     1.011       WALL6.12              1.012           12     0.5000    13     0.5000
    13  HTNC   4.8098E+04     102.3         13     1.015       WALL6.13              1.017           13     0.5000    14     0.5000
    14  HTNC   4.8104E+04     201.8         14     1.022       WALL6.14              1.026           14     0.5000    15     0.5000
    15  HTNC   4.8116E+04     370.4         15     1.035       WALL6.15              1.042           15     0.5000    16     0.5000
    16  HTNC   4.8136E+04     643.3         16     1.058       WALL6.16              1.069           16     0.5000    17     0.5000
    17  HTNC   4.8168E+04     1057.         17     1.094       WALL6.17              1.113           17     0.5000    18     0.5000
    18  HTNC   4.8218E+04     1651.         18     1.151       WALL6.18              1.181           18     0.5000    19     0.5000
    19  HTNC   4.8292E+04     2469.         19     1.237       WALL6.19              1.282           19     0.5000    20     1.0000
    20  HTN    4.3544E+04     3066.         20     1.344       WALL6.20              1.406           21     1.0000
    21  HTN    4.3654E+04     4110.         21     1.488       WALL6.21              1.573           22     1.0000
    22  HTN    4.3798E+04     5360.         22     1.677       WALL6.22              1.788           23     1.0000
    23  HTN    4.3981E+04     6809.         23     1.920       WALL6.23              2.061           24     1.0000
    24  HTN    4.4210E+04     8442.         24     2.223       WALL6.24              2.399           25     1.0000
    25  HTN    4.4490E+04   1.0222E+04      25     2.592       WALL6.25              2.806           26     1.0000
    26  HTN    4.4827E+04   1.2108E+04      26     3.034       WALL6.26              3.286           27     1.0000
    27  HTN    4.5226E+04   1.4046E+04      27     3.549       WALL6.27              3.842           28     1.0000
    28  HTN    4.5689E+04   1.5980E+04      28     4.140       WALL6.28              4.472           29     1.0000
    29  HTN    4.6118E+04   1.7822E+04      29     4.803       WALL6.29              5.172           30     1.0000
```

```
SUBMODEL NAME = WALL6


                                  CALCULATED                                ALLOWED
       MAX DIFF DELTA T PER ITER     DRLXCC(              0)=  0.00000     VS. DRLXCA= 1.000000E-02
       MAX ARITH DELTA T PER ITER    ARLXCC(              0)=  0.00000     VS. ARLXCA= 1.000000E-02
       MAX DIFF DEL T PER TIME STEP  DTMPCC(WALL6       29)=-0.309470     VS. DTMPCA=  2.00000
       MAX ARITH DEL T PER TIME STEP ATMPCC(              0)=  0.00000     VS. ATMPCA= 1.000000E+30
       MIN STABILITY CRITERIA        CSGMIN(WALL6       29)=  37.4339
       MAX STABILITY CRITERIA        CSGMAX(WALL6        8)=  46.4906
       NUMBER OF ITERATIONS          LOOPCT                =        1     VS. NLOOPT=     100
       PROBLEM TIME                  TIMEN                 =  2730.00     VS. TIMEND=  2730.00
       TIME STEP USED                DTIMEU                =  30.0000     VS. DTIMEI=  0.00000

                                DIFFUSION NODES IN INPUT NODE NUMBER ORDER
 T     1=  1.0008     T     2=  1.0017     T     3=  1.0020     T     4=  1.0030     T     5=  1.0036     T     6=  1.0045
 T     7=  1.0051     T     8=  1.0057     T     9=  1.0066     T    10=  1.0074     T    20=  1.4046     T    21=  1.5701
 T    22=  1.7852     T    23=  2.0576     T    24=  2.3940     T    25=  2.8001     T    26=  3.2799     T    27=  3.8349
 T    28=  4.4639     T    29=  5.1640     T    11=  1.0088     T    12=  1.0115     T    13=  1.0168     T    14=  1.0258
 T    15=  1.0417     T    16=  1.0688     T    17=  1.1126     T    18=  1.1803     T    19=  1.2805
                                ARITHMETIC NODES IN INPUT NODE NUMBER ORDER
                                                   ++NONE++
                                HEATER NODES IN INPUT NODE NUMBER ORDER
                                                   ++NONE++
                                BOUNDARY NODES IN INPUT NODE NUMBER ORDER
                                                   ++NONE++
```

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FLUID SUBMODEL NAME = PIPE4   ; FLUID NO. = 9718


       MAX TIME STEP =   1.01189     ; LIMITING TUBE =      16    REASON  = FLOWRATE CHANGE LIMIT
       LAST TIME STEP =   1.01176     VS. DTMAXF/DTMINF =  1.000000E+30 /   0.00000    ;   AVERAGE TIME STEP =  0.425248
       PROBLEM TIME                  TIMEN  =  9.85267     VS. TIMEND  =  9.85267


                                LUMP PARAMETER TABULATION FOR SUBMODEL PIPE4

 LUMP  TYPE     TEMP        PRESSURE     QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

    1  TANK    20.00        8.3826E+04    0.000        0.000        998.3        1.2963E+06    0.000       -7.6294E-06    72.00
    2  TANK    20.00        1.6824E+05    0.000        0.000        998.3        1.2964E+06    0.000       -3.8147E-06    124.0
    3  TANK    20.00        2.5266E+05    0.000        0.000        998.3        1.2964E+06    0.000       -1.1444E-05    176.0
    4  TANK    20.00        3.3708E+05    0.000        0.000        998.3        1.2965E+06    0.000       -3.8147E-06    136.0
    5  TANK    20.00        4.2150E+05    0.000        0.000        998.3        1.2966E+06    0.000       -7.6294E-06    72.00
    6  TANK    20.00        5.0592E+05    0.000        0.000        998.3        1.2967E+06    0.000       -3.8147E-05    96.00
    7  TANK    20.01        5.9034E+05    0.000        0.000        998.3        1.2968E+06    0.000       -1.3351E-04   -32.00
    8  TANK    20.01        6.7475E+05    0.000        0.000        998.3        1.2969E+06    0.000       -7.6294E-06    88.00
    9  TANK    20.01        7.5917E+05    0.000        0.000        998.3        1.2970E+06    0.000       -3.8147E-06    120.0
   10  TANK    20.01        8.4359E+05    0.000        0.000        998.3        1.2971E+06    0.000       -1.1444E-05    116.0
   11  TANK    20.01        8.3989E+05    0.000        0.000        998.3        1.2970E+06    0.000       -3.8147E-06    96.00
   12  TANK    20.01        8.3249E+05    0.000        0.000        998.3        1.2970E+06    0.000       -7.6294E-06    108.0
   13  TANK    20.01        8.2508E+05    0.000        0.000        998.3        1.2970E+06    0.000       -7.6294E-06    144.0
   14  TANK    20.01        8.1768E+05    0.000        0.000        998.3        1.2970E+06    0.000       -1.5259E-05    120.0
   15  TANK    19.96        8.1167E+05    0.000        0.000        998.3        1.2968E+06    0.000        2.2926E-03  -2.1248E+04
   16  TANK    20.01        8.1275E+05    0.000        0.000        998.3        1.2970E+06    0.000       -4.7684E-07    18.50
   17  TANK    20.01        8.1354E+05    0.000        0.000        998.3        1.2970E+06    0.000       -1.4305E-06    19.50
   18  TANK    20.01        8.1433E+05    0.000        0.000        998.3        1.2970E+06    0.000       -1.4305E-06    18.00
   19  TANK    20.01        8.1513E+05    0.000        0.000        998.3        1.2970E+06    0.000       -4.7684E-07    10.00
   20  TANK    20.01        8.1552E+05    0.000        0.000        998.3        1.2970E+06    0.000       -4.7684E-07    16.50
   21  TANK    20.02        7.3397E+05    0.000        0.000        998.3        1.2970E+06    0.000       -9.5367E-07    17.00
   22  TANK    20.02        6.5242E+05    0.000        0.000        998.3        1.2969E+06    0.000       -9.5367E-07    16.00
   23  TANK    20.02        5.7086E+05    0.000        0.000        998.3        1.2968E+06    0.000       -9.5367E-07    16.00
   24  TANK    20.02        4.8931E+05    0.000        0.000        998.3        1.2967E+06    0.000       -9.5367E-07    21.00
   25  TANK    20.02        4.0776E+05    0.000        0.000        998.3        1.2967E+06    0.000       -1.4305E-06    12.50
   26  TANK    20.02        3.2621E+05    0.000        0.000        998.3        1.2966E+06    0.000       -9.5367E-07    17.50
   27  TANK    20.02        2.4465E+05    0.000        0.000        998.3        1.2965E+06    0.000       -9.5367E-07    18.50
   28  TANK    20.02        1.6310E+05    0.000        0.000        998.3        1.2964E+06    0.000       -4.7684E-07    10.50
   29  TANK    20.02        8.1550E+04    0.000        0.000        998.3        1.2963E+06    0.000        2.1935E-05   -382.5
   98  JUNC    20.00        -591.9        0.000        0.000        998.3        1.2962E+06    0.000        3.8147E-06    4.000
   99  JUNC    20.00        -3.245        0.000        0.000        998.3        1.2962E+06    0.000         0.000        0.000
 1000  PLEN    20.00         0.000        0.000        0.000        998.3        1.2962E+06    0.000        -35.35      -4.5814E+07
 2000  PLEN    20.00         0.000        0.000        0.000        998.3        1.2962E+06    0.000        -4.913      -6.3687E+06
 3000  PLEN    20.00         0.000        0.000        0.000        998.3        1.2962E+06    0.000         40.26       5.2239E+07
```

```
FLUID SUBMODEL NAME = PIPE4   ; FLUID NO. = 9718


       MAX TIME STEP =   1.01189     ; LIMITING TUBE =      16    REASON  = FLOWRATE CHANGE LIMIT
       LAST TIME STEP =   1.01176     VS. DTMAXF/DTMINF =  1.000000E+30 /   0.00000    ;   AVERAGE TIME STEP =  0.425248
       PROBLEM TIME                  TIMEN  =  9.85267     VS. TIMEND  =  9.85267


                                   PATH PARAMETER TABULATION FOR SUBMODEL PIPE4

  PATH  TYPE    LMP 1   LMP 2   DUP I      DUP J    STAT   XL UPSTRM    FLOWRATE     DELTA PRES    REYNOLDS    MACH    REGIME

     1  TUBE        98       1   1.0        1.0     NORM     0.000        35.35      -8.4418E+04   2.3548E+05          1 PHASE
     2  TUBE         1       2   1.0        1.0     NORM     0.000        35.35      -8.4418E+04   2.3548E+05          1 PHASE
     3  TUBE         2       3   1.0        1.0     NORM     0.000        35.35      -8.4418E+04   2.3549E+05          1 PHASE
     4  TUBE         3       4   1.0        1.0     NORM     0.000        35.35      -8.4418E+04   2.3549E+05          1 PHASE
     5  TUBE         4       5   1.0        1.0     NORM     0.000        35.35      -8.4418E+04   2.3550E+05          1 PHASE
     6  TUBE         5       6   1.0        1.0     NORM     0.000        35.35      -8.4418E+04   2.3550E+05          1 PHASE
     7  TUBE         6       7   1.0        1.0     NORM     0.000        35.35      -8.4418E+04   2.3551E+05          1 PHASE
     8  TUBE         7       8   1.0        1.0     NORM     0.000        35.35      -8.4418E+04   2.3551E+05          1 PHASE
     9  TUBE         8       9   1.0        1.0     NORM     0.000        35.35      -8.4418E+04   2.3552E+05          1 PHASE
    10  TUBE         9      10   1.0        1.0     NORM     0.000        35.35      -8.4418E+04   2.3552E+05          1 PHASE
    11  TUBE        10      11   1.0        1.0     NORM     0.000        35.35        3701.       2.3552E+05          1 PHASE
    12  TUBE        11      12   1.0        1.0     NORM     0.000        35.35        7402.       2.3553E+05          1 PHASE
    13  TUBE        12      13   1.0        1.0     NORM     0.000        35.35        7402.       2.3553E+05          1 PHASE
    14  TUBE        13      14   1.0        1.0     NORM     0.000        35.35        7402.       2.3553E+05          1 PHASE
    15  TUBE        14      15   1.0        1.0     NORM     0.000        35.35        6015.       2.3554E+05          1 PHASE
    16  TUBE        15      16   1.0        1.0     NORM     0.000       -4.913       -1083.       3.2743E+04          1 PHASE
    17  TUBE        16      17   1.0        1.0     NORM     0.000       -4.913       -792.2       3.2744E+04          1 PHASE
    18  TUBE        17      18   1.0        1.0     NORM     0.000       -4.913       -792.2       3.2745E+04          1 PHASE
    19  TUBE        18      19   1.0        1.0     NORM     0.000       -4.913       -792.2       3.2746E+04          1 PHASE
    20  TUBE        19      20   1.0        1.0     NORM     0.000       -4.913       -396.1       3.2746E+04          1 PHASE
    21  TUBE        20      21   1.0        1.0     NORM     0.000       -4.913       8.1553E+04   3.2747E+04          1 PHASE
    22  TUBE        21      22   1.0        1.0     NORM     0.000       -4.913       8.1553E+04   3.2747E+04          1 PHASE
    23  TUBE        22      23   1.0        1.0     NORM     0.000       -4.913       8.1553E+04   3.2747E+04          1 PHASE
    24  TUBE        23      24   1.0        1.0     NORM     0.000       -4.913       8.1553E+04   3.2748E+04          1 PHASE
    25  TUBE        24      25   1.0        1.0     NORM     0.000       -4.913       8.1553E+04   3.2749E+04          1 PHASE
    26  TUBE        25      26   1.0        1.0     NORM     0.000       -4.913       8.1553E+04   3.2750E+04          1 PHASE
    27  TUBE        26      27   1.0        1.0     NORM     0.000       -4.913       8.1553E+04   3.2750E+04          1 PHASE
    28  TUBE        27      28   1.0        1.0     NORM     0.000       -4.913       8.1553E+04   3.2751E+04          1 PHASE
    29  TUBE        28      29   1.0        1.0     NORM     0.000       -4.913       8.1553E+04   3.2751E+04          1 PHASE
    30  TUBE        29      99   1.0        1.0     NORM     0.000       -4.913       8.1553E+04   3.2734E+04          1 PHASE
    98  LOSS      1000      98   1.0        1.0     NORM     0.000        35.35        591.9
    99  LOSS        99    2000   1.0        1.0     NORM     0.000       -4.913       -3.245
  3000  CTLVLV      15    3000   1.0        1.0     NORM     0.000        40.26       8.1167E+05
```

PROBLEM C: PRESSURE COOKER

This problem simulates a pressure cooker (autoclave) being refilled and returning to operation. This problem was chosen to demonstrate the following FLUINT features:

1. the properties of two-phase (pure substance) homogeneous (untwinned) tanks
2. phase suction options
3. user-supplied heat transfer coefficients
4. user logic for specialized output and customized solutions
5. pressure regulating valves

C.1 Problem Description

A 5 lb$_m$ steel pressure cooker is operating at 15 psig, corresponding to a saturated steam temperature of 250°F (see Figure C-1). The cooker sits on a stove that is adding 500 W of heat to the base, and loses heat to the ambient air due to natural convection. The pressure is regulated by a backpressure control valve at the top of the cooker (a weight sitting on top of a vent). When the pressure is greater than the weight, the valve opens, releasing steam. The cooker can be refilled by injecting pressurized ambient (70°F) liquid water. The effects of any pot roast or other nonfluid contents are ignored. The relevant characteristics are:

Cooker:	
Operating pressure	15 psig
Volume	0.5 ft^3
Base (boiling) area	1 ft^2
Surface (loss) area	3.5 ft^2
Initial liquid	1/2 cup
Wall mass	5 lb$_m$ steel
Stove heat	500 W
Injection source (ambient):	
Temperature	70°F
Pressure	15 psig
Valve:	
Open flow area	0.005 sq. in.
Opening pressure	15 psig.

The heat transfer coefficient for natural convection to the ambient are is estimated to be 1.1 BTU/hr-ft^2-°F.

At time zero, the injector begins to supply liquid to the cooker such that the total mass of the cooker doubles in 30 seconds. The sudden mixing with cool water causes the pressure in the cooker to quickly drop. The response of the cooker is desired, including how far the pressure drops, and how long it takes for the pressure to come back up to operating conditions. Also, the performance of the oscillatory pressure control valve is desired.

C.2 A FLUINT Model

A rigid FLUINT tank will be used to model the pressure cooker itself. The selection of a single tank to simulate the cooker carries the hidden assumption of perfect mixing within the cooker. Imperfect mixing can also be simulated twinned tanks, as demonstrated in Sample Problem F. The amount of liquid inside the tank is an important initial condition, but cannot be specified directly using the input variables PL, TL, and XL. It is therefore set in OPERATIONS using a call to CHGLMP before calling any solution routines.

Before starting the transient, a steady state solution will be run for initial conditions. The tank state will be “frozen” using the HLDLMP routine before the steady state solution, then released afterwards using RELLMP. If these steps were omitted, the steady state solution would predict that the tank would be dry and very hot.

This tank will be tied to a diffusion node representing the wall. The use of a single node precludes the effects of wall gradients, although these could be included if sufficient information were available.

The heat transfer phenomena will be pool boiling; a forced convection HTN or HTNC tie would be inappropriate, so an HTU tie will be used whose UA value is calculated using Rohsenow’s pool boiling correlation, as contained within the POOLBOIL routine (see Section 7 of the main volume). In that routine, the user may specify Csf (surface roughness coefficient) and the factor S (1.0 for water, 1.7 for other fluids), specified as registers CSF (=0.0132) and ESS (=1.0). When using this routine, the user has the option of applying the returned heat transfer coefficient as the UA (after multiplying by the area). However, this UA would be strongly nonlinear. A more robust choice (quicker convergence, larger time steps) is to instead use the UB and UEDT values returned by POOLBOIL, which will be called from FLOGIC 0.

The convective losses to ambient are represented with a 70°F boundary node and a linear conductor equal to the hA product connecting that node to the tank wall.

The resupply injection occurs at a constant rate; an MFRSET connector will be used to transport the liquid from a plenum containing the supply liquid. As an alternate, a liquid tank with a negative VDOT (representing squeezing by a piston) could be used as the injector. This would be inappropriate unless the pressure response of the injector is required.

As usual, the choices for the valve are more difficult. A UPRVLV (upstream pressure regulating valve) might be used. This is investigated as an option later. Alternatively, a check valve model (CHKVLV) might be considered to open and close the valve automatically. However, there is currently no offset pressure available as an option in the CHKVLV model, so a CTLVLV will be used instead. Without knowing more about the valve, an open FK value of 2.0 is selected. (Note that such an oscillating control valve would be unacceptable in an incompressible liquid system because of pressure surges.) Because the valve is on top of the cooker, it will be directed to extract only vapor from the cooker using the phase suction options.

C.3 The Input File

The input file is listed immediately following the last section.

OPTIONS DATA—As with previous examples, a user file (USER1) is named that will contain a summary listing of the output file. Also, a QMAP file will be opened to receive the output generated by a call to NODMAP, which will be inserted later (in OPERATIONS).

CONTROL DATA—English units are chosen, with units of °F and psig. The value of OUTPTF is given as 3 seconds, although this will be modified to reduce output during the recovery phase of the event.

USER DATA—Variables to be used in the logic are declared and initialized. (Registers could have been used equivalently.) Among them is a flag to be used by the logic to distinguish the last minute of the simulation, when the cooker is allowed to run with the control valve oscillating. Also present are variables used to contain statistics about the pressure history during the last minute. The mass in the cooker, SMAS, is defined as the product of the density times volume of Tank #1 if submodel “cooker,” as specified in FLOW DATA below.

REGISTER DATA—Three registers are defined. AREA is the heat transfer area of the base, which (neglecting the sides) becomes the basis of the pool boiling conductance. CSF is the water/steel roughness coefficient used for the pool boiling correlation (see the references for POOLBOIL in Section 7 of the main volume), and ESS is the “S” factor, which is unity for water.

NODE DATA—One thermal submodel named WALL is used. It contains a boundary node (#999) set at ambient temperature, and a diffusion node (#1) representing the steel wall.

CONDUCTOR DATA—One linear conductor (#1) is given between the ambient and the diffusion node, and is set equal to the natural convection heat transfer coefficient times the surface area.

SOURCE DATA—The heat source term of 500 W is placed on the wall node, converting into BTU/hr using the built-in constant “btuhrwat.”

FLOW DATA—One fluid submodel named COOKER is used. The working fluid is “718”, meaning the standard library description of water.* The default pressure is set high such that it is overridden later with saturation. The default initial flowrate is zero, and all lumps are assumed to represent low-velocity stagnation states (LSTAT=STAG).

---

* For such a simple problem, these water properties are adequate. However, the user should instead use a more accurate FPROP block (available at www.crtech.com) for water.

The names and types of the elements are as follows:

TANK 1	pressure cooker (stagnant state)
TIE 1	pool boiling tie from wall node to fluid (see FLOGIC 0)
CTLVLV 1	relief valve
PLENUM 2	exhaust to atmosphere
MFRSET 3	injector
PLENUM 3	injection source

Although air can be included in the model directly, the exhaust is assumed to be saturated steam at ambient pressure. This ambient pressure is a backpressure only, and to introduce a new species into the mixture just to represent a backpressure would be computationally wasteful. If air leakage into the cooker were ever a concern, or if modeling of the start-up of a cooker were a concern with an initial "charge" of cool air and water vapor, then the extra constituent would be needed.

The relief valve is modeled using simple on/off logic: the FK for CTLVLV #1 is set to -1 (meaning closed) if the pressure ever drops below 15 psia, otherwise it is set to 2.0. Refer to Section C.5 for an alternate model using a UPRVLV (pressure regulating) valve instead of a binary "bang-bang" valve.

FLOGIC 0—The pool boiling heat transfer UB and UEDT for the HTU tie is adjusted with a call to POOLBOIL, a library routine (see Section 7 of the main volume). Note that the last argument, the fluid identifier, will be translated into a location in integer array FI. Many other returned results of POOLBOIL are ignored, and are therefore set to temperature variables (ATEST through ZTEST are convenient). One exception is the critical heat flux: a check is made and an error message produced if this limit is exceeded during a transient (NSOL > 1).

FLOGIC 2—This logic block contains three calculations for the transient run. First, pressure statistics are calculated during the last minute of the simulation. This includes the maximum and minimum pressure, and the time-averaged pressure that is found by integrating the pressure profile and dividing by the total time. The control constant DTIMUF, the size of the time step just taken, is used for this calculation.

Second, the code checks to see when the cooker has recovered from the injection, signaling the last minute of the simulation and resetting the output interval to be 3 seconds. Third, preventative logic is added to stop the simulation if the cooker ever dries out.

OUTPUT CALLS—This logic block defines the output to be produced during the transient run at each output interval. This data includes temperatures, pressures, and flowrates. Note that a compressed line of important data is written to the user file USER1.

OPERATIONS—The configuration is built, containing both submodels. Also, the default model name is set to COOKER to avoid extra input. The first order of business is to change the mass in the cooker to comply with the initial conditions of 1/2 cup (or about 1/4 lb_m). The tank state was input using TL and a guessed XL in FLOW DATA. Logic is added here to estimate the desired quality using a call to the VSV (vapor specific volume) routine for water. This quality is then imposed on the tank using the CHGLMP routine.

Second, a steady state solution is invoked to get initial conditions (principally, wall temperature). In order to avoid a trivial answer of a dried-out pot, the tank state is held constant (the tank is turned into a temporary plenum) via a call to HLDLMP. This action is reversed after the steady state call using a call to RELLMP. A call to NODMAP yields detailed information about initial energy flows to and from the tank wall. These results will be contained in the QMAP file specified in OPTIONS DATA.

Third, the fill transient is run as one transient solution for 30 seconds. The second transient is then the recovery response, which will contain one minute of “steady” operation after recovery. During the recovery response, the output interval is increased tenfold to reduce the volume of output. During the “steady” last minute, the time step is limited to 1 second to keep the control valve logic updated (prevent pressure overshoots and undershoots due to lack of control).

C.4 Output Description

The user summary file and the selected portions of the OUTPUT and QMAP files are listed following the input file. Figure C-2 contains a plot of the cooker pressure history.

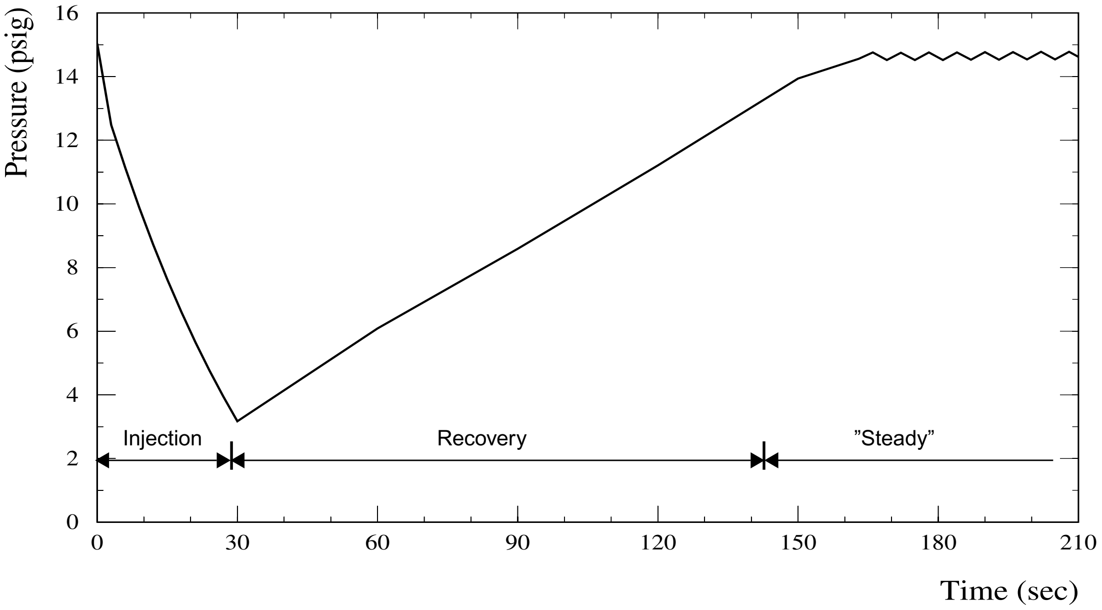


Figure C-1 Pressure History of the Cooker

The injection obviously has a dramatic effect on the cooker because so much mass is being added but so little energy. Unlike an open (constant pressure) pot, the constant volume cooker stays in a saturated state. The pressure drops to about 3 psig, and takes about 2 minutes to recover to the normal value. This occurs despite the fact that the heat into the fluid more than doubles due to the lag of the warm wall. Without the mass of the cooker, the pressure would drop to about -2 psig.

This is an important trait to remember when modeling two-phase fluid systems: *because of the default perfect mixing assumption, significant pressure fluctuations may be caused by irregular flowrates and heat rates.* In the real system, the cooler liquid would not be in equilibrium with the vapor phase until sufficient mass and energy had been exchanged over the course of a few seconds. By assuming perfect mixing, FLUINT assumes that this nonequilibrium stage is negligibly short. Thus, the cooker responds faster than it would in reality. This assumption is normally valid and it greatly expedites the numeric solution. Furthermore, the nonequilibrium exchange of mass and energy is often difficult to characterize with any accuracy. With a few assumptions regarding the physical processes involved, the user may wish to attempt such modeling using twinned tanks. The presence of nonvolatile liquids (perhaps modeling the pot roast in perfect contact with the water) and/or noncondensible gases would have also greatly reduced the pressure change associated with the injection of cold liquid.

In some variations of this model, warnings might be produced by the time step controller when changes are rapid (i.e., when filling starts and when it stops). Strictly, a smaller time step is required at these two points in order to guarantee the specified accuracy (DRLXCA or 0.01 degrees error per time step). However, because these two events are usually brief, relatively little error accumulates, and a reduction in DTIMEH (or DTMAXF) produces the same results. If rapid changes had been more common or frequent, then either a greater error should be accepted or the time step should be constrained.

With respect to the operation of the cooker at “steady-state” (not the initial conditions, but the long term behavior towards the end of the transient), the peak pressure was 15.1 psig, the lowest pressure was 14.7 psig, and the time-averaged pressure was 14.9 psig. The flowrate of the valve when open is about 3.5 lb_m/hr of steam. Comparing that to the total mass lost over the 60 second interval, it can be calculated that the valve was open an average of 20 to 50% percent of the time. Thus, the true pressure profile can be deduced to be a triangular wave with sudden pressure decreases and gradual pressure increases. The profile shown by the output plot is incorrect due to sampling errors: the output is sampled at a frequency smaller than the valve frequency, which is unknown. The user should always be aware of the fact that *perceived* behavior in a time history may be due to the output interval and not to any real model behavior.

In a real pressure cooker the valve area oscillates, but is it always open as long as the pressure is sufficient to lift the counterweight. Such a simulation could be done by calculating the loss factor and/or flow area within the logic blocks as a function of pressure according to a much more detailed dynamic model of the valve/weight system. ODE solvers such as DIFFEQ1 (see Section 7 of the main volume) are available to assist in developing such co-solved models.

Finally, the sensitivity of the pool boiling correlation can be seen in the heat rate tabulated for the last minute of “steady” operation. The power into the fluid fluctuated quickly from 230W to 320W, largely due to fluctuations in the saturation temperature as the system pressure oscillated. The UEDT for the underlying pool boiling correlation is 2.0, meaning the heat flow into the fluid is proportional to the temperature difference to the third (UEDT+1) power.

In many ways, this sample problem represents a simplification of the storage tank analyzed in Sample Problem F. In that analysis, wall gradients are included, and nonequilibrium methods are used to analyze a liquid fill process. The reader should find that comparisons of the differences in modeling and in predicted behavior are very educational.

C.5 Alternate Model Using Pressure Regulator

To demonstrate the use of pressure regulator valves (UPRVLV), the on/off control valve:

```
PA CONN,1,1,2,STAT= VS                        $ VAPOR SUCTION
         DEV       = CTLVLV                   $ RELEASE VALVE
         FK        = (PL#up <= 15)? -1 : 2    $ VALVE CONTROL LOGIC
         AF        = 0.005/144.0              $ GUESS
```

was replaced with a UPRVLV connector, which regulates upstream pressure to maintain a desired set-point PSET. (DPRVLV connectors similarly regulate downstream pressure.) A minimum resistance (K-factor) of the open valve was set to 1.0, resulting in:

```
PA CONN,1,1,2, STAT= VS                       $ VAPOR SUCTION
         DEV       = UPRVLV                   $ PRESSURE REGULATOR
         FKL       = 1.0                      $ LOWER LIMIT
         PSET      = 15.0                     $ SET POINT, PSIG
         AF        = 0.005/144.0              $ GUESS
```

Unlike the on/off valve, the pressure regulator valve has an intrinsic lag, and therefore some sensitivity to initial conditions (especially lacking a steady-state run). The K-factor is initially 1.0, and it increases quickly but not instantly as cold fluid is injected. Similarly, there is some overshoot in the cooker pressure as the valve opens gradually after the pressure exceeds 15 psig. Thus, the “statistics” on pressure oscillations show a greater variation than was achieved with a more ideal on/off valve.

Input File

```
HEADER OPTIONS DATA
TITLE FLUINT SAMPLE PROBLEM 3 - PRESSURE COOKER
        MODEL = PCOOK
         OUTPUT   = prescook.out
         USER1    = prescook.usr
         QMAP     = prescook.map
C
HEADER CONTROL DATA,GLOBAL
         UID      = ENG
         ABSZRO   = -459.6
         PATMOS   = -14.7
         OUTPTF   = 3.0/3600.0      $ 3 SEC INTERVAL TO START
         OUTPUT   = 1000.0          $ JUST TO SATISFY SINDA
C
HEADER USER DATA, GLOBAL
         SMAS     = cooker.vol1*cooker.dl1$ MASS IN COOKER
         IFINAL   = 0                       $ SIGNAL FOR LAST MINUTE
         PMAX     = 0.0                     $ MAX PRESSURE
         PMIN     = 1000.0          $ MIN PRESSURE
         POLD     = 15.0                    $ LAST PRESSURE
         PAVG     = 0.0                     $ TIME AVGD PRESSURE
C
HEADER REGISTER DATA
C SURFACE AREA (OF BASE)
         AREA     = 1.0
C POOL BOILING SURFACE AND FLUID FACTORS
         CSF      = 0.0132 $ WATER AND MECHANICALLY POLISHED STAINLESS
         ESS      = 1.0             $ WATER (ELSE 1.7 FOR OTHER FLUIDS)
C
HEADER NODE DATA, WALL
         1,260.0,5.0*0.11  $ COOKER WALL
         -999,70.0,0.0              $ AMBIENT
HEADER CONDUCTOR DATA, WALL
         1,1,999,1.1*3.5            $ NATL CONV TO AIR
HEADER SOURCE DATA, WALL
         1,500.0/btuhrwat  $ 500 W HEAT INPUT
C
```

```
HEADER FLOW DATA,COOKER,FID=718 $ USE LIBRARY WATER
C
LU DEF,           PL       = 1000.0         $ MAKE SURE PRESSURE
                  LSTAT = STAG
C                                              $ OVERWRITTEN
PA DEF,           FR       = 0.0
C
LU TANK,1, VOL    = 0.5                     $ COOKER
                  XL       = 0.1               $ GUESS
                  TL       = 250.0
T HTU,1,1,WALL.1                    $ POOL BOILING TIE
                  UA       = 1.0               $ WILL USE UB, UEDT, AHT
INSTEAD
                  AHT      = AREA
PA CONN,1,1,2,STAT= VS                      $ VAPOR SUCTION
                  DEV      = CTLVLV         $ RELEASE VALVE
                  FK       = (PL#up <= 15)? -1 : 2$ CONTROL LOGIC
                  AF       = 0.005/144.0    $ GUESS
LU PLEN,2,TL      = 212.0                   $ STEAM EXHAUST
                  XL       = 1.0
LU PLEN,3,TL      = 70.0                    $ INJECTION SOURCE
                  PL       = 15.0
                  XL       = 0.0
PA CONN,3,3,1,DEV = MFRSET          $ INJECTOR (SHUT)
C
HEADER FLOGIC 0, COOKER             $ LOGIC BLOCK
C
C UPDATE UA ACCORDING TO POOLBOIL ROUTINE
C
         CALL                   POOLBOIL(HTEST,UB1,UEDT1,CTEST,RTEST,AT-
EST,BTEST,WALL.T1,TL1
     .            ,CSF,ESS,0.0,COOKER.FI)
C
C WARN IF EXCEEDED CRITICAL FLUX
C
         IF((WALL.T1-TL1)*HTEST .GT. CTEST .AND. NSOL .GT. 1)THEN
                  WRITE(NOUT,*)  ‘ EXCEEDED CRITICAL FLUX,’,CTEST,’, AT
TIME = ‘,TIMEN
         ENDIF
C
```

```
HEADER FLOGIC 2, COOKER             $ LOGIC BLOCK
C
C DURING LAST MINUTE, SAVE UP MAX AND MINIMUM PRESSURES
C
         IF(IFINAL .EQ. 1)THEN
                  PAVG              = PAVG + (SNGL(PL1) + POLD)*DTIMUF*0.5
                  POLD              = SNGL(PL1)
                  PMAX              = MAX(PMAX,POLD)
                  PMIN              = MIN(PMIN,POLD)
         ENDIF
C
C        THIS LOGIC STOPS THE TRANSIENT IF DRIED OUT.
C        IF VALVE OPENS AGAIN (PRESSURE AT 15 PSIG), THEN
C        COMMENCE FINAL MINUTE OF SIMULATION
C
         IF(PL1 .GT. 15.0D0 .AND. TIMEN .GT. 30.0/3600.0 .AND.
     .     IFINAL .NE. 1)THEN
                  TIMEND            = TIMEN + 60.0/3600.0
                  IFINAL            = 1
                  OUTPTF            = 3.0/3600.0
                  WRITE(NUSER1,10) TIMEN*3600.0
10                FORMAT(/’ COOKER AT FULL PRES. AT TIME = ‘,1pG13.4)
         ELSEIF(XL1 .GE. 1.0)THEN
                  TIMEND            = TIMEN
                  WRITE(NUSER1,20) TIMEN*3600.0
20                FORMAT(/’ COOKER DRIED OUT AT TIME = ‘,1pG13.4)
         ENDIF
C
HEADER OUTPUT CALLS, COOKER$ OUTPUT OPERATIONS
        CALL LMPTAB(‘ALL’)
        CALL TIETAB(‘ALL’)
         CALL PTHTAB(‘ALL’)
C
C NOW, THE CONDENSED TABLE OF PARAMETERS ON USER FILE
C FLOWRATES USE SPECIAL FORMAT TO NEGLECT NEAR-ZERO VALUES
C
         IF(NSOL .GE. 2)THEN$ IF TRANSIENT THEN ...
           WRITE(NUSER1,10) 3600.0*TIMEN,PL(1),XL(1),TL(1),WALL.T(1)
     .            ,QDOT(1)*0.293,SMAS,FR(1),FR(3)
         ENDIF
F10      FORMAT(1X,7(1PG12.4,2X),0P,2(F12.2,2X))
C
```

```
HEADER OPERATIONS                   $ LIST OPERATIONS
C
BUILDF CONFIG,COOKER
BUILD CONFIG,WALL
C
DEFMOD COOKER
C
C FIRST, RESET COOKER QUALITY SUCH THAT THERE IS 1/2 CUP WATER
C OR ABOUT 1/4 LBM OF WATER (APPROX EQUAL TO TOTAL MASS)
C
         XTEST    = VOL1/(0.25*VSV(PL1-PATMOS,TL1-ABSZRO,FI718))
         CALL CHGLMP(‘COOKER’,1,’XL’,XTEST,’TL’)
C
C GET INITIAL CONDITIONS
C
         CALL HLDLMP(‘COOKER’,1)  $ HOLD POT STILL FOR STEADY STATE
         CALL STEADY
         CALL NODMAP(‘WALL’,1,1) $ MAP WALL NODE IN DETAIL
         CALL RELLMP(‘COOKER’,1)  $ RELEASE POT FOR TRANSIENT
C
C WRITE OUTPUT HEADER (FORMAT NOT TRANSLATED TO AVOID CONFUSION WITH “T19”
C
         WRITE(NUSER1,10)
FSTART
10       FORMAT(/’   TIME (SEC)’,T19,’P COOKER’,6X,’X COOKER’,6X
     .            ,’T COOKER’,6X,’T WALL’,8X,’HEAT (W)’,6X,’MASS INSIDE’,
     .   5X,’VENT RATE’,5X,’FILL RATE’/)
FSTOP
C
C FIRST TRANSIENT:
C INJECT SO AS TO DOUBLE TOTAL MASS IN 30 SEC
C
         TIMEND            = 30.0/3600.0
         SMFR3             = SMAS/TIMEND
         CALL FWDBCK
C
C NOW SHUT OFF INJECTOR AND HEAT UP UNTIL VALVE OPENS OR ONE HOUR,
C OR DRYOUT
C
         SMFR3             = 0.0
         TIMEND            = 1.0
         OUTPTF            = 30.0/3600.0$ INCREASE INTERVAL
         DTMAXF            = 1.0/3600.0$ LIMIT STEP TO 1 SEC
C                                            $ TO CAPTURE P > 15
         CALL FWDBCK
C
C WRITE OUT SUMMARY OF LAST MINUTE
C
         WRITE(NUSER1,20)PMAX,PMIN,PAVG*3600.0/60.0
```

```
FSTART
20       FORMAT(/’ THE MAXIMUM PRESSURE WAS:’,T40,1PG13.4/
     .          ` THE MINIMUM PRESSURE WAS:’,T40,G13.4/
     .          ` THE TIME-AVG PRESSURE WAS:’,T40,G13.4)
FSTOP
C
END OF DATA
```

Processor Output

```
  TIME (SEC)     P COOKER      X COOKER      T COOKER      T WALL        HEAT (W)      MASS INSIDE     VENT RATE     FILL RATE

   0.000         15.04        0.1446        250.0         254.4         291.9        0.2482            7.25          0.00
   3.000         13.02        0.1231        246.0         252.3         833.3        0.2699            0.00         29.78
   6.000         11.67        0.1075        243.2         249.5         826.7        0.2919            0.00         29.78
   9.000         10.40        9.4713E-02    240.4         246.8         815.2        0.3131            0.00         29.78
   12.00         9.223        8.3989E-02    237.8         244.2         804.3        0.3337            0.00         29.78
   15.00         8.122        7.4932E-02    235.2         241.7         792.1        0.3595            0.00         29.78
   18.00         7.094        6.7216E-02    232.7         239.2         780.1        0.3843            0.00         29.78
   21.00         6.133        6.0590E-02    230.3         236.8         768.6        0.4091            0.00         29.78
   24.00         5.235        5.4860E-02    227.9         234.5         757.3        0.4339            0.00         29.78
   27.00         4.395        4.9873E-02    225.6         232.3         746.2        0.4588            0.00         29.78
   30.00         3.609        4.5509E-02    223.4         230.1         735.5        0.4836            0.00         29.78
   30.00         3.609        4.5509E-02    223.4         230.1         735.5        0.4960            0.00         29.78
   60.00         6.333        5.1825E-02    230.8         234.9         195.0        0.4960            0.00          0.00
   90.00         8.856        5.7629E-02    236.9         241.0         193.2        0.4960            0.00          0.00
   120.0         11.50        6.3669E-02    242.8         246.7         191.4        0.4960            0.00          0.00
   150.0         14.25        6.9928E-02    248.5         252.3         189.6        0.4960            0.00          0.00

COOKER AT FULL PRES. AT TIME =     158.0
   158.0         15.00        7.1632E-02    249.9         253.7         189.1        0.4960            0.00          0.00
   161.0         14.73        7.1199E-02    249.4         254.0         238.2        0.4955            3.56          0.00
   164.0         14.88        7.1613E-02    249.7         254.1         286.2        0.4942            0.00          0.00
   167.0         14.93        7.1838E-02    249.8         254.2         280.4        0.4935            0.00          0.00
   170.0         15.01        7.2119E-02    249.9         254.1         309.8        0.4927            0.00          0.00
   173.0         15.08        7.2402E-02    250.1         254.1         263.5        0.4920            0.00          0.00
   176.0         15.07        7.2507E-02    250.1         254.2         299.1        0.4911            0.00          0.00
   179.0         15.08        7.2654E-02    250.1         254.2         298.1        0.4902            0.00          0.00
   182.0         15.08        7.2790E-02    250.1         254.2         297.8        0.4894            0.00          0.00
   185.0         15.08        7.2928E-02    250.1         254.2         297.9        0.4885            0.00          0.00
   188.0         15.08        7.3066E-02    250.1         254.2         297.9        0.4876            0.00          0.00
   191.0         15.09        7.3205E-02    250.1         254.2         297.9        0.4868            0.00          0.00
   194.0         15.09        7.3344E-02    250.1         254.2         297.9        0.4859            0.00          0.00
   197.0         15.09        7.3483E-02    250.1         254.2         297.9        0.4850            0.00          0.00
   200.0         14.79        7.3003E-02    249.5         254.2         297.9        0.4841            3.57          0.00
   203.0         14.92        7.3405E-02    249.8         254.2         288.1        0.4829            0.00          0.00
   206.0         14.97        7.3663E-02    249.9         254.1         317.6        0.4821            0.00          0.00
   209.0         15.01        7.3870E-02    249.9         254.2         314.2        0.4813            0.00          0.00
   212.0         14.89        7.3768E-02    249.7         254.1         243.4        0.4806            3.59          0.00
   215.0         15.08        7.4287E-02    250.1         254.2         281.3        0.4797            0.00          0.00
   218.0         14.78        7.3804E-02    249.5         254.2         276.1        0.4783            3.57          0.00

THE MAXIMUM PRESSURE WAS:                  15.11
THE MINIMUM PRESSURE WAS:                  14.72
THE TIME-AVG PRESSURE WAS:                 14.92
```

```
                             SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE     6

MODEL = PCOOK                                   FLUINT SAMPLE PROBLEM 3 - PRESSURE COOKER
  FASTIC


 FLUID SUBMODEL NAME = COOKER  ; FLUID NO. =  718


        LOOPCT =     9
        CONVERGENCE STATUS = SUBMODEL CONVERGED AS OF       9 ITERATIONS


                                        LUMP PARAMETER TABULATION FOR SUBMODEL COOKER

  LUMP  TYPE     TEMP        PRESSURE     QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

     1  TANK    250.0         15.04       0.1446       0.9927       0.4964        357.2        996.3        -7.253       -7449.
     2  PLEN    212.0      -4.0171E-02    1.000         1.000       3.7257E-02    1151.        0.000         7.253        8445.
     3  PLEN    70.00         15.00       0.000         0.000        62.00        34.55        0.000         0.000        0.000



 FLUID SUBMODEL NAME = COOKER  ; FLUID NO. =  718


        LOOPCT =     9
        CONVERGENCE STATUS = SUBMODEL CONVERGED AS OF       9 ITERATIONS


                                        TIE PARAMETER TABULATION FOR SUBMODEL COOKER

  TIE   TYPE      UA          QTIE         LUMP     TEF           NODE              TEMP.    2P  PATH 1    FRACT   PATH 2    FRACT

     1  HTU     229.0        996.3           1     250.0      WALL.1               254.4
```

```
                                                         NODE WALL           1

A QMAP OF INPUT DIFF   NODE WALL           1 (INTERNAL      1)

THE PARAMETERS OF NODE WALL           1 ARE:    TEMPERATURE      =   254.351     (DEG.)
                                                CAPACITANCE      =  0.550000     (ENERGY/DEG)
                                                NET SOURCE/SINK  =   709.753     (ENERGY/TIME, INCLUDES TIES)
                                                CAP./SUM OF COND.=  2.362391E-03 (TIME, INCLUDES TIES)


                                         THE ADJOINING NODES TO NODE WALL           1 ARE:

NODE                      CONDUCTOR                     CONDUCTOR    % OF  % OF    HEAT TRANSFER RATE   TEMPERATURE OF
INPUT          (INTERNAL) INPUT   (INTERNAL)   TYPE     VALUE        TYPE  TOTAL   (ENERGY/TIME)        ADJOINING NODE
------------------------- ------------------- --------- ------------- ----- ----- ---------------------- --------------
WALL         999 (     2)         1 (      1)  LINEAR     3.85000     100.0 100.0      -709.753            70.0000



                                         THE ADJOINING LUMPS TO NODE WALL           1 ARE:

  LUMP                    TIE                              TIE                        ADJOINING LUMP PROPERTIES
  MODEL.INPUT    (INTL)   INPUT    (INTL)  TYPE   DUPN     CONDUCTANCE   HEAT RATE       TEMPERATURE     DUPL
-----------------------  ----------------  ---- --------  ------------- ------------- --------------------------
  COOKER.1      (    1)          1 (    1)  HTU   1.000      228.965      -996.311       250.000         1.000

                                              THE TOTALS ON NODE WALL           1 ARE:

                    LINEAR HEAT TRANSFER (CONDUCTION/CONVECTION)...  -709.753
                    RADIATION HEAT TRANSFER........................   0.00000
                    TIE HEAT TRANSFER (FROM LUMPS).................  -996.311
                    HEAT SOURCE/SINKS APPLIED......................   1706.06
                                                                   ---------------
                                                                      0.00000      (ENERGY/TIME)
```

```
                           SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR          PAGE    39

MODEL = PCOOK                          FLUINT SAMPLE PROBLEM 3 - PRESSURE COOKER
  FWDBCK


 FLUID SUBMODEL NAME = COOKER  ; FLUID NO. =  718


        MAX TIME STEP =  8.800282E-04 ; LIMITING TANK =       1    REASON  = QUALITY CHANGE LIMIT
        LAST TIME STEP =  4.166672E-04 VS. DTMAXF/DTMINF =  1.000000E+30 /   0.00000    ;   AVERAGE TIME STEP =  3.544987E-04
        PROBLEM TIME                  TIMEN  = 8.333334E-03 VS. TIMEND  = 8.333334E-03


                                    LUMP PARAMETER TABULATION FOR SUBMODEL COOKER

  LUMP  TYPE     TEMP       PRESSURE     QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

     1  TANK    223.4        3.609       4.5509E-02   0.9840       0.9920        237.4        2510.        29.78        3539.
     2  PLEN    212.0      -4.0171E-02    1.000        1.000       3.7257E-02    1151.        0.000         0.000       0.000
     3  PLEN    70.00        15.00        0.000        0.000        62.00        34.55        0.000        -29.78      -1029.




 FLUID SUBMODEL NAME = COOKER  ; FLUID NO. =  718


        MAX TIME STEP =  8.800282E-04 ; LIMITING TANK =       1    REASON  = QUALITY CHANGE LIMIT
        LAST TIME STEP =  4.166672E-04 VS. DTMAXF/DTMINF =  1.000000E+30 /   0.00000    ;   AVERAGE TIME STEP =  3.544987E-04
        PROBLEM TIME                  TIMEN  = 8.333334E-03 VS. TIMEND  = 8.333334E-03


                                    TIE PARAMETER TABULATION FOR SUBMODEL COOKER

  TIE   TYPE      UA        QTIE         LUMP     TEF           NODE              TEMP.    2P  PATH 1     FRACT   PATH 2    FRACT

     1  HTU     376.6       2510.          1    223.4      WALL.1                230.1
```

PROBLEM D: AQUARIUM FILTER AND AERATOR

This problem describes the optimization and start-up behavior of a home aquarium under-gravel filter. This problem was chosen to demonstrate the following FLUINT features:

1. multiple-constituent flow modeling (without phase change)
2. parametric design options and logical manipulations
3. flow-regime mapping options
4. buoyancy-driven two-phase flow modeling
5. uses for simple capillary devices
6. optimization using the Solver
7. modeling slip flow
8. modeling with dissolved gases

D.1 Problem Description

Under-gravel filters in home aquariums recirculate water through the gravel at the bottom of the tank. They use an air pump to inject air into the bottom of a vertical tube. As the air bubbles rise, they lift liquid from underneath the gravel and aerate the water at the same time. The filter system for one half of a typical 10 gallon tank is depicted in Figure D-1

There are two purposes for this analysis. The first is to determine the optimum flowrate of air that will lift or pump the maximum amount of liquid. The second purpose is to verify the stability of the start-up process at the optimal air flow, and to determine the time required to stabilize the system.

The system parameters are summarized below:

Half-tank dimensions	
Depth	10 inches
Length	10 inches
Width	10 inches
FIlter pipe:	
Total length	10 inches
Inner diameter	3/8 inch
Gravel:	
Thickness	2 inches
Permeability	10^{-8} ft^2
Spacer:	
Thickness	1/4 inch

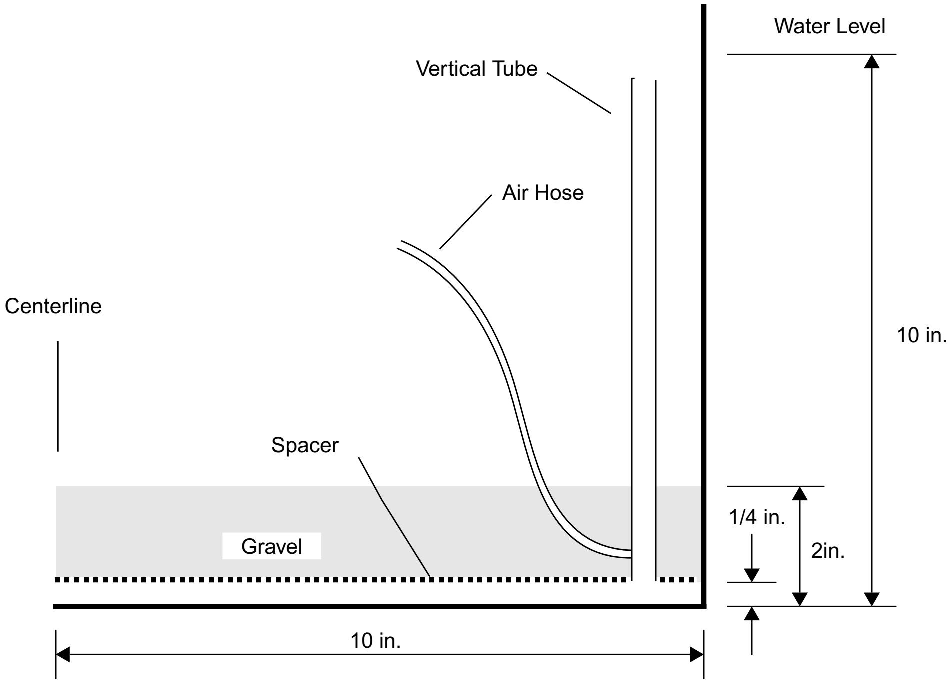


Figure D-1 Aquarium Filter

The optimization of air flow is an interesting problem. Too little air will obviously not lift much liquid, but too much air flow will also be less effective than some intermediate value. As the air flowrate increases, so does the void fraction in the line and the pressure drop through the line, both tending to reduce the liquid flowrate once the air flow has passed the optimum point. At high enough air flowrates, it is even possible to blow bubbles back up through the gravel.

With respect to start-up, as the air begins to flow into the bottom of the pipe, it may find that displacing the liquid in the spacer underneath the gravel is at least temporarily an easier route than lifting a column of liquid.

D.2 A FLUINT Model

Thermal effects are negligible: a single fluid submodel will suffice to model this problem.

The first modeling choice involves the working fluid. A two-phase binary (two-constituent) mixture of air and water is required, since steam cannot be used in this case to represent the air flow. Neglecting water vapor in the air and any phase change associated with that water vapor represents a significant simplification. This simplification, which is effected by choosing to use a 9000 series nonvolatile description of liquid water instead of a full condensible description, is warranted by the cold temperatures of the water: the vapor pressure is small. For this problem, the nonvolatile liquid water description was created by RAPPR and a simple constant-property dry air description was employed.

A second assumption is that the air is not soluble in the water. An alternate model investigates this assumption (Section D.5).

A VFRSET (volume flowrate set) connector will be used to represent the air pump, with a plenum used as a source of air. This representation neglects the pump and the air hose as irrelevant to the current problem. The flowrate of this air pump which maximizes liquid flow through the filter will be found using the built-in optimization capabilities in the SINDA/FLUINT Solver.

A second plenum will represent the liquid, with an elevation representing the surface or top of the vertical tube. A third plenum will be used to represent the top of the gravel, which is at a different pressure than the liquid at the top of the tank. Actually, a junction is used for this lump during a zero-flow initialization such that the exact hydrostatic initial condition is employed relative to the top of the tank. After the initialization, a call to HLDLMP effectively converts the junction to a plenum for the remainder of the analysis.

For the vertical tube, a LINE macro is a natural choice, with air injected in the first lump near the bottom. Since a flow transient response of the tube is desired, tanks and tubes will be used. The choice of discretization to use is limited by the corresponding height of the bottom-most tank where air will be injected; a spatial resolution that is too coarse results in air being injected at a greater elevation. Alterations to the TLEN of the tubes using Sinaps*Plus*® or FloCAD® or using logic statements in OPERATIONS would of course alleviate this concern, but inadequate resolution of the tube will also affect its transient response during start-up. Otherwise, at steady-state, there are no gradients of interest within the pipe and very course resolution would suffice. For this problem, five tanks (2” apart) was found to be adequate.

As was evidenced by preliminary models, the flow regime almost always turns out to be slug.[*] In this regime, the effects of slip flow are negligible and hence homogeneous flow (the default) is assumed. If this conclusion had not been true, twinned tubes could have been chosen to represent the line, allowing vapor to rise faster than the liquid and resulting in a smaller void fraction and hence smaller buoyancy force. In order to verify this assumption, the analysis will first be executed using a homogeneous assumption, and then will be repeated using slip flow. To effect this switch in assumptions, twinned tubes are built but then disabled (using NOSLIP), and a second start-up transient is run after re-awakening the slip flow paths (using GOSLIP).

An inlet loss (K-factor) of 0.5 will be applied to the first bottom-most tube, and an exit loss factor of 0.1 will be applied at the last top-most tube. This LOSS connector is inserted not because its resistance is significant, but because *it is not desirable to use a plenum (nor HLDLMP junction) to represent the density at the top of the tube.* Exhausting to a plenum will skew the buoyancy term of the last path since no matter how much vapor it transports, the exhaust state will remain liquid. The fact that the local state at the exit is really two-phase may be simulated by adding a junction at the end of the tube as a buffer state. A LOSS connector is then used to connect the junction with the plenum. The K-factor for this LOSS cannot be zero, so a small value is used instead.

---

[*] In certain real filters the regime is bubbly, although the behavioral differences between that regime and slug are very small. The actual regime is very sensitive to the nature of air injection, and the tubes are generally too short to allow the regime to fully develop. FLUINT takes neither effect into account, assuming fully developed regimes. This point is made here to reinforce the caution that should be employed with respect to regime predictions.

The gravel will be represented by a CAPIL connector, whose CFC will be calculated on the basis of the flow area, an estimated permeability, and the thickness (A*P/t). The CAPIL will prevent vapor from rising through the gravel, a function fulfilled in reality more by the small holes and slots in the spacer than by the capillary pore size of the gravel. A small pore size (RC) is chosen to neglect this aspect. One significant question is the lack of inertia in a connector and the impact of that assumption on the start-up response. Although the characteristic dimension of the gravel is small, the flow area is large and the flow length (thickness of the gravel, in this case) is small, so neglecting the inertia is acceptable. This assumption, like many contained in this and other examples, was testing by creating a separate model. That model used a tube instead of a CAPIL connector (with STAT=DLS and DH, AF, and TLEN chosen as needed to represent the gravel flow path), and showed no significant differences in results. However, it took longer to execute because of the time step requirements of such a low-inertia path.

The model developed here is shown in Figure D-2, and summarized below:

Fluid submodel FILTER:

PLEN 200	Liquid at top of the tank (stagnant)
PLEN 150	Air supply (stagnant)
JUNC 100	Top of gravel. (This lump is really a plenum via the use of HLDLMP.)
TANK 50	Fluid underneath gravel and spacer (stagnant)
VFRSET 110	Air pump
LINE 1	(TANKS 1-5, TUBES 1-6) Vertical tube, numbered from bottom to top. (Tubes 11-16 for slip flow analysis.)
JUNC 60	Tube exit
LOSS 60	Tube exit loss
CAPIL 100	Gravel

D.3 The Input File

The input file is listed immediately following the last section. Note that this single input file accomplishes three very different objectives: a steady-state optimization operation, a transient start-up simulation, and a second transient simulation enabling slip flow for comparison. Use is made of the NSOL flag, whose value is 0 or 1 during steady-states and 2 or 3 during transients. Although useful for demonstration purposes, two or three distinct input files could have also been used for clarity.

OPTIONS DATA—This section names an output file, as well as a SAVE file. This last file can be postprocessed by EZ-XY® and Sinaps*Plus*®, or could also be used for restart purposes.

CONTROL DATA—English units are chosen, with temperature in Fahrenheit by default (since ABSZRO is not specified). NLOOPS is required and is set to 250. The value of gravitational acceleration (in standard English units if ft/hr^2) is input as ACCELZ, using the built-in constant *grav.*

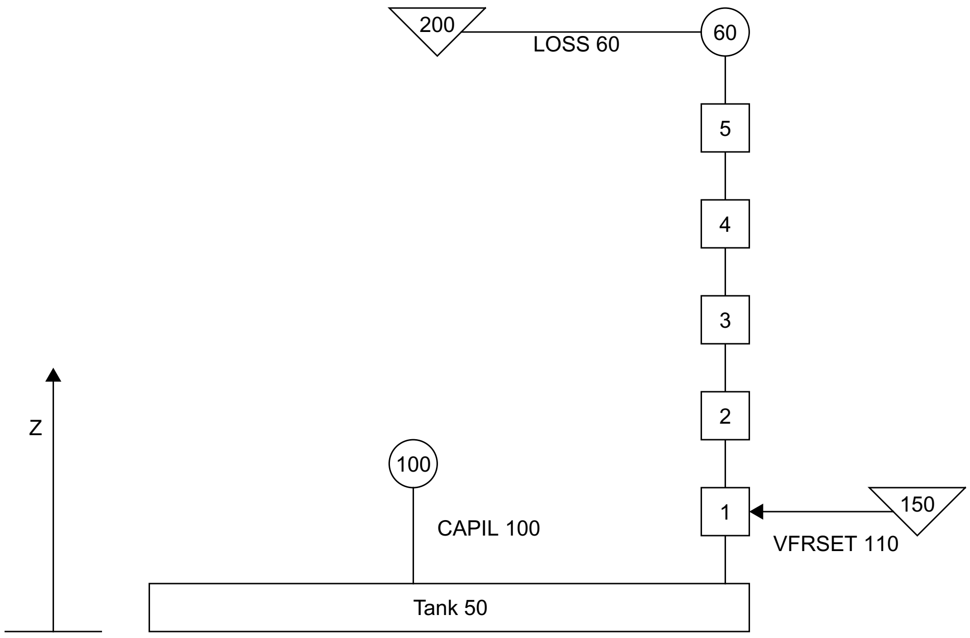


Figure D-2 FLUINT Model of Filter

REGISTER DATA—Several registers are defined to represent the dimensions of the problem. One key register is *AirFr*, which is the volumetric air flow rate. This value will be used as a design variable for optimizing liquid flowrate. The initial value AirFr is equated to unity, since a design variable should never be initialized to zero.

SOLVER DATA—Two control variables for the solver were changed from the default values. GOAL is set to 1.0E30, since OBJECT (which is set to the liquid flowrate) is to be maximized. NLOOPO is set to 50, which limits the number of times PROCEDURE will be called during the optimization portion of the run.

DESIGN DATA—The simplest form of the DESIGN DATA is used in this example. Only one register is used, AirFr and no upper or lower limits are defined. Similarly, no constraints (CONSTRAINT DATA) were needed in this problem.

FPROP DATA—Two blocks are supplied for air (8000 series perfect gas) and for water (9000 series simple incompressible and nonvolatile liquid). Both descriptions use SI units with degrees Kelvin. As long as these units are explicitly stated on the HEADER card, the program will perform the necessary unit conversions needed to comply with the unit set of the master network. Thus, these descriptions can be reused in any model.

The second (water) block was created by the external program RAPPR using the internal library description of water. As such, surface tension and compliance (ST and COMP, respectively) data were included automatically. Although the COMP data is not used in this model, the ST data is required for two-phase flow regime mapping calculations (path IPDC=6 by default).

FLOW DATA—Only one submodel is used: a fluid submodel named FILTER. Refer to the previous section for descriptions of the model.

The two fluids described in the previous FPROP DATA blocks are named as constituents: 9718 (water) as constituent W, and 8000 (air) as constituent A. Since these are the only two constituents, and since one is liquid and one is gas, it is understood that XGA=1.0 and XFW=1.0 for all lumps in the model when either constituent is present.

Liquid water at 14.7 psia and 70˚F is chosen as the default state. A quality (XL) higher than zero implies the presence of air at those temperatures and pressures as well.

A default flowrate of zero is used since the first action in OPERATIONS will be to find the quiescent steady-state to be used for initial conditions in the transient start-up case. Since the fluid properties are unable to handle low (expanded) throat pressures and choked flow is not expected to be a concern, choked flow detection and modeling is turned off by setting MCH=0 for all paths.

Ideally, one air supply plenum and two liquid water plena (one source and one sink) are required. Two water plena are required since they will each be located at a different depth and therefore different pressure. While the pressure differential between these two plena can be calculated using the actual liquid density and the difference in elevations, a more accurate method is to let the program calculate the difference. This is achieved by letting one plenum be a junction during the first zero-flow solution, and then calling HLDLMP to convert it into a plenum for the remainder of the calculations. Otherwise small errors in the pressure differential can result in nonzero flow as an initial condition.

The air pump is simulated by a VFRSET connector. The register AirFr is used to define volumetric flow rate. During the optimization portion of the run AirFR will be adjust such that the flow rate through the CAPIL connector is maximized.

A CAPIL connector is built to represent the gravel, and a comparatively large tank, #50, is used to represent the liquid space at the bottom of the spacer. If air flow never reverses and this control volume could be guaranteed to always contain liquid, then a junction would have sufficed at that location.

A centered LINE macro representing the vertical line is built from the tank at the bottom to the junction at the top, #60. Because of the requirements to capture the start-up response, tanks and tubes are used in this macro. CZ and CZINC arguments assure that the generated tanks will each be at the correct elevation. Twinned tubes (paired sets of tubes) are generated using the “TWIN=” command. This will enable slip flow to be modeled. However, this capability is disabled using logical switches (NOSLIP, GOSLIP calls in OPERATIONS) until the end of the run: slip flow is only needed to compare with a prior homogeneous (equal phasic velocity) assumption.

Finally, a LOSS element representing the exit loss (FK=1.0) is added to close the loop. The AF for this element will be calculated from the default value of DH input earlier. If not for the desire to avoid exhausting into a 100% liquid plenum because of the buoyancy term, this LOSS element and junction 60 could have been eliminated by adding an FK to the last tube in the LINE macro. Individual macro paths can be customized either by logical instructions in OPERATIONS before any solution is performed, or by using FloCAD or Sinaps*Plus*. Although the less desirable of the two, the former method is chosen for demonstration purposes to define an inlet loss factor, as described next.

OPERATIONS—After the required BUILDF statement, an inlet loss factor is applied to the first path in the LINE macro. Homogeneous flow is then assumed via a call to NOSLIP.

A zero-flow case is solved using STEADY (FASTIC) to find the hydrostatic head, and the "temporary junction" 100 is converted into a plenum using the HLDLMP routine. This state is then saved for use as a future initial condition using the SVPART call. This call saves everything except registers to avoid overwriting AirFr later when RESPAR is called.

To find the air flow that yields the maximum liquid flow, the Solver is called. SOLVER will "adjust" the register AirFr (and therefore indirectly SVFR110) until the OBJECT, the flow through the CAPIL connector (FR100), is maximized. SOLVER will internally call PROCEDURE (discussed below) which will call STEADY and (internally) update OBJECT.

After the call to Solver, it is desired to reset the network to initial stagnant conditions as initial conditions for a start-up transient. This state corresponds to the state saved previously by SVPART.

In order to save computational costs, *the UPREG family of routines, which are called internally, is designed to only perform an update if register values have changed.* Unfortunately, in this case that design is somewhat inconvenient. The call to RESPAR will overwrite SVFR110, but *a subsequent call to UPREG will not change anything since AirFr has not changed.* Therefore, to force an update, a call to FORCER is used instead. FORCER basically a heavy-handed version of UPREG: FORCER always propagates register expressions instead of trying to save computational costs (as does UPREG).

As an alternative to the above methods, the 'ALL' option could have been used instead in the original call to SVPART (in which case it is equivalent to the routine SAVPAR), and then the optimum value of AirFr could have been saved prior to the call to RESPAR and then restored afterwards.

A 1 second transient case is initiated using TRANSIENT (FWDBCK).

The last transient is to be repeated, but without the homogeneous flow assumption. After once again retrieving the initial conditions, the slip flow assumption is re-enabled using GOSLIP. Before calling the transient simulation again, the output and SAVE (binary output) files are redirected to new files using the CHGOUT and CHGSAVE utilities.

PROCEDURE—PROCEDURE is the solution sequence needed to evaluate a design and update the objective OBJECT based upon program-provided values of design variables (i.e., those registers defined in DESIGN DATA). PROCEDURE will be called many times by the Solver in its attempt to find the optimum flowrate.

In this example, STEADY (FASTIC) is called to perform a steady state analysis for each new value of AirFR. OBJECT is equated to FILTER.FR100 (see Solver Data), although it could have equivalently been assigned to that value after the call to STEADY. PROCEDURE will continue to be called until the OBJECT (FILTER.FR100) is as close as possible to GOAL (1.0E30, meaning maximize OBJECT).

OUTPUT CALLS—This logic block defines the output to be produced at each output interval. Calls to LMPTAB, LMCTAB, PTHTAB, and TWNTAB are made during the transient run. During the optimization portion of the run information is only written from SOLOUTPUT (discuss next). Calls to SAVE (which writes to the SAVE file) are only made during transients. This action is determined by the value of the NSOL flag.

SOLOUTPUT—This logic block is called from the Solver. Routines DESTAB and CSTTAB are called to status progress of the Solver. LMPTAB, LMCTAB, and PTHTAB are called after the solver is converged. NSTATO is used to indicate when the Solver is converged.

FLOGIC 2—During steady-state optimization option, this block is called at the end of each steady-state analyses. The optimization is terminated if any particular analysis fails to converge, or if the flowrate has reversed and no further analyses are needed.

D.4 Output Description

Sample portions of the output files are listed at the end of this section following the input file listing. Note that the LMCTAB outputs are not very useful in this case, although it and a related routine CNSTAB are helpful if more constituents exist or they are the same phase.

Final results from the optimization portion of the analysis are given following the message “SOLVER CONVERGENCE CRITERIA MET AFTER 25 CALLS TO PROCEDURE.” A flowrate in the air pump of 5.7 ft^3/hr was found to maximize filter flowrate at about 360 lb/hr. From a practical standpoint, an alternative optimum point might be that which minimizes pumping power as long as aeration requirements were met.

As noted before, the flow regimes are almost always slug in this analysis. If the air flowrate had continued to increase, either the annular regime would have resulted or the flowrate through the gravel would have reversed. Indeed, if the flow through the gravel had reversed and if that response were important, then a 1D model of that component would have been inadequate, and greater resolution of the spacer and gravel would have been required.

The flowrates in the vertical tube during the severe ~1 second start-up transient are depicted in Figure D-3. When air is injected near the bottom of the tube, the path of least resistance and inertia is downward, as reflected by the negative flowrates in the figure. Some air ends up in the spacer volume (Tank 50) temporarily, before being swept upwards as the flow is established. Some overshoot in flowrate is experienced as the volumetric flowrate of the displaced water matches the volumetric flowrate of the injected air, but all flowrates settle to the final value within 1 second.

Figure D-4 shows the comparison between the slip flow and homogeneous assumptions as a function of outlet flow rates. The most important figure of merit is the total flowrate: both assumptions yield essentially the same value, so the effects of slip are indeed minimal due to the slug flow regime. In the transient, the slip flow solution overshoots the final flow rate a bit more, but otherwise the responses are similar enough to warrant the original simplifying assumption of homogeneous flow.

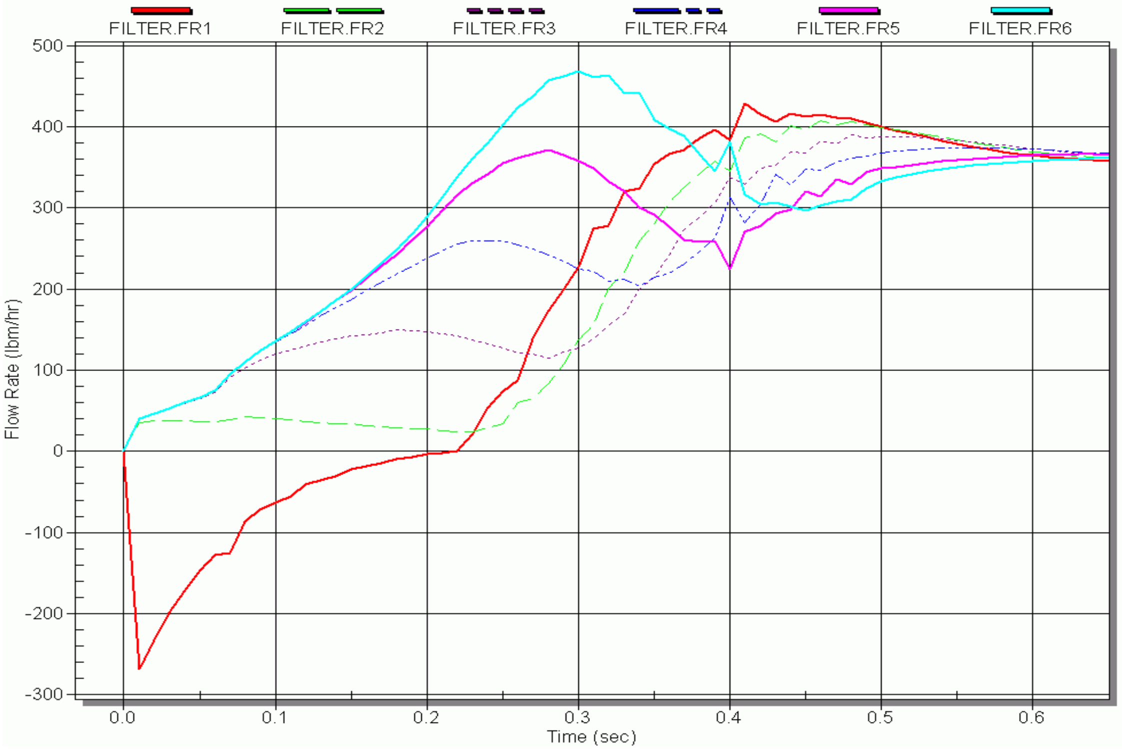


Figure D-3 Flowrate Histories in Vertical Tube During Start-up

Finally, a quick note is necessary regarding the “CAPIL deprimed” messages. This message merely states that liquid exists on both sides of the connector (as intended), and that no capillary interface therefore exists.

D.5 Alternate Model: Dissolved Gas

To illustrate modeling options for dissolved gases, the effects of dissolution of air into water are added. As a first approximation, the air is treated as pure nitrogen for dissolution purposes. To perform such analyses, some extra data is needed for the solute (the 8000 series fluid):

```
HEADER FPROP DATA, 8000, SI, 0.0        $ DESCRIBE AIR
        RGAS    = gasrsi/28.97
        CP = 1002.0, K = 7.4E-3, V = 5.38E-6
C
C FOR DISSOLVED GAS INFO, TREAT AIR AS PURE N2
C FOR N2 FROM SONNTAG AND VAN WYLEN
         TCRIT    = 126.2,           PCRIT    = 3392221.9
C FROM REID ET AL., TABLE 3-10 PG 65 WSRK, V*
         WSRK     = 0.0358
         VNB      = 31.76E-3
AT PSAT, 63.15,12500.2
```

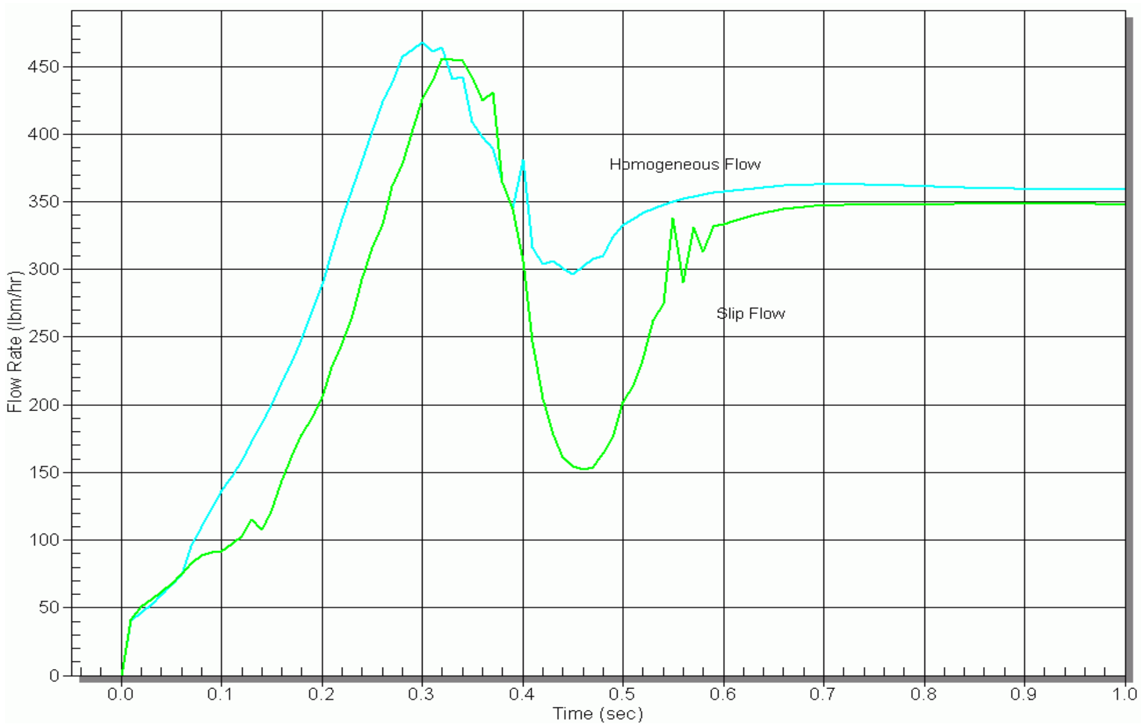


Figure D-4 Slip Flow vs. Homogeneous Flow

Actually, the saturation data is only needed if Raoult’s Law of equilibrium dissolution is followed. Instead, data for Henry’s constants of nitrogen in water is added using MIXTURE DATA. The data is in the form of Henry’s constant versus temperature:

```
HEADER MIXTURE DATA,BIN, 8000,9718,ENG,0.0
C        DATA FOR N2 IN WATER, REFERENCE COHEN, PG 109
C        UNITS ARE IN ATM/MOLE FRACTION, TEMPERATURE DEG R
         UNITS=1
AT,HL, 1, 1.               $ ONE “FAKE” PRESSURE IS GIVEN
          500.,  102600.,            560.,  102600.,
          610.,  120900.,            660.,  123100.,
          710.,  114500.,            760.,   99800.,
          810.,   83000.,            860.,   66200.,
          910.,   50700.,            960.,   37100.,
         1010.,   25600.,           1060.,    15800.
```

The routine CNSTAB is added to track dissolved species.

The results of this alternate model are nearly indistinguishable from the previous case, since the amount of mass associated with the solute are negligible. At the optimum flowrate, the solute has reached 12% saturation by the top of the tube.

Input File

```
HEADER OPTIONS DATA
TITLE FLUINT SAMPLE PROBLEM D - AQUARIUM FILTER MODEL
C
         OUTPUT   = fishpipe.out
         SAVE     = fishtran.sav
C
HEADER CONTROL DATA, GLOBAL
         UID      = ENG                    $ ENGLISH UNITS
         NLOOPS   = 250
         ACCELZ   = grav                   $ GRAVITY IN ENG UNITS
         RERRF    = 0.001                  $ Tight for Solver
C
HEADER REGISTER DATA
C AIR FLOW RATE
         AirFr             = 1.0           $ air volumetric flowrate
         Diam              = (3/8)/12      $ filter tube diameter
         Length            = 10/12         $ filter tube height
         Depth             = 12/12         $ Water depth
         GravArea          = 10*10/12^2    $ Gravel area
         GravThk           = 2/12          $ Gravel Thickness
         GravPerm          = 1.0E-8        $ Gravel Permeability
C
HEADER SOLVER DATA
         NLOOPO   = 50            $ MAXIMUM NUMBER LOOPS FOR THE SOLVER
C
C MAXIMIZE FLOW RATE THROUGH THE GRAVEL BY ADJUSTING THE
C DESIGN VARIABLE AirFr
C
         GOAL     = 1.0E30        $ MAXIMIZE THE OBJECTIVE
         OBJECT   = FILTER.FR100  $ THE OBJECTIVE IS THE FILTER FLOWRATE
C
HEADER DESIGN DATA
C AIR FLOW WILL BE MAXIMIZED
         AirFr                    $ THE DESIGN VARIABLE IS THE AIR FLOW-
RATE
C
HEADER FPROP DATA, 8000, SI, 0.0$ DESCRIBE AIR
         RGAS     = gasrsi/28.97
         CP       = 1002.0
         K        = 7.4E-3
         V        = 5.38E-6
C
```

```
HEADER FPROP DATA, 9718, SI , 0.0
C
C   THIS FLUID DESCRIPTION WAS CREATED BY RAPPR FOR FLUID  718
C   PROPERTIES ARE ACCURATE FOR SATURATED LIQUID OVER FULL
C   RANGE WITH MAXIMUM ERROR IN LIQUID PROPERTIES  = 25.00 PERCENT
C
         TMIN =      273.16669    ,    TMAX =      638.88892
         MOLW =      17.998760
         PCRIT =     22105978.    ,    TCRIT =     647.27777
         WSRK =     0.38519999    ,    PHI =       2.5999999
C
AT,V,      273.16669    , 1.72305526E-03
           282.08099    , 1.35571975E-03
           292.08099    , 1.06284779E-03
           303.08099    , 8.35646119E-04
           315.08099    , 6.61102706E-04
           328.08099    , 5.27636264E-04
           343.08099    , 4.19578311E-04
           360.08099    , 3.34689452E-04
           380.08099    , 2.66381132E-04
           404.08099    , 2.11503982E-04
           433.08099    , 1.68134415E-04
           469.08099    , 1.33836904E-04
           515.08099    , 1.06845895E-04
           578.08099    , 8.52193625E-05
           638.88892    , 7.27354782E-05
AT,K,      273.16669    , 0.57114619
           619.08099    , 0.45613882
           638.88892    , 0.40892443
AT,D,      273.16669    ,  1000.3812
           521.08099    ,  799.16998
           602.08099    ,  638.20776
           637.08099    ,  505.41394
           638.88892    ,  493.60999
AT,ST,     273.16669    , 7.02163428E-02
           381.08099    , 5.61446026E-02
           440.08099    , 4.47488278E-02
           638.88892    , 8.59237858E-04
AT,CP,     273.16669    ,  4648.9043
           394.08099    ,  4278.9937
           577.08099    ,  5723.9995
           623.08099    ,  7688.0244
           635.69446    ,  9072.4492
AT,COMP,   273.16669    , 4.08310830E-10
           274.08099    , 4.09223072E-10
           374.08099    , 5.46158285E-10
           446.08099    , 7.30300709E-10
           498.08099    , 9.77743775E-10
           535.08099    , 1.30751676E-09
```

```
           562.08099    , 1.75050840E-09
           582.08099    , 2.34340458E-09
           597.08099    , 3.15694448E-09
           608.08099    , 4.30773417E-09
           615.08099    , 5.74858960E-09
           620.08099    , 7.75211895E-09
           624.08099    , 1.09920482E-08
           627.08099    , 1.61637264E-08
           629.08099    , 2.33439419E-08
           631.08099    , 4.02251139E-08
           632.51599    , 7.62920536E-08
C
HEADER FLOW DATA, FILTER
         FIDW     = 9718   $ WATER
         FIDA     = 8000   $ AIR
C
LU DEF, PL= 14.7                    $ DEFAULT STATE
         XL       = 0.0
         TL       = 70.0
PA DEF, FR= 0.0
         DH       = Diam
         MCH      = 0               $ DISABLE CHOKING CHECKS
C
LU PLEN, 200                        $ TOP OF FILTER PIPE
         CZ       = Length
         LSTAT    = STAG
C
C JUNCTION FOR ZERO FLOW CASE, PLENUM OTHERWISE
C
LU JUNC, 100                        $ BOTTOM, ABOVE GRAVEL
         CZ       = GravThk
         LSTAT    = STAG
LU PLEN, 150                        $ AIR SOURCE
         XL       = 1.0
         LSTAT    = STAG
PA CONN, 100, 100, 50               $ GRAVEL RESISTANCE
         DEV      = CAPIL
         RC       = 1.0E-6          $ SMALL, IRRELEVANT
C ROUGH GUESS A = 100 SQIN, L = 2 in, P = 1.0E-8 ft2
         CFC      = GravArea*GravPerm/GravThk
PA CONN, 110, 150, 1                $ AIR PUMP
         FR       = 0.0
         DEV      = VFRSET
         SVFR     = AirFr
LU TANK, 50                         $ BOTTOM UNDER GRAVEL
         CZ       = 0.0
         VOL      = GravArea*0.25/12.0
         LSTAT    = STAG
C
```

```
M LINE,1,C,1,1,50,60                $ VERTICAL LINE
         NSEG     = 5
         twin     = 11
         TLENT    = Length
         DHS      = Diam
         IPDC     = 6
C        CZ       = Length/(2*NSEG),CZINC    = Length/(NSEG)
         CZ       = Length/10.0,    CZINC    = Length/5.0
C
C THIS LUMP IS THERE SUCH THAT EXIT CONDITION IS
C NOT 100% LIQUID (PLENUM) FOR BOUYANCY TERM
C
LU JUNC, 60
         CZ       = Length
PA CONN, 60, 60, 200                $ EXHAUST, HORIZONTAL
         DEV      = LOSS
         FK       = 0.1
C
HEADER OPERATIONS
BUILDF FISHPIPE, FILTER
DEFMOD FILTER
C
C INLET LOSSES
C
         FK1      = 0.5
         FK11     = 0.5
C
C TURN OFF SLIP FLOW FOR NOW
C
         CALL NOSLIP('FILTER',0)
C
C THIS INITIALIZES THE SYSTEM AT ZERO FLOWRATE
C
         AirFr    = 0.0
         CALL STEADY
         CALL HLDLMP('FILTER',100)
C
C DON'T SAVE REGISTERS:
C
         CALL SVPART('-R',MTEST)
C
C FIND THE OPTIMUM AIR FLOW THAT MAXIMIZES LIQUID FLOW
C TAKE AT MOST 90% OF THE FLOW THAT CAUSES FLOW BACK THROUGH
C GRAVEL IF FLOW REVERSES
C
C DON'T START A DESIGN VARIABLE AT ZERO!
C
         AirFr    = 1.0
         CALL SOLVER
```

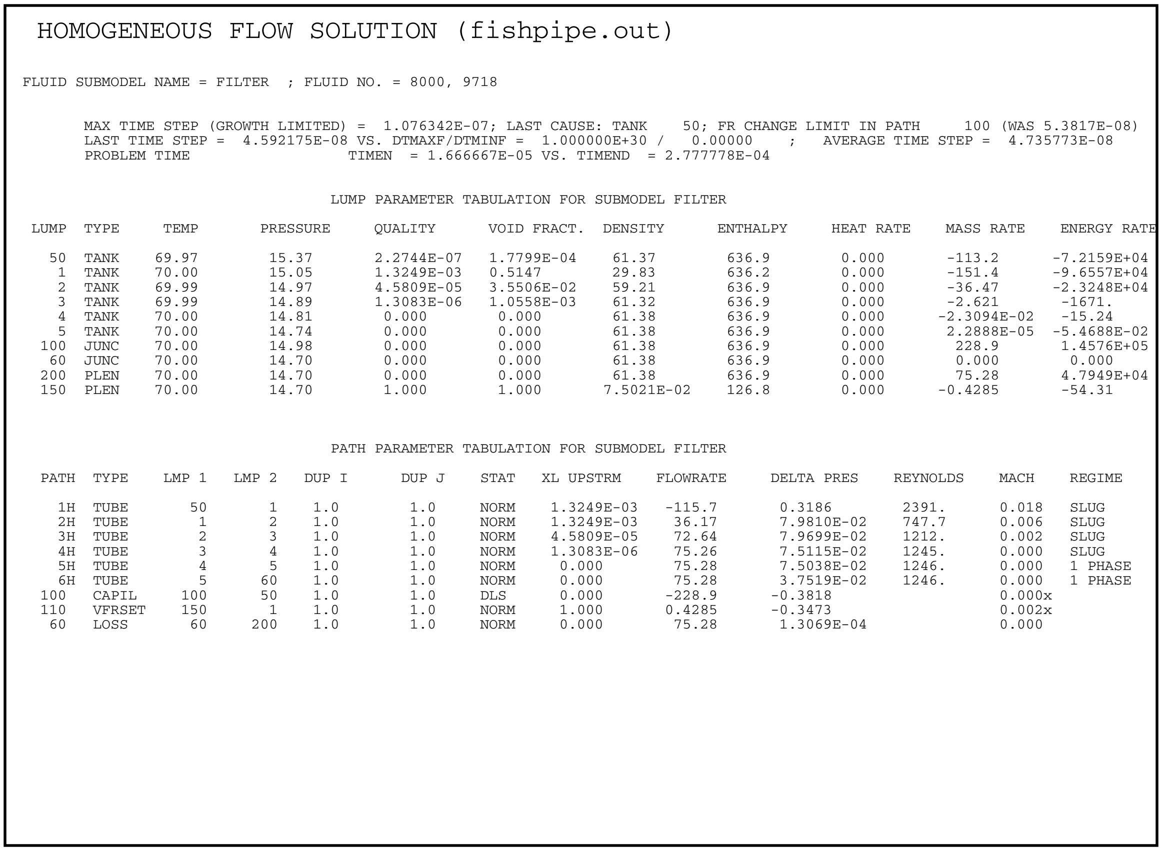
```
C
          CALL LMPTAB(‘ALL’)
          CALL LMCTAB(‘ALL’)
          CALL PTHTAB(‘ALL’)
C
C START-UP SIMULATION
C NOW START FROM QUIET, ADD OPTIMUM FLOW AND RUN FOR 10 SECONDS
C
          CALL RESPAR(MTEST)
          CALL FORCER
C
          TIMEND   = 1.0/3600.0
          OUTPTF   = 0.02/3600.0
C
          CALL TRANSIENT
c
c SEE IF SLIP MAKES A DIFFERENCE
c
          CALL RESPAR(MTEST)
          CALL FORCER
          CALL GOSLIP(‘FILTER’,0)
          TIMEN = 0.0
          TIMEND   = 1.0/3600.0
          OUTPTF   = 0.02/3600.0
          CALL CHGOUT(‘fishpipeT.out’)
          CALL CHGSAVE(‘fishtranT.sav’)
          CALL TRANSIENT
C
```

```
HEADER PROCEDURE
         CALL STEADY
C
HEADER OUTPUT CALLS, FILTER
C
C WRITE TO SAVE FILE FOR TRANSIENT POSTPROCESSING
         IF (NSOL .GT. 1) THEN
                  CALL SAVE(‘ALL’,0)
                  CALL LMPTAB(‘ALL’)
                  CALL LMCTAB(‘ALL’)
                  CALL PTHTAB(‘ALL’)
                  CALL TWNTAB(‘all’)
         ENDIF
C
HEADER SOLOUTPUT CALLS
C
         CALL DESTAB
         CALL CSTTAB
         IF (NSTATO .EQ. 0) THEN
                  CALL LMPTAB(‘ALL’)
                  CALL LMCTAB(‘ALL’)
                  CALL PTHTAB(‘ALL’)
         ENDIF
C
HEADER FLOGIC 2, FILTER
C
C FOR STEADY STATES, IF THE WATER FLOW RATE REVERSES
C USE 90% OF AIR FLOWRATE THAT CAUSED REVERSAL
C
         IF(NSOL .LE. 1)THEN
                  IF (LOOPCT .GE. NLOOPS) LOOPCO = NLOOPO
                  IF(FR100 .LT. 0.0) THEN
                           AirFr    = 0.9*AirFr
                           LOOPCO = NLOOPO
                           WRITE(NOUT,100) AirFr
                  ENDIF
         ENDIF
100    FORMAT(5X,’OPTIMIZATION TERMINATED FLOW REVERSAL. AIR FLOW RATE =
‘, F10.5)
END OF DATA
```

Processor Output

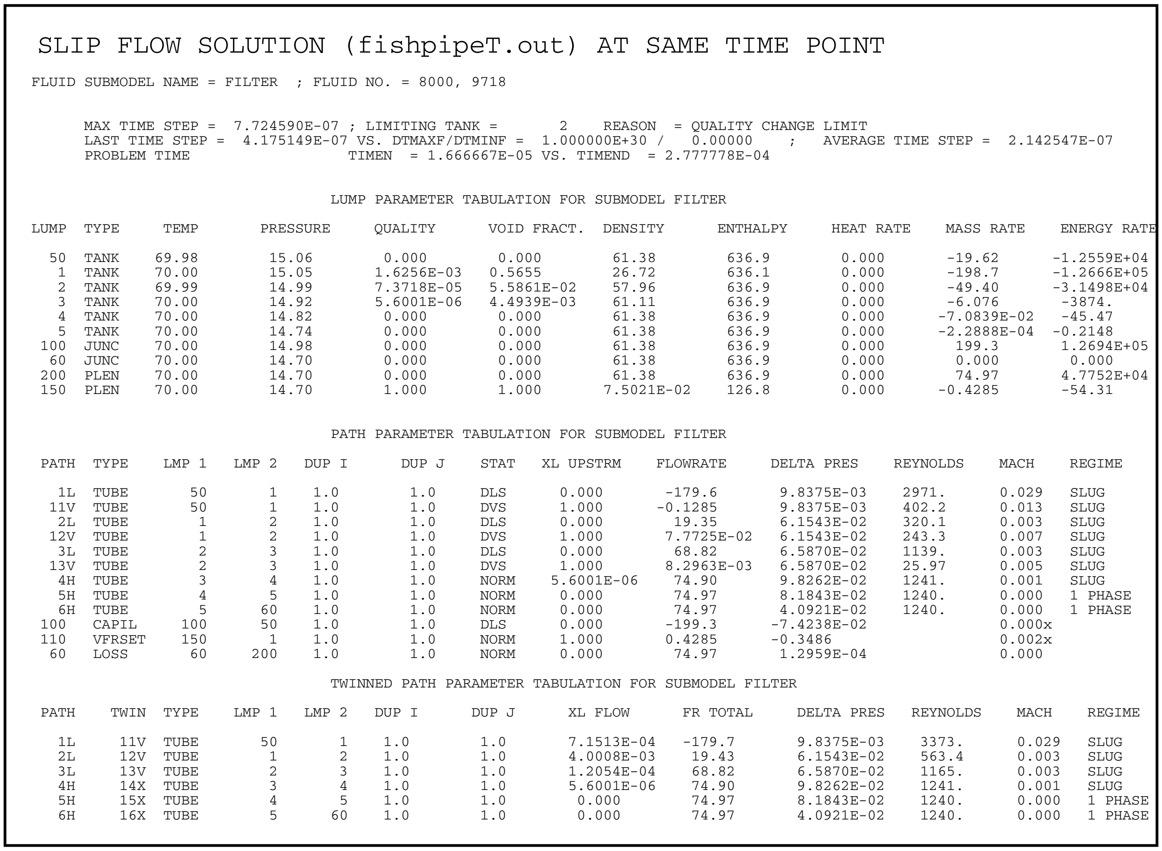
```
SOLVER CONVERGENCE CRITERIA MET AFTER    25 CALLS TO PROCEDURE

                           SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE     7

MODEL = SINDA                       FLUINT SAMPLE PROBLEM D - AQUARIUM FILTER MODEL


        NUMBER OF DESIGN VARIABLES =         1            TOTAL NO. OF CONSTRAINTS =           0
        CALLS TO PROCEDURE (LOOPCO) =       25            VS. MAXIMUM (NLOOPO) =              50  (   0   FINISHED   )
        CURRENT OBJECTIVE VALUE (OBJECT) =   358.840      VS. TARGET (GOAL) =  1.000000E+30 (MAXIMIZE)
        METHO = 2, NERVUS = 0, RCACTO =  0.100000    , RCERRO =  3.000000E-03, DELOBJ =   0.00000

                                    DESIGN VARIABLE TABULATION

NAME AND STATUS       LOWER LIMIT AND STATUS          VALUE          UPPER LIMIT AND STATUS

AIRFR    (ACTIVE)    -1.00000E+30  (FIXED)            5.7114         1.00000E+30  (FIXED)
```

```
 FLUID SUBMODEL NAME = FILTER   ; FLUID NO. = 8000, 9718


        LOOPCT =      2
        CONVERGENCE STATUS = SUBMODEL CONVERGED AS OF       2 ITERATIONS


                                    LUMP PARAMETER TABULATION FOR SUBMODEL FILTER

  LUMP  TYPE     TEMP       PRESSURE     QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

    50  TANK    70.00        15.05        0.000        0.000        61.38        636.9        0.000        0.000        0.000
     1  TANK    70.00        14.92        1.1927E-03   0.4905       31.31        636.3        0.000       -2.7686E-05  -1.6869E-02
     2  TANK    70.00        14.87        1.1927E-03   0.4913       31.26        636.3        0.000        0.000        0.000
     3  TANK    70.00        14.82        1.1927E-03   0.4921       31.21        636.3        0.000        0.000        0.000
     4  TANK    70.00        14.78        1.1927E-03   0.4929       31.16        636.3        0.000        0.000       -1.5625E-02
     5  TANK    70.00        14.73        1.1927E-03   0.4937       31.11        636.3        0.000        0.000        0.000
   100  JUNC    70.00        14.98        0.000        0.000        61.38        636.9        0.000       -358.8       -2.2853E+05
    60  JUNC    70.00        14.71        1.1927E-03   0.4941       31.09        636.3        0.000        0.000       -1.5625E-02
   200  PLEN    70.00        14.70        0.000        0.000        61.38        636.9        0.000         359.2       2.2859E+05
   150  PLEN    70.00        14.70        1.000        1.000        7.5021E-02   126.8        0.000       -0.4285       -54.31



 FLUID SUBMODEL NAME = FILTER   ; FLUID NO. = 8000, 9718


        LOOPCT =      2
        CONVERGENCE STATUS = SUBMODEL CONVERGED AS OF       2 ITERATIONS


                                    PATH PARAMETER TABULATION FOR SUBMODEL FILTER

    PATH  TYPE    LMP 1    LMP 2    DUP I       DUP J     STAT    XL UPSTRM     FLOWRATE     DELTA PRES     REYNOLDS     MACH    REGIME

     1H  TUBE       50        1  1.0        1.0      NORM     0.000      358.8        0.1326       5937.      0.000x  1 PHASE
     2H  TUBE        1        2  1.0        1.0      NORM    1.1927E-03     359.2        4.7086E-02   7278.      0.052    SLUG
     3H  TUBE        2        3  1.0        1.0      NORM    1.1927E-03     359.2        4.6908E-02   7278.      0.053    SLUG
     4H  TUBE        3        4  1.0        1.0      NORM    1.1927E-03     359.2        4.6869E-02   7278.      0.053    SLUG
     5H  TUBE        4        5  1.0        1.0      NORM    1.1927E-03     359.2        4.6830E-02   7278.      0.053    SLUG
     6H  TUBE        5       60  1.0        1.0      NORM    1.1927E-03     359.2        2.3308E-02   7278.      0.053    SLUG
   100   CAPIL     100       50  1.0        1.0      DLS      0.000      358.8       -6.5288E-02                0.000x
   110   VFRSET    150        1  1.0        1.0      NORM     1.000     0.4285       -0.2169                    0.002x
    60   LOSS       60      200  1.0        1.0      NORM    1.1927E-03     359.2        5.8755E-03                0.053
```



HOMOGENEOUS FLOW SOLUTION (fishpipe.out)

```
FLUID SUBMODEL NAME = FILTER   ; FLUID NO. = 8000, 9718

       MAX TIME STEP (GROWTH LIMITED) =  1.076342E-07; LAST CAUSE: TANK    50; FR CHANGE LIMIT IN PATH     100 (WAS 5.3817E-08)
       LAST TIME STEP =  4.592175E-08 VS. DTMAXF/DTMINF =  1.000000E+30 /   0.00000    ;   AVERAGE TIME STEP =  4.735773E-08
       PROBLEM TIME                   TIMEN   = 1.666667E-05 VS. TIMEND  = 2.777778E-04

                                          LUMP PARAMETER TABULATION FOR SUBMODEL FILTER

 LUMP   TYPE      TEMP        PRESSURE     QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

   50   TANK    69.97         15.37        2.2744E-07   1.7799E-04   61.37        636.9        0.000        -113.2       -7.2159E+04
    1   TANK    70.00         15.05        1.3249E-03   0.5147       29.83        636.2        0.000        -151.4       -9.6557E+04
    2   TANK    69.99         14.97        4.5809E-05   3.5506E-02   59.21        636.9        0.000        -36.47       -2.3248E+04
    3   TANK    69.99         14.89        1.3083E-06   1.0558E-03   61.32        636.9        0.000        -2.621        -1671.
    4   TANK    70.00         14.81         0.000        0.000       61.38        636.9        0.000       -2.3094E-02   -15.24
    5   TANK    70.00         14.74         0.000        0.000       61.38        636.9        0.000        2.2888E-05  -5.4688E-02
  100   JUNC    70.00         14.98         0.000        0.000       61.38        636.9        0.000         228.9       1.4576E+05
   60   JUNC    70.00         14.70         0.000        0.000       61.38        636.9        0.000         0.000        0.000
  200   PLEN    70.00         14.70         0.000        0.000       61.38        636.9        0.000         75.28       4.7949E+04
  150   PLEN    70.00         14.70         1.000        1.000      7.5021E-02    126.8        0.000       -0.4285       -54.31


                                          PATH PARAMETER TABULATION FOR SUBMODEL FILTER

  PATH  TYPE     LMP 1   LMP 2   DUP I      DUP J     STAT   XL UPSTRM    FLOWRATE     DELTA PRES    REYNOLDS    MACH     REGIME

    1H  TUBE       50       1    1.0        1.0       NORM    1.3249E-03   -115.7       0.3186       2391.       0.018    SLUG
    2H  TUBE        1       2    1.0        1.0       NORM    1.3249E-03    36.17       7.9810E-02   747.7       0.006    SLUG
    3H  TUBE        2       3    1.0        1.0       NORM    4.5809E-05    72.64       7.9699E-02   1212.       0.002    SLUG
    4H  TUBE        3       4    1.0        1.0       NORM    1.3083E-06    75.26       7.5115E-02   1245.       0.000    SLUG
    5H  TUBE        4       5    1.0        1.0       NORM     0.000        75.28       7.5038E-02   1246.       0.000    1 PHASE
    6H  TUBE        5      60    1.0        1.0       NORM     0.000        75.28       3.7519E-02   1246.       0.000    1 PHASE
  100   CAPIL     100      50    1.0        1.0       DLS      0.000       -228.9      -0.3818                   0.000x
  110   VFRSET    150       1    1.0        1.0       NORM     1.000       0.4285      -0.3473                   0.002x
   60   LOSS       60     200    1.0        1.0       NORM     0.000        75.28       1.3069E-04               0.000
```



SLIP FLOW SOLUTION (fishpipeT.out) AT SAME TIME POINT

```
FLUID SUBMODEL NAME = FILTER   ; FLUID NO. = 8000, 9718

       MAX TIME STEP =  7.724590E-07 ; LIMITING TANK =        2    REASON   = QUALITY CHANGE LIMIT
       LAST TIME STEP =  4.175149E-07 VS. DTMAXF/DTMINF =  1.000000E+30 /   0.00000    ;   AVERAGE TIME STEP =  2.142547E-07
       PROBLEM TIME                   TIMEN   = 1.666667E-05 VS. TIMEND  = 2.777778E-04

                                          LUMP PARAMETER TABULATION FOR SUBMODEL FILTER

 LUMP   TYPE      TEMP        PRESSURE     QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

   50   TANK    69.98         15.06         0.000        0.000       61.38        636.9        0.000        -19.62       -1.2559E+04
    1   TANK    70.00         15.05        1.6256E-03   0.5655       26.72        636.1        0.000        -198.7       -1.2666E+05
    2   TANK    69.99         14.99        7.3718E-05   5.5861E-02   57.96        636.9        0.000        -49.40       -3.1498E+04
    3   TANK    70.00         14.92        5.6001E-06   4.4939E-03   61.11        636.9        0.000        -6.076        -3874.
    4   TANK    70.00         14.82         0.000        0.000       61.38        636.9        0.000       -7.0839E-02   -45.47
    5   TANK    70.00         14.74         0.000        0.000       61.38        636.9        0.000       -2.2888E-04  -0.2148
  100   JUNC    70.00         14.98         0.000        0.000       61.38        636.9        0.000         199.3       1.2694E+05
   60   JUNC    70.00         14.70         0.000        0.000       61.38        636.9        0.000         0.000        0.000
  200   PLEN    70.00         14.70         0.000        0.000       61.38        636.9        0.000         74.97       4.7752E+04
  150   PLEN    70.00         14.70         1.000        1.000      7.5021E-02    126.8        0.000       -0.4285       -54.31

                                          PATH PARAMETER TABULATION FOR SUBMODEL FILTER

  PATH  TYPE     LMP 1   LMP 2   DUP I      DUP J     STAT   XL UPSTRM    FLOWRATE     DELTA PRES    REYNOLDS    MACH     REGIME

    1L  TUBE       50       1    1.0        1.0       DLS      0.000       -179.6       9.8375E-03   2971.       0.029    SLUG
   11V  TUBE       50       1    1.0        1.0       DVS      1.000      -0.1285       9.8375E-03   402.2       0.013    SLUG
    2L  TUBE        1       2    1.0        1.0       DLS      0.000        19.35       6.1543E-02   320.1       0.003    SLUG
   12V  TUBE        1       2    1.0        1.0       DVS      1.000       7.7725E-02   6.1543E-02   243.3       0.007    SLUG
    3L  TUBE        2       3    1.0        1.0       DLS      0.000        68.82       6.5870E-02   1139.       0.003    SLUG
   13V  TUBE        2       3    1.0        1.0       DVS      1.000       8.2963E-03   6.5870E-02   25.97       0.005    SLUG
    4H  TUBE        3       4    1.0        1.0       NORM    5.6001E-06    74.90       9.8262E-02   1241.       0.001    SLUG
    5H  TUBE        4       5    1.0        1.0       NORM     0.000        74.97       8.1843E-02   1240.       0.000    1 PHASE
    6H  TUBE        5      60    1.0        1.0       NORM     0.000        74.97       4.0921E-02   1240.       0.000    1 PHASE
  100   CAPIL     100      50    1.0        1.0       DLS      0.000       -199.3      -7.4238E-02               0.000x
  110   VFRSET    150       1    1.0        1.0       NORM     1.000       0.4285      -0.3486                   0.002x
   60   LOSS       60     200    1.0        1.0       NORM     0.000        74.97       1.2959E-04               0.000
                                          TWINNED PATH PARAMETER TABULATION FOR SUBMODEL FILTER

  PATH    TWIN   TYPE     LMP 1   LMP 2   DUP I      DUP J      XL FLOW      FR TOTAL     DELTA PRES    REYNOLDS    MACH     REGIME

    1L     11V   TUBE       50       1    1.0        1.0        7.1513E-04   -179.7       9.8375E-03    3373.       0.029    SLUG
    2L     12V   TUBE        1       2    1.0        1.0        4.0008E-03    19.43       6.1543E-02    563.4       0.003    SLUG
    3L     13V   TUBE        2       3    1.0        1.0        1.2054E-04    68.82       6.5870E-02    1165.       0.003    SLUG
    4H     14X   TUBE        3       4    1.0        1.0        5.6001E-06    74.90       9.8262E-02    1241.       0.001    SLUG
    5H     15X   TUBE        4       5    1.0        1.0         0.000        74.97       8.1843E-02    1240.       0.000    1 PHASE
    6H     16X   TUBE        5      60    1.0        1.0         0.000        74.97       4.0921E-02    1240.       0.000    1 PHASE
```

PROBLEM E: CAPILLARY PUMPED LOOP START-UP[*]

In heat pipes, surface tension forces provide the pumping power necessary to circulate a working fluid between an evaporator and a condenser. A *capillary pumped loop* (CPL) works the same way, but the liquid flow is separated from the vapor flow for efficiency. A CPL resembles a simple mechanically pumped loop except that no pump is needed; the capillary structure in the specialized evaporators provides the pumping action. For this reason, the evaporators in CPLs are usually referred to as evaporator-pumps (EPs).

CPLs, and related loop heat pipes (LHPs), are being used in spacecraft thermal transport systems and are also under investigation for electronics cooling applications. By avoiding mechanical pumps and control valves, CPLs and LHPs have no moving parts and require little parasitic power. However, because of the dependence on capillary forces, they are sensitive to gravity and can transport only a limited amount of energy over a limited distance.[†]

This problem was chosen to demonstrate the following FLUINT features:

1. component models (CAPPMP)
2. capillary devices
3. initializing two-phase states
4. modeling with junctions
5. “half-length” modeling and associated accelerations
6. uses of heat transfer area fractions
7. duplication factors and dual one-way conductors
8. using restart options
9. overriding convective heat transfer calculations
10. modeling a real system

This problem is worked as both a detailed model and a simplified model. The simplified model demonstrates the use of heater junctions, RAPPR-generated simplified fluids, and other time-saving methods and assumptions. In a special subsection at the end of this chapter (page E-41), the simplified problem is then used to correlate several uncertainties in the system to available test data.

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[*] This sample problem should ***not*** be taken as a representative method to model CPLs and LHPs. Nor should it be taken as representative of the current state of the art, since the system described herein is nearing two decades old. C&R maintains more relevant examples for this specialized area.

[†] 24 kW over a distance of 10m was demonstrated by the team that is currently part of Swales and Associates.

E.1 Problem Description

A prototype aluminum/ammonia CPL was flown in a space shuttle Getaway Special (GAS canister) experiment.* The CPL (Figure E-1) consisted of two EPs, a temperature-controlling reservoir, and a combined condenser/subcooler. The fixed-volume reservoir was cold-biased and used a heater to maintain a constant temperature. The condenser piping was embedded in a radiator plate as shown in Figure E-2. This “piping” was actually an axially-grooved heat pipe extrusion, shown in cross-section in Figure E-3.

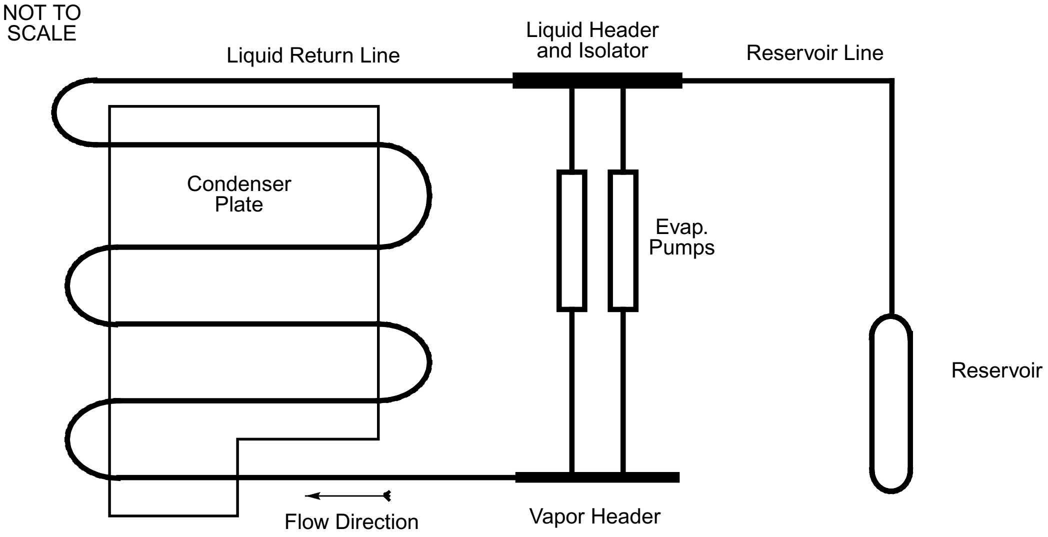

Figure E-1 Schematic of CPL GAS System

The radiator plate was mounted to a 65 kg aluminum sink plate using a thermal bonding material. The sink plate could radiate only a limited percentage of the total CPL throughput; the rejection capability was purposely undersized to investigate performance under varying rejection temperatures.

The evaporator consisted of a tubular polyethylene wick. Liquid was supplied to the inner diameter with evaporation occurring at the outer diameter of the wick, where the wick was in contact with the tips of 45 grooves running axially along the inner pipe wall. The evaporator extrusion, like the condenser, was a trapezoidal groove heat pipe cross-section. The “isolator” used virtually the same wick inside of the liquid header. The purpose of an isolator is to prevent deprime (or loss of capillary pumping) in one EP from causing deprime in the adjacent EP.

In one experimental run, the entire system was initially resting at 6.6°C with the exception of the reservoir which initially at 29°C and *presumably* held at that temperature. At time zero, a dissi-

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* Most of the information in this example was extracted from the User’s Manual for the CPL Modeler, Version 1.2, written by L. Neiswanger, R. Schweickart, J. Ku, and E. Itkin. Some data were estimated. The author would like to thank Mr. Schweickart, for his extra assistance in preparing this model.

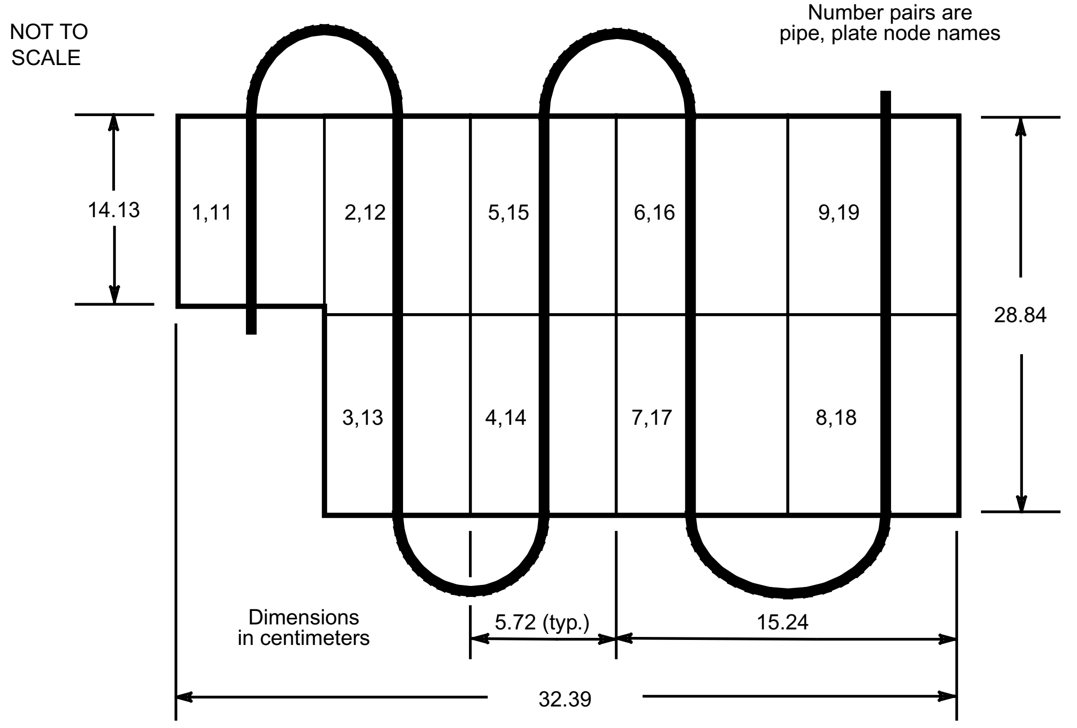


Figure E-2 Condenser Plate Size and Node Names

pation of 255 Watts was applied to the outside of each EP. The sink plate began to warm up, and the temperature increased linearly from 6.6°C to about 17°C by the end of the experiment, 42 minutes later. The goal of this problem is to simulate this experimental run.

The parameters for this CPL system are listed below:

Reservoir:	
Reference (saturation) temperature	29°C
Connecting line length	70 cm
Connecting line diameter	(see condenser)
Evaporators:	
Number	2
Active length	8.89 cm
Power input	255 W
Thermal capacitance of an EP	137.7 J/K
Radial conductance through pipe	158.6 W/K
Evaporative heat transfer coefficient	2500 W/m^2-K
Number of axial grooves per EP	45
Groove hydraulic diameter	1.4 mm
Groove flow area	1.5E-6 m^2

Evaporator inlet/outlet lines:

Liquid supply line length	15.24 cm
Liquid supply line ID	4.572 mm
Vapor exhaust line length	7.94 cm
Vapor exhaust line ID	6.604 mm
Vapor exhaust line capacitance	5 J/K

Wick (evaporators and isolators):

Wick ID	1.113 cm
Wick OD, evaporator	2.286 cm
Wick OD, isolator	2.134 cm
Pumping radius	16.5E-6 m
Permeability	2.6E-13 m^2

Headers (liquid header contains isolator):

Vapor header length	12.7 cm
Vapor header ID	1.41 cm
Vapor header capacitance	10 J/K
Liquid header length	12.7 cm
Liquid header ID	2.134 cm

Condenser line (axially grooved):

Total length	1.57 m
Number of axial grooves	16
Vapor core diameter	4.70 mm
Total wetted perimeter	47.1 mm
Total flow area	27.2 mm^2
Hydraulic diameter	2.31 mm
Effective diameter (estimated)	5 mm
Total groove flow area	9.9 mm^2
Capillary pumping radius	0.61 mm
Tube ID to plate conductance (per tube length)	1.19 W/cm-K
Tube capacitance (per length)	0.547 J/cm-K

Line from condenser to liquid header:

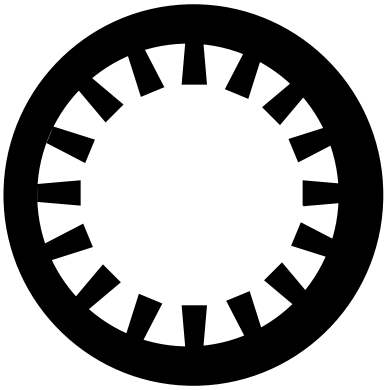
Total length	15 cm
Line ID	(see condenser)

Condenser plate:

Capacitance per unit area	2.85 J/cm^2-K
Aluminum thermal conductivity	165 W/m-K
Thickness	1.27 cm
Conductance to sink per unit area	0.32 W/cm^2-K

E.2 A SINDA/FLUINT Model

The event to be simulated is almost purely a radiator transient. The start-up transients last less than one minute and can be neglected compared to the length of the experiment.* For this reason, the analysis could be started by assuming that the evaporators and headers are already cleared of liquid and that vapor is just beginning to arrive in the condenser. As will be shown later, this assumption leads to perfectly valid results with small computational cost. However, *for demonstration purposes,* this analysis will include the start-up transient and the extra complexity and computational time needed to resolve such events. Good modeling practices would suggest dropping this level of detail unless the start-up itself were the purpose of the analysis. (Section E.5 contains a description of a greatly simplified model for comparison purposes.)



Outer dia:	7.94 mm
Inner dia:	6.43 mm
Vapor core dia:	4.70 mm
No. of grooves:	16
Cap. radius:	0.61 mm
Tot. Grv. Area:	9.9 mm^2

Figure E-3 Cross Section of Condenser Extrusion

As the first modeling decision, a plenum is used to model the reservoir. This decision is forced by the lack of data concerning the reservoir, but would probably be a valid choice in any case. This modeling choice is equivalent to assuming perfect temperature control in the reservoir. The plenum will be assumed to remain as saturated liquid at 29°C,† and will be designated as stagnant. Other modeling choices for the reservoir include a single tank or a pair of twinned tanks (one for the vapor, one for the liquid). Without twinned tanks or the idealization of a plenum, when cold liquid dumps into the accumulator during start-up, the behavior of a single tank may be far from reality due to the perfect mixing (equilibrium) assumption: the pressure in a single perfectly mixed tank will drop too fast. Twinned tanks would model the fact that liquid entering the reservoir tends to compress and heat the vapor, initially raising the pressure until the two phases return to an equilibrium pressure below the initial value. Given enough reservoir design and initial condition information, a nonequilibrium model could be developed using twinned tanks, as shown in Sample Problem F. However, lacking such information, a plenum will be used in this model: the reservoir will be assumed to be so large as to be unresponsive.

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* *Very* different modeling practices would have been used had the first few seconds of start-up been of interest, and those methods are in turn inapplicable to longer term transients. *The time scale of interest is paramount in determining appropriate and efficient modeling choices.*

† The temperature of the reservoir is used as a correlation parameter in a later subsection.

No volume is attributed to the reservoir connecting line since this does not take part in the recirculation of the fluid.

Because of the relatively small volume in the condenser and because the system response is expected to be dominated by the response of the sink, junctions and STUBE connectors will be used to model the condenser. Nine segments are adequate to represent the radiator/plate system. Centered discretization is used not only because it is recommended for two-phase flow, but because it facilitates tying to thermal nodes centered in each plate section (Figure E-2). An additional STUBE connector is placed at the outlet of the condenser to represent the liquid return line. Because of the long radius bends and other smooth transitions, additional head losses are small. A K-factor of 0.37 is attributed to the inlet, and radii of curvature are specified for the bends, though because of the small losses involved no attempt is made to start and stop a curved path at exactly the bend locations. Neither is any attempt made to augment single-phase heat transfer with the HTCURVE routine, since the heat transfer regime of importance is two-phase, which is relatively insensitive to curvature.

Because of the presence of axial grooves in the condenser piping, the modeling decisions surrounding the condenser itself deserve significant discussion. These grooves have the effect of preferentially trapping and redistributing liquid, maintaining a relatively constant void fraction.* Detailed simulations of the separate passages were performed but did not yield significantly different results over those produced by a very simple treatment: a effective diameter assumption.

The grooved cross section and the existence of two-phase flow certainly make the use of a hydraulic diameter assumption questionable: the separation effect of the grooves is not included and the resulting hydraulic diameter is too small even for single-phase flow. A larger effective diameter DEFF (slightly larger than the vapor core diameter) is therefore used for pressure drop purposes, while the smaller hydraulic diameter DH is still required since it is used for heat transfer area calculations.

More important is the impact of the grooves on the heat transfer calculations. Use of the standard annular condensation correlation ROHSEN (implied by the use of HTN or HTNC ties in an HX macro) would predict axially decreasing heat transfer coefficients as the liquid layer builds up, whereas in the actual case liquid is redistributed somewhat evenly by the grooves.

Kamotani’s correlation for grooved condensation heat transfer is:

$$H = \frac{N_G K_L}{0.0221 + \dfrac{K_L t}{K_w w}}$$

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* Because a relatively large pumping radius implies minimal pressure differences between phases (at least compared to axial gradients), only one lump is needed to represent both phases: parallel LINE or HX macros are not needed for grooves and the vapor core. This would not be true in a heat pipe, where the axial pressure gradient must be less than the surface tension gradient. This does not preclude the use of twinned (slip flow) paths along a single row of lumps, but such a model requires more effort than the results justify in order to be faithful to the noncircular geometry (i.e. the user must calculate appropriate values for FD, FC, etc.).

where:

H	heat transfer coefficient
K_L	liquid conductivity (0.54 W/m-K at 270K)
K_W	wall conductivity (165 W/m-K)
N_G	groove density (about 1080 per meter)
t	groove thickness (height, about 0.86 mm)
w	groove width (at interface, about 0.36 mm)

A quality of 0.025 corresponds to completely filled liquid grooves and a dry vapor core. Above this quality (e.g., which is the case for nearly all of the two-phase region in the condenser), a constant groove heat transfer coefficient such as the above correlation might be applicable. Below this quality, the heat transfer coefficient must blend smoothly into the a single-phase convection value as the central core fills. A composite heat transfer correlation will be used: a simple arithmetic averaging of the ROHSEN predictions with the above Kamotani correlation.

This could be accomplished with HTU ties whose UA is updated in FLOGIC 0 in a Fortran DO LOOP. However, this treatment would create an instability at low qualities if the UA were predicted as an *explicit* function of junction quality, which is an instantaneous parameter. If the quality is currently 0.0, a low single-phase UA might cause the quality to jump up near that of the upstream quality. If the quality is currently above 0.025, a high two-phase UA might drive the quality down to 0.0.

There are several ways to deal with this instability. First, the user might add heavy damping to the UA prediction such as by using a weighted average of the new and old UA values. Such damping is relatively easy to implement but has hidden drawbacks such as slowing the solution or artificially retarding the condenser response, and can actually cause instabilities if done improperly. Second, the user might base the UA prediction on the quality of the upstream lump (perhaps using the XTRACT subroutine to simplify the DO LOOP logic). This method is very stable and easy to implement, but alters the results slightly. Third, the user can *implicitly* predict the UA and the corresponding junction quality. This method is stable but difficult to implement since relaxation iterations are often required.

Fourth, the user can alter the basic condensation routine ROHSEN to include the groove heat transfer correlation and place the alternate version in SUBROUTINES. This method, which is used in this sample problem, causes the replacement routine to be linked preferentially over the standard version in the processor library. This replacement method takes advantage of internal FLUINT logic that performs the implicit solution mentioned in the third option, and has the additional benefit of improving the low quality (slug flow) heat transfer coefficient based on scaling factors inherent in the ROHSEN routine. However, the main drawback to this method is that condensation heat transfer would then be altered for all HTN and HTNC ties in all fluid submodels. Therefore, special logic is added into the new ROHSEN routine to avoid groove heat transfer correlations unless the flow area matches that of the condenser: 2.72E-5 m^2. The normal ROHSEN correlation then applies to the evaporator outlet header and to any other fluid submodels that might be added later.

Kamotani's correlation predicts 19,400 W/m^2-K at 270K. When used as an ammonia heat pipe condenser, the heat transfer coefficient for the extruded section was determined experimentally to be 11,800 W/m^2-K at 270K, based on vapor core diameter. As will be seen in later sections, it is not immediately clear which value should be used. Analyses were performed with both coefficients (the fixed heat pipe value was scaled to higher temperatures by assuming proportionality with liquid conductivity). In all cases, predicted temperatures are too low, perhaps due to other causes such as overestimation of plate capacitance or underestimation of thermal conductances to the base plate.* Therefore, higher values of the two-phase heat transfer coefficient cause a better match at the inlet of the condenser at the price of a worse match at the outlet. Higher coefficients also affect run time by decreasing the thermal time constant CSGMIN. In this sample problem and averaging of Kamotani's correlation and the Rohsenow correlation is used, representing a process somewhere in between normal liquid films and grooved condensation.

With regard to the thermal model of the condenser plate, the nodalization will correspond to that of the condenser piping.† The distinction between the tubing and the plate warrants separate nodes because of the importance of the correct wall temperature on the two-phase heat transfer. Each tube node will conduct energy to a corresponding plate node. Even though their mass is relatively small and they will be adjacent to the relatively large conductance resulting from two-phase heat transfer, the pipe nodes will be modeled as diffusion nodes for illustration purposes. In the simplified model that follows, significant savings will be demonstrated by reversing this decision and using arithmetic nodes instead.

Figure E-2 contains the names and locations of the plate and tube nodes and lumps. The plate nodes will conduct energy to adjacent plate nodes as well as to the sink. Fin efficiencies of 63% and 51% are attributed to the plate-to-sink conductances‡ since the plate nodes exist at the root of each "fin." The sink itself is modeled with a boundary node whose temperature is updated linearly with time.

The distance between the two EPs is small in relation to the diameters of the headers; the pressure differentials between these two points will be completely negligible. Thus, one tank will be used to model each header. A higher fidelity model could be built using two tanks per header, connected by a STUBE connectors representing the header itself, but this would be implicitly ask the program to split analytic hairs. More importantly, this simplifying assumption permits symmetry to be exploited. One EP will be modeled, and duplication factors at the inlet and outlet of the headers will be set to 2.0. As will be seen, the entire model (including the thermal portion) must be consistent with this time-saving symmetry.

An inlet tank (subcooled liquid) will contain the volume of the inlet line and the liquid header, as well as the volume in the condenser. An adjacent tank will represent the volume inside *one* evaporator pump. Both of these tanks will be designated as stagnant since their volumes are large compared to the flow passages in and out of them: velocities are nearly zero within those tanks. These two tanks are separated by a CAPIL connector that represents the isolator. While the vapor-

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* Refer to the correlation to test data described at the end of this sample problem. The heat transfer coefficient in the condenser is treated as one of the key uncertainties.

† This example problem predates the fast computers and improved solution methods of today, as well as the existence of codes such as Thermal Desktop which make geometrically faithful models, whether finite difference or finite element, easy to build. Such detailed models have been made since, and they have validated the simplified model used in this example.

‡ These conductances are treated as uncertainties in the correlation example at the end of this chapter.

barrier effects should not be important in this example, the pressure-flowrate behavior of a wick is easily taken into account with this device. (The only other FLUINT connectors that exhibit a linear loss are a NULL connector and an STUBE connector with FPOW=0.0.) An upstream duplication factor (DUPI) of 2.0 is applied to the CAPIL connector. This means that two such passages exist from the point of view of the inlet header. Models of the header itself and the inlet tubing are ignored because of negligible pressure losses in these elements compared to the wick losses.

The EP pumping action can be modeled with the CAPPMP component model. A tie will be made in this macro to a node representing the evaporator wall, with the UA value being based on a number estimated from experimental results. The upstream end of this CAPPMP will be connected to the tank representing the liquid side of the EP. Also, a tank is needed to model the outlet (vapor) header. Normally, a WICK iface should be used in parallel with the CAPPMP when tanks are used as the end-point lumps, and a USER ftie (perhaps using the WETWICK and CYLWICK routines) can also be added in parallel to cover “back conduction” in the slow moving liquid, but these details are neglected here.

Many modeling options are possible to connect the CAPPMP with the outlet header. First, they may be connected directly, ignoring any heat transfer or losses associated with the grooves or the outlet plumbing. This would be appropriate for a model that did not focus on the start-up events. For the purposes of this model, extra lumps and paths will be used to represent the grooves and the outlet line.

The choice of tanks versus junctions for these evaporator outlet lumps is important. Junctions are preferred for several reasons in this particular example. First, the energy and time it takes to clear liquid out of these small volumes is not as important as it might seem. Both are proportional to the mass of *vapor* in them, not liquid! Almost all of the liquid initially in these lumps will be *displaced* by generated vapor rather than *evaporated*. Also, vapor tanks are sensitive to cold shocking in such applications: if the pressure on the liquid side became larger than that on the vapor side, an unrealistically sudden collapse of the vapor tank pressure would occur. Therefore, junctions will be used. The only reason one might wish to use a tank for the grooves is to allow the CAPPMP to reprime more realistically. If the CAPPMP deprimes, the flow reverses immediately in the vapor junction and the quality may instantly become too small to allow reprime. This tendency will be offset by the movement of the HTM tie, which will move to the vapor junction in the event of a deprime. This outlet junction is the vapor side by default. To avoid the default vapor side, the VAPOR keyword should be used.

A call to SPRIME will be used to clear the grooves when the wall temperature exceeds saturation. This call will start the pumping action in the CAPPMP. Once the pumping action starts, vapor will start to flow immediately into the subcooled outlet header, where it will initially collapse. This logic would not be necessary if a tank had been used or if the initial flowrate were nonzero. Because there is no initial flow in the junction, the presence of the deprimed CAPPMP tie on it has no effect: heat cannot be added into a junction that has no flow through it. No flow is present until the CAPPMP has primed—the model must be bootstrapped into action.

An STUBE will be used to represent the flow in the EP vapor grooves. It will represent a single groove, and will have duplication factors of 45 on both ends. (From the point of view of the entire system, 90 such grooves exists. This is an example of exploiting a symmetry within a symmetry.)

Because vapor is generated along the length of these grooves, the flowrate is zero at one end and increases linearly toward the exhaust end. Therefore, the STUBE will be modeled at only half the actual length, and will carry the full flowrate. This is the “half-length” method described in the main volume (Section 3). The acceleration of the fluid due to the radial injection is taken into account with an AC factor. This optional acceleration results in approximately 20% added pressure drop in this case. A similar factor applies to the vapor header, although in this case the factor is an approximation because the “injection” is not uniform. The vapor header is also assumed to be stagnant.

A thermal model is needed to describe the evaporator and outlet header structure. (Similar models of the inlet structure are neglected because of negligible temperature changes and small single-phase heat transfer coefficients.) Three nodes are needed for the evaporator wall, the exhaust line, and the vapor header wall. To avoid small diffusion nodes, the exhaust line will be an arithmetic node and its mass will be lumped into the adjacent header node. Small axial conductors are added between these nodes. The addition of such conductors, while having a negligible impact on system response, has the benefit of complying with a SINDA requirement that no node be thermally isolated even if it is tied to a fluid lump. Otherwise, a single node could have been used. Because two exhaust lines exist from the point of view of the header, dual one-way conductors will be used for that connection. This is the SINDA equivalent of the FLUINT duplication factors, and could be avoided by the use of tie duplication factors.

A fluid tie will be made between the exhaust line node and the junction inside. This is the reason for the use of an STUBE connector for this line even though the pressure drop is negligible: it facilitates heat transfer calculations. Similarly, a tie is made between the header wall node using an STUBE connector representing the half-length of the header. Because of the half-length assumption, an area fraction of 2.0 is applied to the tie to return the heat transfer area to its full value. An additional estimated factor is applied to increase the heat transfer due to the impingement of the exhaust flow on the opposite wall of the vapor header and the related increased mixing of the fluid. Otherwise, a fully-developed convection correlation would underpredict the heat transfer coefficient. Although the acceleration in the header is included, the real purpose of the STUBE is to facilitate heat transfer calculations, not to accurately model the small pressure losses in the header.

Surprisingly, the behavior of the exhaust line and header walls is critical to the successful start-up of the loop. These provide the thermal inertia required to *slowly* clear the vapor header of liquid. With adiabatic boundary conditions in this part of the loop (or too-warm walls or too rapid heating), the CPL deprimes while clearing fluid out of the vapor header due to the large transient resistance through the condenser. A cold wall helps condense some of the excess vapor from the evaporator, giving the header time to empty.

The names and types of the network elements composing the total model are summarized below, and shown schematically in Figure E-4:

CPL FLUID SUBMODEL:

PLENUM 99	Reservoir (stagnant)
STUBE 99	Reservoir connecting line, plus exit loss into reservoir
TANK 10	Inlet (liquid) header (stagnant)
CAPIL 300	Isolator wick
TANK 20	Liquid inside of EP (stagnant)

CAPPMP	EP
JUNCTION 1000	Center junction
”NULL” 1000,2000	Inlet and outlet specialized connectors
JUNC 30	Evaporator groove
STUBE 30	Evaporator groove, half length
JUNC 35	Evaporator outlet, exhaust line
STUBE 35	Vapor exhaust line
TANK 40	Outlet (vapor) header (stagnant)
STUBE 40	Vapor header line, half length
JUNCTION 50	Condenser inlet
JUNCTIONS 1-9	Condenser/subcooler
STUBES 1-10	Condenser/subcooler, plus contraction and bend losses
JUNCTION 100	Condenser outlet
STUBE 100	Liquid return line

EVAP THERMAL SUBMODEL:

NODE 1000	Evaporator wall
NODE 1500	Exhaust line wall, arithmetic
NODE 2000	Vapor header wall, contains mass of #1500
CONDUCTOR 1000	Evap to exhaust (both ways)
CONDUCTOR 1500	Exhaust to header (one way, double value)
CONDUCTOR 1501	Header to exhaust (one way, single value)
CONDUCTOR 2000	Header to plate inlet (both ways)

PLATE THERMAL SUBMODEL:

NODES 1-9	Condenser/subcooler piping
NODES 11-19	Condenser plate
NODE 300	Sink (boundary)
CONDUCTORS 1nn	Tube to plate
CONDUCTORS 3nn	Plate to sink
CONDUCTORS 2nn	Plate to plate, perp. to flow (tube to tube)
CONDUCTORS 4nn	Plate to plate, flowwise (axial)

E.3 The Input File

The input file is provided on the following pages.

To demonstrate restart options, this analysis is performed in two parts. The first run covers the first two minutes of real time, after which a restart file is produced. The second run starts by reading in the restart file and finishing the last forty minutes of analysis. Only the input file for the first run is shown; the input file for the second run can be generated from this file by commenting out two statements and uncommenting two others, as shown in the first two header blocks of the input file.

Restart options are often used to save steady-state results, or as in this case, to break up a large run into smaller parts to avoid losing results due to machine failures. When restarting FLUINT models, *all* parameters must be saved and replaced. Only global user data is never replaced to aid

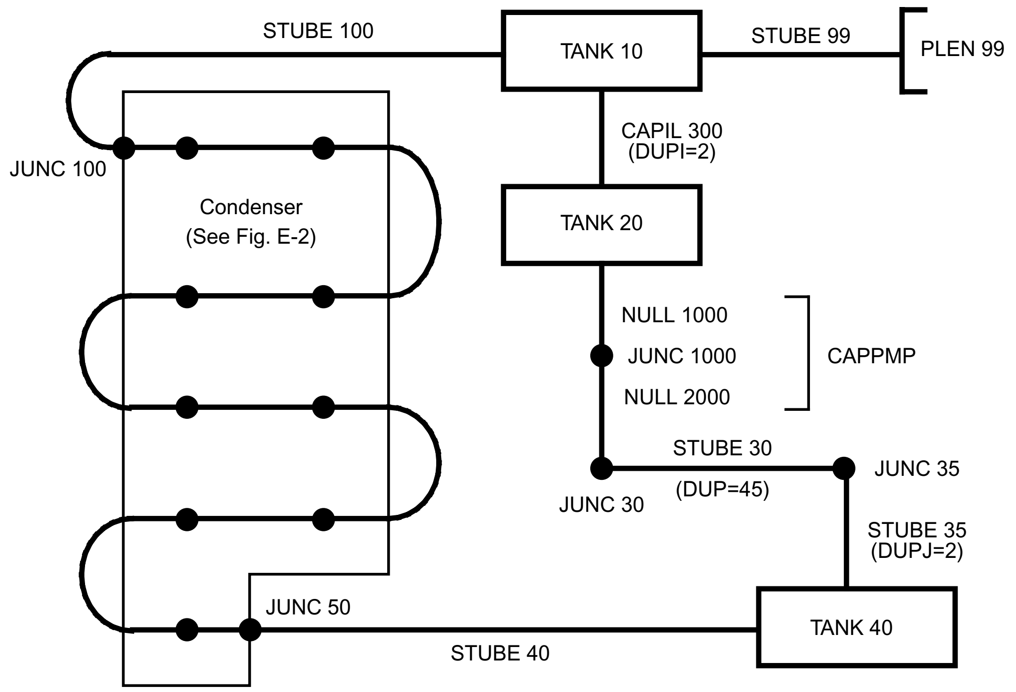

Figure E-4 Schematic of FLUINT Network

logical control of restarts. The basic restriction behind restarts is that the model must be the same as that saved. No elements, user data, or arrays can be added or deleted (although values can change).

OPTIONS DATA—As with previous examples, a summary file is written to USER1. Also, a QMAP file is named to contain output from an optional FLOMAP call. For the first run, a restart output (RSO) file is named. This file is used as a restart input (RSI) file for the second run.

CONTROL DATA—The unit system will be SI, with temperature in units of degrees Celsius. The problem will run for 42 minutes, with output produced at 6 second intervals for the first run, and then two minute intervals thereafter (in the second run). Because a single thermal model OUTPUT CALLS will be used, the fluid model output interval, which is required, is set to a large number. A maximum time step of 10 seconds is allowed.

USER DATA—Two variables (TSAT and IFLAG) are used to mediate the initialization of the CAPPMP when the evaporator wall temperature exceeds the saturation value for the first time. The evaporation UA will be initially zero, and then replaced with UAEVAP when the CAPPMP is started. Note that single-phase heat transfer is neglected since the system flowrate will be negligibly small until the CAPPMP starts pumping.

The NTEST variable is used to control the restart logic. For the first run, NTEST is zero. The tail end of the output for the first run lists record or “key” 236 as being written. This value is then used for NTEST during the second run to both signal an available restart file and to “unlock” the appropriate event saved in that file.

FLOW DATA—The default is set to be subcooled liquid at 6.6°C. The pressure could be estimated and then overwritten later (via CHGLMP calls in OPERATIONS) to exactly correspond to saturation at 29°C, but instead the PL! option is used to mandate the desired pressure, which was determined by previous runs but could have been adequately determined from saturation tables. The default diameter and flow area correspond to that of the grooved condenser, which is the most common pipe size used. The initial flowrate is assumed to be zero.

A small compliance is used in the inlet tank (#20) to avoid unrealistic pressure spikes in an otherwise fixed-volume liquid tank. Such a compliance is optional in the tank located at the end of the condenser (Tank 10). Note that the vapor header compliance is larger than those of the other tanks. This helps prevent unrealistic surges in pressure when the tanks first starts to boil and vapor displaces liquid. Ordinarily, this surge lasts only a few time steps until the rest of the system can adjust. However, in a capillary model such surges may cause the device to deprime.

The evaporator section is defined first, including the ties to the corresponding thermal nodes. The upstream end of the CAPIL connector is assigned a duplication factor of 2.0 (DUPI), while the downstream end of the CAPPMP macro (DUPJ) is assigned the same value. This means that adding 255W to the CAPPMP junction is equivalent to adding 510W to the whole system. Note that in the calculation of CFC for the isolator and the evaporator wick, the logarithmic form of the “conduction” equation is used. The CFC through a cylindrical wick is given in the manual as $2 \bullet \pi \bullet P \bullet L/\ln(r_o/r_i)$, where P is the permeability, L is the length, and r_o and r_i are the outer and inner radii of the tube, respectively.

When the CAPPMP is defined, an HTM tie is made to the evaporator wall node. The UA value is zero until the wall temperature exceeds saturation and evaporation can commence. This tie will actually exist as an HTU tie on junction 30, the default vapor side, until the CAPPMP primes. The tie will then jump to the CAPPMP junction and become an HTM tie. In either case, the user may reset the UA value. Note also that XVH and XVL are set below the default values. This makes the CAPPMP more resistant to deprime caused by liquid in the outlet.

The STUBE representing the vapor grooves is assigned one half of the real length because of radial injection, as is the header STUBE. Similar methods could have been used in the liquid header and the liquid passage inside the EP wick if these had been modeled.

The condenser/subcooler is generated with a centered HX macrocommand. Note that the last condenser leg (the subcooler) is spaced farther apart than the other legs. This difference is neglected to facilitate input using one HX command. K-factor losses are to be added for the inlet contraction and the bend losses, but these cannot be added to the HX command or they would be applied to every generated connector. Instead, the FK and CURV values are initialized later in OPERATIONS for selected connectors in the macro.

The initial state of the condenser is subcooled liquid. Being composed of junctions, the state inside the condenser will change instantly when the flow starts moving. Recall that DH and AF must be explicitly defined in an HX or LINE macro via the DHS and AFS input keywords. DEFF is optional, and defaults to DH (or DHS) if it is absent.

The reservoir will exchange only saturated liquid with the system. While the plenum could be initialized in that state by setting a zero pressure and XL=0.0, here the quality is set to 0.1 and liquid suction is used on the connecting line. The RLS option is used since the plenum is on the defined downstream end of the line. Alternatively, the positive flow direction could be chosen as *from* the plenum, and the LS option would then be specified.

NODE DATA—In the PLATE submodel, the sink and the tube and plate nodes are generated. Note that the difference is capacitance between tube nodes was neglected, while the capacitance of the different sizes of plate nodes was input faithfully. In the EVAP model, the three evaporator and outlet wall nodes are defined. The initial temperatures are all 6.6°C.

CONDUCTOR DATA—In the PLATE submodel, the differences between the tube node locations are neglected for the conductances to the plate, while the plate-to-plate and sink-to-plate conductors take size differences into account. The axial tube conduction, while almost negligibly small, is added into the axial plate conduction term. In the EVAP submodel, small axial conductors are used, one of which connects to the inlet of the condenser. Note the use of dual one-way conductors to be consistent with the symmetries exploited in the adjacent fluid submodel.

FLOGIC 0—Logic is used to “kick start” the CAPPMP when the wall temperature exceeds saturation. DTMPCA is used to prevent the thermal model from stepping too far past this important transition. The minimum allowable time step is then adjusted to allow smaller time steps during the sudden purge event, but to require larger time steps at other times. Time steps cannot be specified: DTMINF simply states the minimum affordable time step below which the program should produce output and halt.

FLOGIC 1—In case of difficulties in modeling, preventative logic is added here to detect deprime in the EP. When a CAPPMP is primed, the GK values of the NULL connectors are zero. All such FLUINT “set-up” calculations, such as the updating of junctions, lump QDOTs, and connector GK and HK values are performed between FLOGIC 0 and FLOGIC 1. This fact is exploited here in combination with a check on the UA value. If the CAPPMP has just deprimed, a FLOMAP and other outputs are written to help the user debug the inputs, and FLOGIC 2 will terminate the run. Such preventative measures are invaluable in the process of arriving at a reasonable model.

FLOGIC 2—If the CAPPMP deprimes, the run will be terminated as signaled by resetting TIMEND. TIMEND should not be reset in FLOGIC 0 or 1 to avoid nonpositive time steps.

VARIABLES 1—The only calculation performed here is the update of the sink temperature as a function of time. This could have been placed within the definition of the node in NODE DATA.

OUTPUT CALLS—Lump, path, and tie tabulations are written each output interval along with nodal temperatures. The summary file contains the temperatures for the first 7 pipe nodes, along with pressure gain and flowrate information. After two minutes of simulation, the output interval is increased to two minutes.

OPERATIONS—After building both the thermal submodels and the fluid submodel as one configuration, the first order of business is initialize the condenser FK and CURV values.*

Second, NTEST is checked to see if this is the first or second run. If a restart run is available, the results previously saved from the first run are loaded back into the program. Output intervals and time step controls are *subsequently* readjusted to reflect the relatively calm network that can be expected after the system has started. Note that if these constants had been reset *before* the call to RESTAR, the values would have been overwritten by the RESTAR call. Because named user constants are not saved or restarted, IFLAG must be manually reset to signal that the CAPPMP has already started. For the same reason, the initialization of TSAT need only be performed once. TSAT will be very close to 29°C. When the header for the user file has been written, FWDBCK ("TRANSIENT") is called to start the transient integration (or finish it, in the case of the second run). If this is the first run (signaled by zero NTEST), results are saved in the RSO file for use in the second run.

SUBROUTINES—The replacement version of ROHSEN was copied from the processor library, modified to include Kamotani's grooved heat transfer correlation in the special case where the flow area exactly matches that of the condenser extrusion (and the quality is not too much to flood the central passage), and appended to the input file as SUBROUTINES. This file could also be inserted. SPELLOFF and FSTOP commands are used before this routine to turn off the spell checker and the translator, respectively.

E.4 Output Description

The user summary files and selected printings from the OUTPUT files of the two runs are provided on the pages following the input listings.

As a preliminary remark, note that the difference in pressures between the CAPPMP lumps does not include the pressure drop though the wick itself when the device is primed. This pressure drop is taken into account internally by the CAPPMP model to determine the pressure differential at the liquid/vapor interface.

With regards to the start-up transient (see Figure E-5), the CPL primes and begins to pump after about 12 seconds. The vapor header reaches saturation and begins to empty after about 20 seconds. The system has nearly achieved a hydrodynamic steady-state after about 30 seconds, which is clearly negligible compared to the total experimental run if the user is simply interested in overall thermal response. In fact, *much of the computational cost of this run is incurred between 20 seconds and 30 seconds,* during the relatively explosive clearing of the vapor header.

However, the events that occur within the first few seconds are very important from the viewpoint of a CPL designer. As noted before, if the user neglects the thermal inertia in the plumbing at the outlet of the evaporator, the CPL will deprime because it is unable to provide sufficient head to transiently clear the outlet of liquid. In other words, to avoid excessive pressure rises in the outlet, the *volumetric* flowrate of the saturated fluid that enters the condenser (flowing to the reservoir) must equal the *volumetric* flowrate of the saturated vapor being generated in the EPs. This implies a substantial transient flowrate through the condenser, roughly equal to the mass flowrate through the evaporators (~4e-4 kg/s) times the ratio of liquid to vapor densities (~600/8.8 = 68) for a total transient flowrate of approximately 2.8e-2 kg/s. Even neglecting the inertia in the condenser and reservoir

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* Sinaps*Plus* and FloCAD users would find it easier to apply the FK and CURV values to the correct macro elements directly. Such individual editing of network elements within a macro is not supported by SINDA/FLUINT.

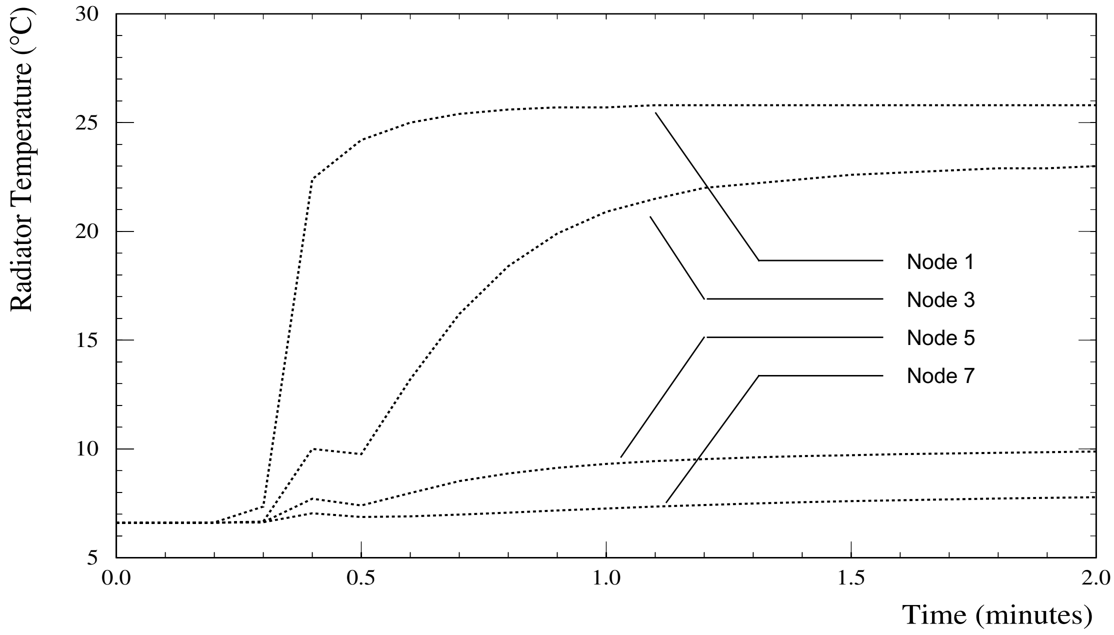

Figure E-5 Condenser Pipe Wall Temperatures: First Two Minutes

lines, the static resistance results in a pressure gradient several times greater than the pumping provided by the wick. Hence, deprime occurs. (The EP may subsequently reprime, although modeling such behavior requires a tank rather than a junction to represent the grooves.) When the heat transfer to the cold outlet plumbing is included, this purge event is spread over time, reducing the peak flowrate to a manageable level: approximately 7e-3 kg/s or one fourth of the peak adiabatic value.

This implies that there is a limit on the power that can be applied to a flooded CPL, and that this limit is lower than the ultimate steady-state power limit. Furthermore, this limit decreases substantially in a CPL with negligible mass in the outlet or with initially warm walls, or with a large flow resistance in the condenser. Other phenomena help overcome this transient limit, and that the CPL may partially rather than completely deprime.

It should be apparent that the start-up of the CPL, modeling in detail, is not as trivial as it might first appear. The cost of including such detail should be apparent to the reader (see also Section E.5 for a comparison with a simplified model; note the cost of the first run covering the start-up is a significant fraction of the total cost even though the second run covers twenty times as much real time). What might not be apparent is that *the time and effort required of the user is often proportional to the computational time required by the program.* This may contradict some user's intuition that the more work left to the computer, the less work the user must perform. However, this is a "tool box" code, meant to be scalable to various levels of detail by exploiting the user's knowledge, available information, and expertise to simplify the problem. *The more detail users request and the fewer assumptions they make, the more data they must supply, and the more the accuracy of this supplied data becomes critical.*

Most of the interesting events during this start-up event are not evident because they all happen within one output interval. A common mistake in reviewing outputs is to neglect the sampling errors inherent in the requested output interval: the resulting profiles are “connect-the-dot” simplifications of the real profile, and important maxima and minima can easily be excluded.

After the start-up, the flowrate gradually increases because the temperature at the inlet of the EPs gradually rises. The CAPPMP model does not normally include any appreciable superheating of the vapor; 255W accomplished more boiling and less sensible heating as the inlet temperature approaches saturation.

Figure E-6 displays the long term temperature histories for selected pipe wall nodes, along with the bracketing flight data. The first pipe segment contains the most vapor flow and so heats up quickly, whereas the last segment only starts to enter the two-phase regime at the end of the run.

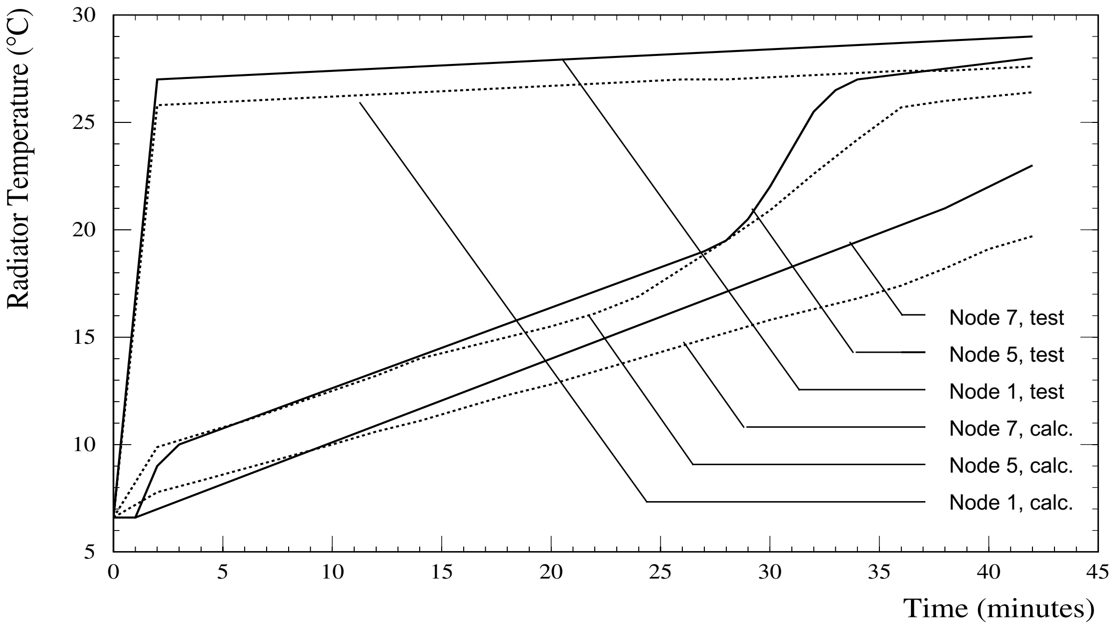

Figure E-6 Condenser Pipe Wall Temperature Histories

The latter part of this analysis is essentially a test of the condensation heat transfer correlation, and of the values of capacitance and conductance in the thermal model of the condenser. Overall, the comparison is adequate—the trends are the same over the same time scales even though the lines do not lie on top of each other. Like the flight article, segment 7 just begins to enter the two-phase region 42 minutes after heat is applied. However, the simulation consistently falls about 2°C short of the flight data, especially at the inlet of the condenser (segment 1).

This difference is due either to overestimation of the pipe-to-sink conductance, overestimation of the pipe/plate capacitance, significant superheating, or to an effective reservoir pressure that is higher than the initial value (saturation at 29°C), or perhaps combinations of all four. Evidence for the last two reasons (superheat and/or increased set point) is the fact that the tubes became as hot as

30°C during the flight test, which implies that the fluid temperature must have been even warmer. In the FLUINT model, the fluid was never warmer than 29°C because superheating was neglected and the reservoir was assumed to maintain a constant 29°C temperature. The most likely explanation is the lack (in the model) of nonequilibrium compression of the vapor in the reservoir, which raises the set point temporarily (but perhaps long enough for this entire event). Better characterization of both the nonequilibrium reservoir response and the superheat in the evaporator would require more information and more detailed models. The data in this example was taken from the User's Manual for a now-abandoned computer program specifically designed to analyze CPLs. It is interesting to note that the predictions made by that program closely match those made by FLUINT, including falling short of the inlet pipe temperature by at least the same margin.

The above comparison is made using best-guess data. In "PROBLEM E VARIATION: CORRELATION TO TEST DATA" on page 41, an automated correlation is performed varying four of the uncertainties presumed to be most important in this best-guess data, with substantially improved comparisons resulting from this calibration step.

Examination of the output file reveals some warnings produced during the first run. A message is printed to notify the user that the isolator and the evaporator have deprimed because they are surrounded by liquid. These can be easily be ignored. The isolator never was primed and never should be. The evaporator is not primed until the liquid is cleared from one side, at which time a reprime advisory is printed. Note that a capillary device can still block vapor flow if deprimed unless the pressure difference exceeds the capillary limit. In the FLUINT sense, “primed” means either stopped flow (all vapor on one side and adiabatic) or a flowrate proportional to the heat input and *independent of pressure gradient.*

Another message warns that “discontinuities in flow rates” have been detected. This too can be ignored since the velocities are so small that abrupt changes in flow area do not need separate models of the reduction or contraction process.

E.5 A Simplified Model for Comparison

As noted above, the real focus of this comparison is the condenser and radiator response. The above model can be tremendously simplified and still yield similar results if the start-up event is neglected. Such streamlined models are important for uses such as optimization and automated test data correlation, as will be performed in a later subsection. An input file for such a simplified analysis is provided after the input file for the detailed case.

Almost all details in the evaporator have been neglected. The evaporator pump is modeled simply as an MFRSET connector that pumps through a heater junction set for saturated vapor. Heater junctions are named by calls to HTRLMP. The flowrate is adjusted according to the difference in enthalpies between saturated vapor (as given by the enthalpy of the heater junction) and the enthalpy of the subcooled inlet. The inlet is represented by a tank containing the volume of the entire system. (Actually, since the vapor sides are swept clear fairly early in the transient, this volume should really be reduced to include only the liquid portions.) This model simply takes into account decreased subcooling in the inlet, which is a second-order correction needed to assure that the power input does not drift from 510W total. (The enthalpy in a heater junction is fixed and the QDOT required to maintain that state is calculated instead of being specified via QL or ties or fties.)

The thermal model of the evaporator section has been dropped, along with any detailed descriptions of flow losses. Because an MFRSET and heater junction representation of a capillary pump cannot deprime, such details are meaningless. The thermal model of the plate and the fluid model of the condenser are exactly the same as above. Thus, most of the fluid model is really used to set the correct boundary conditions for the condenser.

An fast but limited-range description of ammonia was used to greatly reduce run time with virtually no loss of detail or accuracy. The FPROP block was produced using RAPPR[*] and is exact at 29°C, the constant saturation condition in this example. The range is determined by the error tolerance input to RAPPR: in this case 20% for liquid properties and 10% for vapor properties. The limiting factor in the range limit is usually liquid specific heat. Note that such large error tolerances do not affect the results, which closely match predictions made using the full library ammonia description (FID=717). This invariance is due to the dominance of two-phase energy exchange compared to single-phase exchange—the heat of vaporization is exact, and large errors in the liquid specific heat are negligible.

The same time savings could have similarly applied to the full model discussed previously. This alternate description and methods for producing similar 6000 series descriptions are discussed in the main volume of the User's Manual. The PR8000 and PR9000 routines may also be used to produce simplified 8000 (gas only) and 9000 (liquid only) descriptions of standard library fluids.

Unlike the full model described in previous sections, a steady-state analysis is performed before the transient in this abbreviated model. The purpose of this steady-state is to initialize the flowrate and its associated effects throughout the system. Otherwise, smaller time steps will result in the transient because of poor initial conditions. To preserve the correct initial temperatures of the thermal submodel, DRPMOD and ADDMOD are used to place the thermal submodel into a boundary state during the steady-state run. (Alternatively, only the diffusion nodes need be held, and this can be accomplished using a call to HTRMOD and RELMOD instead.)

As with the restarted run in the previous model, the main time step limit was caused by SINDA: the characteristic time of the condenser (CSGMIN) was very small compared to the run time. (FLUINT UA's are summed into the SINDA CSGMIN product, but ties are not otherwise treated like conductors in transients.) Requiring the use of diffusion nodes for the pipe itself is therefore the main cause of the time step limit. Replacing these pipe nodes with arithmetic nodes (as is done in this example) and moving their mass to the adjacent plate nodes ***reduces the run time threefold with no difference in results.***

The results are nearly indistinguishable from results of the previous run. However, the computational cost for this run was a small fraction of the cost of the full model, not counting the savings in engineering time. This should help illustrate the importance of avoiding unnecessary details with

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[*] As of Version 4.7, RAPPR has been obsoleted, having been replaced by utilities PR8000 and PR9000. The ability of RAPPR to make a simplified two-phase fluid has therefore been lost, but this feature was rarely if ever utiltized due to the dominance of large tabular-style 6000 series FPROP blocks. The RAPPR-generated block referred to in this example problem has been left in place since it serves as an example of a 6000 series FPROP block that is very unlike the common tabular-style blocks.

FLUINT. Frivolous details are much more easily tolerated in a thermal model, where the phenomena are simpler and the response times generally orders-of-magnitude larger. **If you don't need it, don't ask for it. If you don't know it, don't include it.**

Input File

```
HEADER OPTIONS DATA
TITLE FLUINT SAMPLE MODEL 5 - CPL GET AWAY SPECIAL (GAS) EXPERIMENT
C FIRST RUN ++++++++++++
C         RSO      = cplgas.rsi
C         OUTPUT   = cplgas.out
C         USER1    = cplgas.usr
C SECOND RUN ++++++++++++
          RSI      = cplgas.rsi
          OUTPUT   = cplgas2.out
          USER1    = cplgas2.usr
C
C EMERGENCY MAP FILE
          QMAP     = cplgas.map
C
HEADER CONTROL DATA, GLOBAL
          UID      = SI
          ABSZRO   = -273.16
          TIMEND   = 120.0            $ START FIRST TWO MINUTES
          OUTPUT   = 6.0              $ OUTPUT EVERY 6 SEC. INIT.
          OUTPTF   = 1.0E30           $ FAKE OUTPUT FOR FLUINT
          DTMAXF   = 10.0             $ MAX 10 SEC TIME STEP
C
HEADER USER DATA,GLOBAL
C FIRST RUN ++++++++++++
C         NTEST    = 0                $ RESTART FLAG: SET TO RECORD
C SECOND RUN ++++++++++++
          NTEST    = 143              $ RESTART FLAG: SET TO RECORD
          TSAT     = 29.0             $ SATURATION PRESSURE
          IFLAG    = 0                $ FLAG FOR KICK START OF CAPPMP
C FOR EVAPORATION, USE 2500 W/M2-K AND OUTER WICK AREA
          UAEVAP   = 2500.0*0.0889*0.02286*pi
```

```
HEADER FLOW DATA,CPL,FID=717                 $ START LOOP DESCRIPTION
C
C SET MODEL DEFAULTS
C SET PRESSURE FOR ALL LUMPS AT SATURATION FOR 29C
C
LU DEF,  TL = 6.6,PL! = 1.1323E6, XL = 0.0
PA DEF, FR = 0.0                             $ SHUT DOWN INITIALLY
C
C 0.0153 SQ IN TOTAL GROOVE AREA
C FOR 1-PHASE GROOVED LINE, USE HYD DIA ASSUM, AF = TOTAL
C PERIMETER = 16*3*0.034 + 16*0.014” = 1.856” = 4.71E-2 m
C FLOW AREA = 16.0*6.17E-7 + 0.25*PI*4.699E-3**2 = 2.72E-5
C
         DH = 4.*2.72E-5/4.71E-2             $ DH FOR MOST PIPING
         AF = 2.72E-5
C
C DEFINE TANKS IN EVAPORATOR
C
LU TANK,10,VOL = 54.1E-6, LSTAT = STAG       $ LIQUID HEADER (COLD)
LU TANK,20,VOL = 25.4E-6, LSTAT = STAG       $ ONE EVAP PUMP (LIQUID)
                  COMP = 0.01/PL#this        $ GUESS
C
C ADD DUPED VAPOR GROOVES AND LINE OUT OF EVAP PUMP (DUPED DOWNSTR)
C
LU JUNC,30
C
C VAPOR GROOVES (45 TOTAL)
C
PA CONN,30,30,35,DUP = 45.0
         DEV = STUBE
         TLEN = 0.0889/2.0          $ USE HALF LENGTH ASSUMPTION
         DH = 1.4E-3
         AF = 1.5E-6
         UPF = 1.0
         AC = -1/(DL#up*AF#this^2)  $ ACCEL IN GROOVES
LU JUNC,35
C
C LINE TO HEADER
C
PA CONN,35,35,40
         DUPJ = 2.0                 $ DOWNSTREAM DUPED TWICE
         DEV      = STUBE
         TLEN = 0.079
         DH = 6.6E-3,AF = -1.0
         UPF = 1.0
C
C TIE OUTLET LINE TO HEADER MASS
C
T HTN,35,35, EVAP.1500, 35
```

```
C
C THE FOLLOWING COMPLIANCE IS VERY LARGE BUT THIS DOESN'T
C MATTER SINCE THE RATIO OF THE CAPILLARY PRESSURE HEAD
C TO THE ABS PRESSURE IS SMALL. MAX VOL CHANGE ABOUT 0.2%
C THIS ASSURES MINIMAL SURGE FOR TRANSITION TO TWO-PHASE
C TO PREVENT ARTIFICIAL DEPRIME
C
LU TANK,40,VOL = 20.0E-6            $ VAPOR HEADER
         COMP = 1.0/PL#this         $ MORE COMPLIANCE FOR TRANSITION
         LSTAG = STAG
C
PA CONN,40,40,50,DEV = STUBE,UPF= 1.0
         TLEN = 0.127,DH = 0.0141,AF = -1.0
         AC = -1/(DL#up*AF#this^2)  $ ACCEL IN MANIFOLD
C
C TIE HEADER TO MASS TO ADD THAT INERTIA.
C USE AREA FRACTION OF 2.0 TO RETURN TO FULL AREA
C THEN MULTIPLY BY FACTOR OF 2.0 FOR IMPINGEMENT AND
C MIXING EFFECTS IN OUTLET
C
T HTN,40,40,EVAP.2000,40, 2.0*2.0
C
LU JUNC,50
C
C DEFINE CAPILLARY DEVICES IN EVAPORATORS
C (LIQUID LINES IGNORED AS NEGLIGIBLE COMPARED TO WICK DROPS
C
PA CONN,300,10,20, DUPI = 2.0       $ UPSTREAM DUPED TWICE
         DEV = CAPIL
         RC = 1.65E-5
C HALF OF CFC FOR ONE HALF OF ISOLATOR
         CFC = 2.0*pi*0.1270*2.6E-13/ln(2.134/1.113)/2.0
C
M CAPPMP,2,TIE,1000,1000,2000,20,30,1000,EVAP.1000,
         RC = 1.65E-5
         CFC = 2.0*pi*0.0889*2.6E-13/ln(2.286/1.113)
         XVH = 0.95                 $ 95% DRY IS ENOUGH TO PRIME
         XVL = 0.9                  $ 90% DRY IS TOO WET TO PRIME
         UA = 0.0                   $ OFF UNTIL WALL HOT ENOUGH
C
C DEFINE CONDENSER: 9 CENTERED SEGMENTS OF 1.57 M TOTAL LENGTH
C
M HX,1,C,1,1,1,PLATE.1,50,100,NSEG = 9       $ VAPOR LINE
         TLENT = 1.57
         DHS = 4.*2.72E-5/4.71E-2
         DEFF = 0.005
         AFS = 2.72E-5
         LU = JUNC,PA = STUBE       $ LOW TEMPORAL RESOLUTION
C
```

```
C DEFINE CONDENSER OUTLET JUNCTION
C
LU JUNC,100
C
C ADD 15 CM LINE TO LIQUID HEADER
C
PA CONN,100,100,10,DEV = STUBE,TLEN = 0.15
         DEFF = 0.005
C
C FINALLY, ADD RESERVOIR AND LINE BETWEEN IT AND LIQUID HEADER
C INITIALIZE PLENUM AS TWO PHASE BUT USE LIQUID SUCTION
C (EASY WAY TO GET SATURATED LIQUID)
C
LU PLEN,99,TL = 29.0, XL = 0.1                $ SAT LIQUID
C        VOL = 2.8E-4                         $ IF WERE TANK
         LSTAT = STAG
C
PA CONN,99,10,99, STAT = RLS                  $ LIQ FROM PLEN SIDE
         DEV = STUBE,TLEN = 0.70              $ 70 CM
         DEFF = 0.005
C
HEADER NODE DATA, PLATE
C
C BOUNDARY
         -300,6.6,0.0
C
C PIPE NODES
C
         GEN,1,9,1,6.6,85.9/9.0
C
C RADIATOR NODES
C
         11,6.6,230.3                         $ FIRST HALF PASS
         GEN,12,4,1,6.6,216.75                $ NEXT TWO PASS
         GEN,16,4,1,6.6,289.0                 $ LENGTH TWO PASSES
C
HEADER NODE DATA, EVAP
C
C  WALL OF EVAPORATOR
         1000,6.6,137.7
C  WALL OF OUTLET LINE
         1500,6.6,-1.0
C  WALL OF HEADER/OUTLET (INCLUDE EXHAUST MASS)
         2000,6.6,15.0
C
```

```
HEADER CONDUCTOR DATA,EVAP
C
C CONDUCTANCE EVAP TO OUTLET LINE MASS
         1000,1000,1500,0.04
C
C CONDUCTANCE TO HEADER NODE MASS
C NOTE DUAL ONE-WAY CONDUCTORS MEAN THAN PLATE SEES TWO EVAPS.
C
         1500,-1500,2000,2.0*0.04              $ HEADER SEES 2 EVAP
         1501,1500,-2000,1.0*0.04              $ EVAP SEES 1 HEADER
         2000,2000,PLATE.1,0.1                 $ COND SEES 1 HEADER
C
HEADER SOURCE DATA, EVAP
C
         1000,255.0                            $ 255W (510W TOTAL)
C
HEADER CONDUCTOR DATA, PLATE
C
C BOUNDARY TO PLATE THROUGH COTHERM
C 63% and 51% FIN EFFICIENCIES
C
         301,11,300,25.6*0.63
         GEN,302,4,1,12,1,300,0,24.4*0.63
         GEN,306,4,1,16,1,300,0,32.4*0.51
C
C RADIAL: TUBE WALL AND SADDLE WELD
C
         GEN,101,9,1,1,1,11,1,17.2
C
C AXIAL: ALONG FLOW DIRECTION
C
         423,12,13,0.85
         445,14,15,0.85
         467,16,17,0.85
         489,18,19,1.13
C
C SIDE: ACROSS FLOW DIRECTION
C
         212,11,12,5.28
         224,12,15,5.28
         235,13,14,5.28
         247,14,17,5.28
         256,15,16,5.28
         279,17,18,3.17
         268,16,19,3.17
C
```

```
HEADER FLOGIC 0, CPL
C
         IF(IFLAG .EQ. 0)THEN
                  IF(EVAP.T1000 .GT. TSAT)THEN
C EMPTY OUTLET JUNCTION AND START EVAPORATION TO KICK START CAPPMP
                           IFLAG             = 1
                           UA1000            = UAEVAP
                           CALL SPRIME('CPL',20,30,RC1000,1)
                  ELSE
C KEEP EVAP NODE FROM OVERSHOOTING SATURATION BY MORE THAN 1 DEGREE
                           EVAP.DTMPCA       = TSAT + 1.0 - EVAP.T1000
                  ENDIF
         ELSE
                  EVAP.DTMPCA     = 5.0
         ENDIF
C
C ALLOW SMALL TIME STEP DURING CLEARING PROCESS,
C SHOULD TAKE BIGGER STEPS AFTER RESTART
C
         IF(XL40 .GE. 1.0 .OR. XL40 .LE. 0.0)THEN
                  DTMINF            = 1.0E-3
                  IF(NTEST .NE. 0) DTMINF= 1.0E-2
         ELSE
                  DTMINF            = 1.0E-5
         ENDIF
C
HEADER FLOGIC 1,CPL
C
C THIS LOGIC PRINTS A FLOMAP AND OTHER OUTPUT IF THE
C EVAPORATOR PUMPS DRY-OUT OR DEPRIME
C FLOGIC 2 WILL SIGNAL STOP
C
         IF(UA1000*GK1000 .GT. 0.0) THEN
                  CALL LMPTAB('ALL')
                  CALL TIETAB('ALL')
                  CALL PTHTAB('ALL')
                  CALL FLOMAP('ALL',1)
         ENDIF
C
```

```
HEADER FLOGIC 2,CPL
C
C THIS LOGIC STOPS SIMULATION IF THE
C EVAPORATOR PUMPS DRY-OUT OR DEPRIME
C
         IF(UA1000*GK1000 .GT. 0.0)  TIMEND= TIMEN
C
HEADER VARIABLES 1, PLATE
C
C UPDATE SINK TEMPERATURE LINEARLY
         T300              = 6.6 + (17.0 - 6.6)*TIMEM/(42.0*60.0)
C
HEADER OUTPUT CALLS,PLATE
         CALL LMPTAB('ALL')
         CALL TIETAB('ALL')
         CALL PTHTAB('ALL')
         CALL TPRINT('ALL')
         WRITE(NUSER1,10)TIMEN/60.0,T1,T2,T3,T4,T5,T6,T7
     .      ,CPL.PL30-CPL.PL20,CPL.FR40
10      FORMAT(1X,1PG11.4,4X,8G10.3,2G11.4)
C
```

```
HEADER OPERATIONS
C
BUILD GAS,PLATE,EVAP
BUILDF GAS,CPL
C
DEFMOD CPL
C
C ADD LOSS FOR SUDDEN CONTRACTION AT INLET OF CONDENSER,
C AND 4 CONDENSER BENDS IN APPROXIMATE LOCATION
C
         FK1      = 0.37
         CURV3    = 0.0572
         CURV5    = 0.0572
         CURV7    = 0.0572
         CURV9    = 0.08
C
C CHECK TO SEE IF THIS IS SECOND RUN (RESTART)
C
         IF(NTEST .NE. 0)THEN$ IF RESTART AVAIL:
                  CALL RESTAR(NTEST)          $ RESET NETWORK
                  IFLAG    = 1                $ CAPPMP ALREADY GOING
                  TIMEND   = 42.0*60.0        $ FINISH 42 MINUTES
                  PLATE.OUTPUT = 120.0        $ TWO MINUTE OUTPUT INTVL
                  CPL.OUTPTF = 120.0          $ TWO MINUTE OUTPUT INTVL
         ELSE
                  TSAT     = VTS(PL99-PATMOS,CPL.FI) + ABSZRO
         ENDIF
C
C WRITE TRANSIENT HEADER
C
         WRITE(NUSER1,10)(MTEST,MTEST=1,7)
10       FORMAT(/' CPL - RADIATOR TEMPERATURE RESPONSE TO STEP INPUT,',
     .    ' PLUS SYSTEM PRESSURE DROP AND RADIATOR FLOWRATE'//
     .   '   TIME (MIN)',T15,7(4X,'REG.',I2),4X,'DELTA P',4X,'FLOWRATE'/)
C
C RUN TRANSIENT (FINISH FOR RESTART RUN)
C
         CALL TRANSIENT
         IF(NTEST .EQ. 0)CALL RESAVE('ALL')
C
```

```
HEADER SUBROUTINES
SPELLOFF
FSTART
C
C USE MODIFIED ROHSENOW CORRELATION: IF AF IS EQUAL TO CORRECT
C VALUE AND XL IS GREATER THAN 0.025, THEN USE KAMOTANI'S
C AVERAGED WITH ROHSEN ELSE BLEND INTO ROHSENOW AT LOW QUALITY
C
         REAL FUNCTION ROHSEN(WA,D,AF,TW,P,T,X,ALF,FI)
C
C Purpose:
C        ROSHENHOW'S CONDENSATION HEAT TRANSFER CORRELATION
C        (BASED ON WORK BY TRAVISS)
C
C
C Argument List Definitions:
C        WA      - Abs value of flowrate
C        D       - Diameter
C        AF      - Path flow area
C        TW      - Wall (node) temperature
C        P       - Total gas pressure
C        T       - Temperature
C        X       - Quality
C        ALF     - Void fraction
C        FI      - Fluid identifier array
C
C---------END OF DESCRIPTION -------
C
         DOUBLE PRECISION P
         REAL WA,D,AF,TW,T,X,ALF,XTTCO,CUTOFF,TKL,TLIQ,VCONDF,VISL,XNU
     .   ,VISV,RHOL,RHOV,VDL,VSV,FX,CPL,VCPF,XC,Y,REL,F2,PRL,HL,DITTUS
     .  ,XPOW,RATIO,DVAP,DLIQ,HFG,FRACT,VVISCF,VVISCV,XTT,XTTTMP,HCOND
         INTEGER FI(1),NFL
         COMMON /LSTSAT/ DLIQ,DVAP,HFG
C
C        FX       XTT
C        0.1      24.203035
C        0.15     11.023539
C        0.5      1.2684654
C        1.0      0.42202932
C        20.0     9.347339E-3
C
         SAVE XTTCO,CUTOFF
         DATA XTTCO,CUTOFF/1.2684654,0.50/
C
C ======================== MODIFICATIONS TO STANDARD LIBRARY ROUTINE
         SAVE AFG,DIAVC
         DATA AFG/2.72E-5/,DIAVC/4.7E-3/
C ========================
```

```
C
         NFL               = FI(2)
         IF(NFL .EQ. 8 .OR. NFL .EQ. 9 .OR. NFL .EQ. -1 .OR. NFL .EQ. -2
     .     .OR. NFL .EQ. -11)THEN
                  CALL ABNORM(‘ROHSEN’,FI(1),’ ILLEGAL FLUID ‘)
                  RETURN
         ENDIF
         TLIQ              = 0.75*TW + 0.25*T
C
C AVOID CALLING FOR LIQUID PROPERTIES IN VAPOR REGIME IF HEATED
C VOLATILE MIXTURE THAT INCLUDES NONVOLATILE LIQUID
C
         IF(NFL .LE. -102) TLIQ= MIN(T,TLIQ)
C
C BLEND IN WITH SINGLE PHASE
C
         IF(ALF .LT. 0.5)THEN
                  FRACT             = 1.5*ALF
                  TLIQ              = FRACT*TW + (1.0-FRACT)*T
         ELSEIF(MAX(X,ALF) .EQ. 1.0)THEN
                  TLIQ              = TW
                  TKL               = VCONDF(TLIQ,FI)
C
C USE MAX NUSSELT OF 1.0E5
C
                  ROHSEN            = 1.0E5*TKL/D
                  RETURN
         ENDIF
         TKL               = VCONDF(TLIQ,FI)
         VISL              = VVISCF(TLIQ,FI)
         VISV              = VVISCV(P,T,FI)
         IF(HFG .NE. 0.0)THEN
                  RHOL              = DLIQ
                  RHOV              = DVAP
         ELSE
                  RHOL              = VDL(TLIQ,FI)
                  RHOV              = 1.0/VSV(P,T,FI)
         ENDIF
C
C THE MARTINELLI PARAMETER WAS LISTED IN 1973 ROHSENOW/HARNETT
C HANDBOOK OF HEAT TRANSFER AS:
         XTTTMP            = (VISL/VISV)**(0.1)*SQRT(RHOV/RHOL)
C
C THIS IS THE SAME AS THAT USED IN CHEN’S EVAPORATIVE CORRELATION
C AND MANY OTHER SOURCES.  NOW, BOTH THE 1985 VERSION AND
C HESTRONI’S HANDBOOK OF MULTIPHASE SYSTEMS LIST THE VISCOSITY
C RATIO INVERTED:
C        XTTTMP            = (VISV/VISL)**(0.1)*SQRT(RHOV/RHOL)
C THE ABOVE DISAGREES WITH THE ORIGINAL PAPER (TRAVISS 1973)
```

```
C AND WILL BE IGNORED.  COEFF. IS UP TO 80% LOWER AS A RESULT.
C
         XTT                = XTTTMP*((1.0-X)/X)**(0.9)
         FX                 = 0.15*( 1.0/XTT + 2.85*XTT**(-0.476) )
         CPL                = VCPF(P,TLIQ,FI)
         PRL                = VISL*CPL/TKL
C
C OFFICIALLY, BREAKPOINTS ARE 50 AND 1125.  USE FOLLOWING FOR LESS
C DISCONTINUITY IN REYNOLDS NUMBER
C
         IF(FX .LT. CUTOFF) THEN
                  Y                  = (XTTCO/XTTTMP)**(1.0/0.9)
                  XC                 = 1.0/(1.0 + Y)
                  REL                = WA*(1.0-XC)*D/(AF*VISL)
         ELSE
                  REL                = WA*(1.0-X)*D/(AF*VISL)
         ENDIF
C
         IF(REL .GE. 1200.0)THEN
                  F2                 = 5.0*PRL + 5.0*ALOG(1.0+5.0*PRL)
     .                               + 2.5*ALOG(0.0031*REL**(0.812))
         ELSE IF( REL .GE. 52.3 )THEN
                  F2                 = 5.0*PRL + 5.0*ALOG(1.0 + PRL*
     .                               (0.09636*REL**(0.585)-1.0))
         ELSE
                  F2                 = 0.707*PRL*SQRT(REL)
         ENDIF
C
         HL                 = DITTUS(WA,D,AF,TW,P,T,0.0,FI)
C
         IF( FX .GE. 1.0) THEN
C
C        SKIP TRANSITION TO SINGLE-PHASE VAPOR (INHERENTLY STABLE)
C        JUST AS TRANSITION TO SINGLE-PHASE LIQUID IS STABLE FOR BOILING
C
                  XNU                = FX**(1.15)*PRL*REL**(0.9)/F2
                  HCOND              = MIN(1.0E5,XNU)*TKL/D
         ELSEIF( FX .GE. CUTOFF )THEN
                  XNU                = FX*PRL*REL**(0.9)/F2
                  HCOND              = XNU*TKL/D
         ELSE
C
C LOW QUALITY, INTERPOLATE WITH LIQUID DITTUS
C MAKE SURE TWO PHASE H IS >= SINGLE PHASE H AT SAME FLOWRATE
C (THIS IS NEARLY THE SAME AS THE SLUG FLOW TRANSITION
C HCOND SCALES ROUGHLY WITH X**.8 FOR LOW X. ( FX > 1.0)
C HCOND SCALES ROUGHLY WITH X**.7 FOR LOW X. ( FX < 1.0)
C (THIS IS SIMILAR TO X**.76 IN THE SHAH CORRELATION)
C SCALE POWER WITH QUALITY TO LESSEN XL=0 DISCONTINUITY
```

```
C
                  XNU                 = CUTOFF*PRL*REL**(0.9)/F2
                  HCOND               = XNU*TKL/D
                  IF(HCOND .GT. HL)THEN
                           RATIO               = X/XC
                           XPOW                = 1.0 - 0.3*RATIO
                           HCOND               =   HL    +    (HCOND-HL)*RA-
TIO**XPOW
                  ENDIF
         ENDIF
C
C ======================== MODIFICATIONS TO STANDARD LIBRARY ROUTINE
         R                 = MAX(HL,HCOND)
C
C CORRECTED KAMOTANI CORRELATION FOR HEAT TRANSFER
C USING HEAT PIPE TEST DATA
C
        IF((ABS(AF/AFG) - 1.0) .LE. 1.0E-5)THEN
                HG              = 1.083E3*TKL/
     .                          (0.0221+TKL*.034/(.014*165.))
C
C TAKE RATIO OF HEAT TRANSFER AREA TO OLD WETTED PERIMETER
C USE VAPOR CORE DIAMETER AS BASIS FOR KAMOTANI'S CORRELATION
C
                HG              = HG*3.1416*DIAVC/(4.*AF/D)
C
C SMOOTH IN GROOVE RESULTS IF ACTIVE WITH CUBIC SMOOTHING FUNCTION
C
                IF(X .LT. QUALOW)THEN
                        RATIO           = X/QUALOW
                        SMOOTH          = (3. - 2.*RATIO)*RATIO**2
                        HG              = HG*SMOOTH + (1.0-SMOOTH)*R
                ENDIF
                R               = 0.5*(HG+R)
        ENDIF
C
        ROHSEN          = R
C ========================
C
         RETURN
         END
END OF DATA
```

```
C ======================================================================
C THIS IS THE INPUT FILE FOR THE SIMPLIFIED CPL START-UP, FOCUSING
C ON THE THERMAL EVENT AND NEGLECTING THE SHORT HYDRODYNAMIC EVENT
C ======================================================================
C
HEADER OPTIONS DATA
TITLE FLUINT SAMPLE MODEL 6-SIMPLIFIED CPL GET AWAY SPECIAL (GAS)
         OUTPUT   = cplpdq.out
         USER1    = cplpdq.usr
C
HEADER CONTROL DATA, GLOBAL
         UID      = SI
         ABSZRO   = -273.16
         OUTPUT   = 120.0                    $ OUTPUT EVERY 2 MINUTES
         OUTPTF   = 120.0
         DTMAXF   = 10.0                     $ MAX 10 SEC TIME STEP
         NLOOPS   = 200
C
HEADER USER DATA, GLOBAL
         POWER    = 2.0*255.0                $ 510.0 WATTS TOTAL
C
C GET FAST FLUID DESC. PRODUCED BY RAPPR FOR NH3 @ 29C
C
INSERT cplpdq.inc
C
HEADER FLOW DATA,CPL,FID=6717$ START LOOP DESCRIPTION
C
C SET MODEL DEFAULTS
C SET PRESSURE FOR ALL LUMPS AT SATURATION FOR 29C
C
LU DEF,  TL = 6.6,PL! = 1.1323E6, XL = 0.0
PA DEF,  FR = 0.0                            $ SHUT DOWN INITIALLY
C
C 0.0153 SQ IN TOTAL GROOVE AREA
C FOR 1-PHASE GROOVED LINE, USE HYD DIA ASSUM, AF = TOTAL
C PERIMETER = 16*3*0.034 + 16*0.014” = 1.856” = 4.71E-2 m
C FLOW AREA = 16.0*6.17E-7 + 0.25*PI*4.699E-3**2 = 2.72E-5
C
                  DH = 4.*2.72E-5/4.71E-2
                  AF = 2.72E-5
C
C DEFINE SINGLE SUBCOOLED TANK AS EVAPORATOR INLET
C
LU TANK,10,VOL = 125.0E-6  $ LIQUID HEADER (COLD)
         LSTAT=STAG, COMP = 0.01/pl#this$ GUESS
C
C USE MFRSET AS PUMP
C
PA CONN,1040,10,40,DEV = MFRSET
```

```
C
C CONDENSER INLET (HEATER JUNCTION)
C SET AS SATURATED VAPOR
C
LU JUNC,40,XL = 1.0$ SAT VAPOR
C
C DEFINE CONDENSER: 9 CENTERED SEGMENTS OF 1.57 M TOTAL LENGTH
C WILL USE MODIFIED ROHSENOW CORRELATION FOR GROOVE HEAT TRANSFER
C IF APPROPROPRIATE AF IS USED
C
M HX,1,C,1,1,1,PLATE.1,40,10,NSEG = 9          $ VAPOR LINE
         TLENT = 1.57
         DHS = 4.*2.72E-5/4.71E-2
         DEFF = 0.005
         AFS = 2.72E-5
         LU = JUNC,PA = STUBE                   $ LOW TEMPORAL RESOLUTION
C
C FINALLY, ADD RESERVOIR AND LINE BETWEEN IT AND LIQUID HEADER
C INITIALIZE PLENUM AS TWO PHASE BUT USE LIQUID SUCTION
C (EASY WAY TO GET SATURATED LIQUID)
C
LU PLEN,99,XL = 0.1                             $ SAT LIQUID
C                 VOL = 2.8E-4                  $ IF WERE TANK
         LSTAT = STAG
C
PA CONN,99,10,99, STAT = RLS                    $ LIQ FROM PLEN SIDE
         DEV = STUBE,TLEN = 0.70                $ 70 CM
         DEFF = 0.005
C
HEADER NODE DATA, PLATE
C
C BOUNDARY
         -300,6.6,0.0
C
C PIPE NODES: MOVE MASS INTO HEAVIER RADIATOR NODES
C
C        GEN,1,9,1,6.6,85.9/9.0
         GEN,1,9,1,6.6,-1.0
C
C RADIATOR NODES
C
         11,6.6,  85.9/9.0   + 230.3               $ FIRST HALF PASS
         GEN,12,4,1,6.6,85.9/9.0 + 216.75          $ NEXT TWO PASS
         GEN,16,4,1,6.6,85.9/9.0 + 289.0           $ LENGTH TWO PASSES
C
```

```
HEADER CONDUCTOR DATA, PLATE
C
C BOUNDARY TO PLATE THROUGH COTHERM
C 63% and 51% FIN EFFICIENCIES
C
          301,11,300,25.6*0.63
          GEN,302,4,1,12,1,300,0,24.4*0.63
          GEN,306,4,1,16,1,300,0,32.4*0.51
C
C RADIAL: TUBE WALL AND SADDLE WELD
C
          GEN,101,9,1,1,1,11,1,17.2
C
C AXIAL: ALONG FLOW DIRECTION
C
          423,12,13,0.85
          445,14,15,0.85
          467,16,17,0.85
          489,18,19,1.13
C
C SIDE: ACROSS FLOW DIRECTION
C
          212,11,12,5.28
          224,12,15,5.28
          235,13,14,5.28
          247,14,17,5.28
          256,15,16,5.28
          279,17,18,3.17
          268,16,19,3.17
C
HEADER FLOGIC 0, CPL
C
C MAKE SURE HEATER JUNCTION STAYS VAPOR
C
          CALL CHGLMP('CPL',40,'XL',1.0,'PL')
C
C SET MFRSET FOR CORRECT VOLUMETRIC FLOWRATE
C
          SMFR1040 = POWER/(HL40 - HL10)
C
HEADER VARIABLES 1, PLATE
C
C UPDATE SINK TEMPERATURE LINEARLY
          T300              = 6.6 + (17.0 - 6.6)*TIMEM/(42.0*60.0)
C
```

```
HEADER OUTPUT CALLS,CPL
         CALL LMPTAB('ALL')
         CALL TIETAB('ALL')
         CALL PTHTAB('ALL')
HEADER OUTPUT CALLS,PLATE
         CALL TPRINT('ALL')
         IF(NSOL .GT. 1)WRITE(NUSER1,10)TIMEN/60.0,T1,T2,T3,T4,T5,T6,T7
     .     ,CPL.PL40-CPL.PL10,CPL.FR1040
10      FORMAT(1X,1PG11.4,4X,8G10.3,2G11.4)
C
HEADER OPERATIONS
C
BUILD GAS,PLATE
BUILDF GAS,CPL
C
DEFMOD CPL
C
C HOLD HEATER JUNCTION ENTHALPY
C
         CALL HTRLMP('CPL',40)
C
C RUN STEADY STATE TO GET FLUID INITIAL CONDITIONS HOLDING THERMAL
C HOLD TANK 10 TOO SINCE INITIALLY NO FLOW
C
         CALL DRPMOD('PLATE')
         CALL HLDLMP('CPL',10)
         CALL STEADY
         CALL ADDMOD('PLATE')
         CALL RELLMP('CPL',10)
C
C RUN TRANSIENT
C
C WRITE TRANSIENT HEADER
C
         WRITE(NUSER1,10)(MTEST,MTEST=1,7)
10      FORMAT(/' CPL - RADIATOR TEMPERATURE RESPONSE TO STEP INPUT,',
     .    ' PLUS SYSTEM PRESSURE DROP AND RADIATOR FLOWRATE'//
     .   '   TIME (MIN)',T15,7(4X,'REG.',I2),4X,'DELTA P',4X,'FLOWRATE'/)
C
         TIMEND   = 42.0*60.0       $ START 42 MINUTES TRANSIENT
         CALL TRANSIENT
C
HEADER SUBROUTINES

         (SKIPPED: SAME AS MAIN MODEL.)

END OF DATA
```

```
C ====================================================================
C RAPPR GENERATED INSERT FILE FOR ALTERNATE INPUT FILE
C ====================================================================
C
HEADER FPROP DATA, 6717, SI , 0.0
C
C   THIS FLUID DESCRIPTION WAS CREATED BY RAPPR FOR FLUID  717
C   AND IS ACCURATE FOR TEMPERATURES NEAR   302.15
C   MAXIMUM ERROR IN LIQUID PROPERTIES = 20.00 PERCENT
C   MAXIMUM ERROR IN VAPOR PROPERTIES  = 10.00 PERCENT
C   MAXIMUM LIQUID (SATURATION) TEMP. =   331.55490
C
         TCRIT =     405.59998    ,    PCRIT =     11282378.
         TGMAX =     331.55490    ,    PGMAX =     2496161.5
         TMIN =      267.78616
         DIFV =      20.700001    ,    MOLW =      17.009514
         PHI  =      1.0000000
C
VINIT
       DOUBLE PRECISION POLD,PSAT
       SAVE TOLD,TTOC,A,B,BINV,C,CINV,TREF,DLIQ,DLDT
       SAVE CPVAP,CPVDT,REFF,BC,POLD,TTOCX,TSAT,DLDP,DLDPT
       DATA A,B,BINV/  20.802042     , -12773.754    ,-7.82855204E-05/
       DATA C,CINV,TREF/ -1.3183613     ,-0.75851744     ,  302.14999     /
       DATA DLIQ,DLDT/  596.95667     , -1.5352054     /
       DATA CPVAP,CPVDT,TOLD,TSAT/  3058.6499     ,  24.452654     ,2*0.0/
       DATA REFF,BC,POLD/  426.70825     ,  16840.422     ,0.0D0/
       DATA DLDP,DLDPT/ 9.64974333E-07, 1.29314524E-08/
C
VSV
       V      = REFF*T/SNGL(P)
C
VDL
       D      = DLIQ + (T-TREF)*DLDT
C
VCPV
       CP     = CPVAP + (T-TREF)*CPVDT
C
VTAV2
       T      = TLOOKS(H,CPVAP,CPVDT,TREF,0.0,0.0)
       V      = REFF*T/SNGL(P)
C
VH
       H      = HINTS(CPVAP,CPVDT,TREF,0.0,T)
C
VTS
       IF(P .NE. POLD)THEN
            TTOCX  = (ALOG(SNGL(P))-A)*BINV
            TSAT   = TTOCX**CINV
```

```
            POLD    = P
        ENDIF
        T       = TSAT
C
VDPDT
        IF(P .NE. POLD)THEN
            TTOCX   = (ALOG(SNGL(P))-A)*BINV
            TSAT    = TTOCX**CINV
            POLD    = P
        ENDIF
        DPDT    = BC*SNGL(P)*TTOCX/TSAT
C
VHFG
        IF(T .NE. TOLD)THEN
            IF(T .EQ. TSAT)THEN
                TTOC    = TTOCX
                TOLD    = TSAT
            ELSE
                TTOC    = T**C
                TOLD    = T
            ENDIF
        ENDIF
        VLIQ    = 1.0/(DLIQ + (T-TREF)*DLDT)
        HFG     = BC*SNGL(P)*(V-VLIQ)*TTOC
C
VPS
        IF(T .NE. TOLD)THEN
            IF(T .EQ. TSAT)THEN
                TTOC    = TTOCX
                TOLD    = TSAT
            ELSE
                TTOC    = T**C
                TOLD    = T
            ENDIF
        ENDIF
        P       = DBLE(EXP(A+B*TTOC))
C
VDPDTT
        IF(T .NE. TOLD)THEN
            IF(T .EQ. TSAT)THEN
                TTOC    = TTOCX
                TOLD    = TSAT
            ELSE
                TTOC    = T**C
                TOLD    = T
            ENDIF
        ENDIF
        DPDT    = BC*EXP(A+B*TTOC)*TTOC/T
C
```

```
VCONDF
       COND    =  0.47210324     + (T-TREF)*(-2.31996831E-03)
C
VVISCF
       VISC    =  1.37435200E-04 + (T-TREF)*(-1.49908169E-06)
C
VCONDV
       COND    =  2.48712618E-02 + (T-TREF)*( 1.05783671E-04)
C
VVISCV
       VISC    =  1.03307348E-05 + (T-TREF)*( 3.60964201E-08)
C
VST
       ST      =  1.91859473E-02 + (T-TREF)*(-2.33207902E-04)
C
VDLC
       IF(T .NE. TOLD)THEN
            IF(T .EQ. TSAT)THEN
                 TTOC    = TTOCX
                 TOLD    = TSAT
            ELSE
                 TTOC    = T**C
                 TOLD    = T
            ENDIF
       ENDIF
       PSAT    = DBLE(EXP(A+B*TTOC))
       DSAT    =   596.95667     + (T-TREF)*( -1.5352054    )
       DLD     =  9.64974333E-07 + (T-TREF)*( 1.29314524E-08)
       D       = DSAT + MAX(0.0,SNGL(P-PSAT))*DLD
C
VS
       PHI     = SINTS(CPVAP,CPVDT,TREF,  267.78616    ,T)
       S       = PHI - REFF*ALOG(REFF*T/(V*  349573.94    ))
C
C ====================================================================
C END OF ALTERNATE INPUTS
C ====================================================================
```

Processor Output

```
CPL - RADIATOR TEMPERATURE RESPONSE TO STEP INPUT, PLUS SYSTEM PRESSURE DROP AND RADIATOR FLOWRATE

  TIME (MIN)    REG. 1    REG. 2    REG. 3    REG. 4    REG. 5    REG. 6    REG. 7    DELTA P    FLOWRATE

 0.000          6.60      6.60      6.60      6.60      6.60      6.60      6.60      0.00      0.000
 0.1000          6.60      6.60      6.60      6.60      6.60      6.60      6.60     8.872E-04 4.1701E-08
 0.2000          6.61      6.61      6.61      6.61      6.61      6.61      6.61     3.000E-03 1.4503E-07
 0.3000          7.36      6.78      6.66      6.64      6.63      6.63      6.63      196.     3.1126E-04
 0.4000          22.4      13.8      9.96      8.38      7.69      7.23      7.03      304.     4.9531E-04
 0.5000          24.2      22.0      9.87      7.83      7.41      6.95      6.87      352.     3.5582E-04
 0.6000          25.0      23.4      13.3      8.81      7.98      7.05      6.91      388.     3.7978E-04
 0.7000          25.4      24.0      16.2      9.63      8.52      7.20      6.98      410.     3.9400E-04
 0.8000          25.6      24.3      18.4      10.1      8.87      7.32      7.07      420.     4.0029E-04
 0.9000          25.7      24.4      19.9      10.5      9.12      7.44      7.17      427.     4.0352E-04
  1.000          25.7      24.5      20.9      10.8      9.30      7.54      7.26      430.     4.0502E-04
  1.100          25.8      24.6      21.5      11.0      9.43      7.62      7.35      432.     4.0589E-04
  1.200          25.8      24.6      22.0      11.2      9.53      7.69      7.42      433.     4.0629E-04
  1.300          25.8      24.6      22.3      11.4      9.60      7.74      7.49      434.     4.0651E-04
  1.400          25.8      24.6      22.5      11.5      9.66      7.79      7.55      434.     4.0663E-04
  1.500          25.8      24.6      22.6      11.5      9.71      7.83      7.60      434.     4.0669E-04
  1.600          25.8      24.7      22.7      11.6      9.75      7.87      7.64      435.     4.0673E-04
  1.700          25.8      24.6      22.8      11.7      9.79      7.91      7.68      435.     4.0676E-04
  1.800          25.8      24.7      22.9      11.7      9.82      7.94      7.72      435.     4.0679E-04
  1.900          25.8      24.7      22.9      11.8      9.85      7.97      7.75      435.     4.0680E-04
  2.000          25.8      24.7      23.0      11.8      9.88      8.00      7.78      435.     4.0682E-04

  (second, resstarted run)

  TIME (MIN)    REG. 1    REG. 2    REG. 3    REG. 4    REG. 5    REG. 6    REG. 7    DELTA P    FLOWRATE

  2.000          25.8      24.7      23.0      11.8      9.88      8.00      7.78      435.     4.0682E-04
  4.000          25.9      24.8      23.7      12.6      10.5      8.53      8.32      438.     4.0714E-04
  6.000          26.0      25.0      24.0      13.7      11.1      9.10      8.88      441.     4.0768E-04
  8.000          26.1      25.1      24.2      14.8      11.8      9.68      9.44      445.     4.0837E-04
  10.00          26.2      25.3      24.4      16.0      12.5      10.3      10.0      448.     4.0912E-04
  12.00          26.3      25.4      24.7      17.1      13.2      10.8      10.6      451.     4.0990E-04
  14.00          26.4      25.5      24.9      18.2      13.9      11.4      11.1      454.     4.1068E-04
  16.00          26.5      25.7      25.1      19.5      14.5      12.0      11.7      457.     4.1147E-04
  18.00          26.6      25.8      25.3      21.0      15.0      12.5      12.3      460.     4.1226E-04
  20.00          26.7      25.9      25.5      22.4      15.5      13.0      12.8      466.     4.1304E-04
  22.00          26.8      26.0      25.6      23.8      16.1      13.5      13.4      470.     4.1383E-04
  24.00          26.9      26.2      25.8      24.9      16.9      14.1      14.0      475.     4.1462E-04
  26.00          27.0      26.3      26.0      25.1      18.2      14.9      14.6      481.     4.1544E-04
  28.00          27.0      26.4      26.1      25.4      19.5      15.8      15.2      487.     4.1628E-04
  30.00          27.1      26.6      26.3      25.6      20.9      16.7      15.7      491.     4.1714E-04
  32.00          27.2      26.7      26.4      25.8      22.6      17.3      16.3      497.     4.1800E-04
  34.00          27.3      26.8      26.5      26.0      24.2      18.0      16.8      503.     4.1884E-04
  36.00          27.4      27.0      26.7      26.1      25.7      18.9      17.4      509.     4.1969E-04
  38.00          27.5      27.1      26.8      26.3      26.0      20.4      18.2      518.     4.2059E-04
  40.00          27.5      27.2      26.9      26.5      26.2      22.0      19.1      529.     4.2150E-04
  42.00          27.6      27.3      27.0      26.6      26.4      23.9      19.7      538.     4.2262E-04
```

(comparison with simplified model)

```
CPL - RADIATOR TEMPERATURE RESPONSE TO STEP INPUT, PLUS SYSTEM PRESSURE DROP AND RADIATOR FLOWRATE

  TIME (MIN)    REG. 1    REG. 2    REG. 3    REG. 4    REG. 5    REG. 6    REG. 7    DELTA P    FLOWRATE

  0.000          6.60      6.60      6.60      6.60      6.60      6.60      6.60      13.5     4.0857E-04
  2.000          25.8      24.7      23.1      11.8      9.83      7.95      7.76      68.8     4.0876E-04
  4.000          25.9      24.8      23.7      12.7      10.4      8.49      8.30      72.3     4.0919E-04
  6.000          26.0      25.0      24.0      13.8      11.1      9.06      8.86      76.5     4.0975E-04
  8.000          26.1      25.1      24.2      14.9      11.8      9.64      9.43      81.1     4.1037E-04
  10.00          26.2      25.3      24.4      16.0      12.5      10.2      10.0      84.8     4.1103E-04
  12.00          26.3      25.4      24.7      17.1      13.2      10.8      10.6      88.2     4.1172E-04
  14.00          26.4      25.5      24.9      18.2      13.9      11.4      11.1      91.4     4.1243E-04
  16.00          26.5      25.7      25.1      19.6      14.5      11.9      11.7      94.7     4.1314E-04
  18.00          26.6      25.8      25.3      21.0      15.0      12.4      12.3      97.8     4.1386E-04
  20.00          26.7      25.9      25.5      22.5      15.5      12.9      12.8      103.     4.1459E-04
  22.00          26.8      26.0      25.6      23.8      16.1      13.5      13.4      108.     4.1532E-04
  24.00          26.9      26.2      25.8      24.9      16.9      14.1      14.0      112.     4.1606E-04
  26.00          26.9      26.3      26.0      25.1      18.2      14.9      14.6      118.     4.1682E-04
  28.00          27.0      26.4      26.1      25.3      19.5      15.8      15.1      124.     4.1760E-04
  30.00          27.1      26.6      26.2      25.6      20.9      16.6      15.7      128.     4.1839E-04
  32.00          27.2      26.7      26.4      25.8      22.5      17.3      16.2      134.     4.1920E-04
  34.00          27.3      26.8      26.5      26.0      24.2      18.0      16.8      141.     4.1999E-04
  36.00          27.4      27.0      26.7      26.1      25.6      18.8      17.3      147.     4.2079E-04
  38.00          27.4      27.1      26.8      26.3      26.0      20.4      18.2      156.     4.2164E-04
  40.00          27.5      27.2      26.9      26.5      26.2      21.9      19.1      164.     4.2257E-04
  42.00          27.6      27.3      27.0      26.6      26.4      23.8      19.7      174.     4.2353E-04
```

```
        MAX TIME STEP =   163.510      ; LIMITING TANK =       20     REASON  = DENSITY CHANGE LIMIT
        LAST TIME STEP =   1.86950      VS. DTMAXF/DTMINF =   10.0000      /  1.000000E-03;   AVERAGE TIME STEP =    1.17408
        PROBLEM TIME                   TIMEN   =  120.000      VS. TIMEND   =  120.000


                                        LUMP PARAMETER TABULATION FOR SUBMODEL CPL

  LUMP  TYPE     TEMP       PRESSURE     QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

    10  TANK    7.170      1.1323E+06    0.000        0.000        628.8       2.1533E+05    0.000      -3.2193E-08   7.7593E-02
    20  TANK    7.039      1.1319E+06    0.000        0.000        629.0       2.1473E+05    0.000      -5.8062E-08   0.1100
    40  TANK    29.48      1.1324E+06    1.000        1.000        8.760       1.4675E+06  -6.8902E-02  -3.2014E-10  -1.7630E-04
    30  JUNC    29.01      1.1324E+06    1.000        1.000        8.783       1.4660E+06    0.000        0.000        0.000
    35  JUNC    29.53      1.1324E+06    1.000        1.000        8.757       1.4676E+06    0.3258       0.000       1.3679E-05
    50  JUNC    29.48      1.1324E+06    1.000        1.000        8.760       1.4675E+06    0.000        0.000        0.000
  1000  JUNC    29.00      1.1322E+06    1.000        1.000        8.781       1.4660E+06    254.5        0.000       6.2561E-04
     1  JUNC    29.00      1.1324E+06   0.6615       0.9925        13.18       1.0770E+06   -158.8        0.000      -3.0518E-05
     2  JUNC    29.00      1.1323E+06   0.3239       0.9702        26.30       6.8902E+05   -157.8       5.8208E-11   3.0518E-05
     3  JUNC    29.00      1.1323E+06   1.8511E-02   0.5618       266.5       3.3800E+05   -142.8        0.000        0.000
     4  JUNC    16.66      1.1323E+06    0.000        0.000       615.3       2.5911E+05   -32.09       2.9104E-11   7.6294E-06
     5  JUNC    11.36      1.1323E+06    0.000        0.000       622.9       2.3463E+05   -9.960      -2.9104E-11  -7.6294E-06
     6  JUNC    8.725      1.1323E+06    0.000        0.000       626.6       2.2248E+05   -4.942        0.000        0.000
     7  JUNC    7.984      1.1323E+06    0.000        0.000       627.7       2.1907E+05   -1.387        0.000        0.000
     8  JUNC    7.399      1.1323E+06    0.000        0.000       628.5       2.1638E+05   -1.093        0.000        0.000
     9  JUNC    7.215      1.1323E+06    0.000        0.000       628.7       2.1554E+05  -0.3438        0.000        0.000
   100  JUNC    7.215      1.1323E+06    0.000        0.000       628.7       2.1554E+05    0.000       2.9104E-11   7.6294E-06
    99  PLEN    29.00      1.1323E+06   0.1000       0.8831       77.55       4.3165E+05    0.000       1.4855E-07   3.1988E-02




                                        TIE PARAMETER TABULATION FOR SUBMODEL CPL

  TIE   TYPE      UA          QTIE         LUMP     TEF           NODE                 TEMP.    2P  PATH 1     FRACT   PATH 2     FRACT

    35  HTN    9.1982E-02   0.3258          35     29.53      EVAP.1500             33.08           35     1.0000
    40  HTN    0.5299      -6.8902E-02      40     29.48      EVAP.2000             29.35           40     4.0000
  1000  HTM     15.96        254.5        1000     29.00      EVAP.1000             44.95
     1  HTNC    49.94       -158.8           1     29.00      PLATE.1               25.83            1     1.0000        2     0.5000
     2  HTNC    36.54       -157.8           2     29.00      PLATE.2               24.68            2     0.5000        3     0.5000
     3  HTNC    23.66       -142.8           3     29.00      PLATE.3               22.99            3     0.5000        4     0.5000
     4  HTNC    6.592       -32.09           4     16.66      PLATE.4               11.80            4     0.5000        5     0.5000
     5  HTNC    6.701       -9.960           5     11.36      PLATE.5               9.877            5     0.5000        6     0.5000
     6  HTNC    6.769       -4.942           6     8.725      PLATE.6               7.996            6     0.5000        7     0.5000
     7  HTNC    6.784       -1.387           7     7.984      PLATE.7               7.779            7     0.5000        8     0.5000
     8  HTNC    6.801       -1.093           8     7.399      PLATE.8               7.238            8     0.5000        9     0.5000
     9  HTNC    6.805      -0.3438           9     7.215      PLATE.9               7.164            9     0.5000       10     1.0000
```

```
                                        PATH PARAMETER TABULATION FOR SUBMODEL CPL

   PATH  TYPE     LMP 1   LMP 2   DUP I      DUP J    STAT   XL UPSTRM    FLOWRATE     DELTA PRES    REYNOLDS    MACH     REGIME

     30  STUBE       30      35    45.        45.     NORM     1.000      4.5202E-06     3.607        408.4      0.001    1 PHASE
     35  STUBE       35      40    1.0        2.0     NORM     1.000      2.0341E-04    0.9970        3791.      0.002    1 PHASE
     40  STUBE       40      50    1.0        1.0     NORM     1.000      4.0682E-04     1.309        3550.      0.001    1 PHASE
    300  CAPIL       10      20    2.0        1.0     DLS      0.000      2.0335E-04     355.3                   0.000
   1000  NULL        20    1000    1.0        1.0     LS       0.000      2.0341E-04    -217.7                   0.000x
   2000  NULL      1000      30    1.0        1.0     RLS      1.000      2.0341E-04    -217.7                   0.002
      1  STUBE       50       1    1.0        1.0     NORM     1.000      4.0682E-04     17.58        7227.      0.004    1 PHASE
      2  STUBE        1       2    1.0        1.0     NORM    0.6615      4.0682E-04     27.10        4973.      0.004    ANNULAR
      3  STUBE        2       3    1.0        1.0     NORM    0.3239      4.0682E-04     12.20        2713.      0.003    ANNULAR
      4  STUBE        3       4    1.0        1.0     NORM    1.8511E-02  4.0682E-04     1.967        668.1      0.001    SLUG
      5  STUBE        4       5    1.0        1.0     NORM     0.000      4.0682E-04     2.862        474.8      0.000    1 PHASE
      6  STUBE        5       6    1.0        1.0     NORM     0.000      4.0682E-04     1.960        447.6      0.000    1 PHASE
      7  STUBE        6       7    1.0        1.0     NORM     0.000      4.0682E-04     2.953        434.6      0.000    1 PHASE
      8  STUBE        7       8    1.0        1.0     NORM     0.000      4.0682E-04     2.003        431.1      0.000    1 PHASE
      9  STUBE        8       9    1.0        1.0     NORM     0.000      4.0682E-04     2.819        428.3      0.000    1 PHASE
     10  STUBE        9     100    1.0        1.0     NORM     0.000      4.0682E-04     1.006        427.4      0.000    1 PHASE
    100  STUBE      100      10    1.0        1.0     NORM     0.000      4.0682E-04     1.730        427.4      0.000    1 PHASE
     99  STUBE       10      99    1.0        1.0     RLS      0.000      1.4855E-07    2.6937E-03   0.1560      0.000    1 PHASE




 SUBMODEL NAME = PLATE


                                  CALCULATED                                    ALLOWED
        MAX DIFF DELTA T PER ITER      DRLXCC(PLATE          3)= 4.463763E-04 VS. DRLXCA= 1.000000E-02
        MAX ARITH DELTA T PER ITER     ARLXCC(               0)=  0.00000     VS. ARLXCA= 1.000000E-02
        MAX DIFF DEL T PER TIME STEP   DTMPCC(PLATE          3)= 1.812485E-02 VS. DTMPCA= 1.000000E+30
        MAX ARITH DEL T PER TIME STEP  ATMPCC(               0)=  0.00000     VS. ATMPCA= 1.000000E+30
        MIN STABILITY CRITERIA         CSGMIN(PLATE          1)= 0.141940
        MAX STABILITY CRITERIA         CSGMAX(PLATE         19)=  7.60046
        NUMBER OF ITERATIONS           LOOPCT                  =        3     VS. NLOOPT=      100
        PROBLEM TIME                   TIMEN                   =  120.000     VS. TIMEND=  120.000
        MEAN PROBLEM TIME              TIMEM                   =  119.065
        AVERAGE TIME STEP USED SINCE LAST OUTPUT               =  1.50000     VS. DTIMEI=  0.00000
        THIS SUBMODEL CONTAINS TIME STEP LIMITING NODE:                  2

                                 DIFFUSION NODES IN INPUT NODE NUMBER ORDER
 T     1=  25.830     T     2=  24.681     T     3=  22.990     T     4=  11.795     T     5=  9.8766     T     6=  7.9955
 T     7=  7.7795     T     8=  7.2384     T     9=  7.1641     T    11=  16.575     T    12=  15.509     T    13=  14.691
 T    14=  9.9323     T    15=  9.2999     T    16=  7.7107     T    17=  7.7017     T    18=  7.1773     T    19=  7.1466
                                 ARITHMETIC NODES IN INPUT NODE NUMBER ORDER
                                                  ++NONE++
                                 HEATER NODES IN INPUT NODE NUMBER ORDER
                                                  ++NONE++
                                 BOUNDARY NODES IN INPUT NODE NUMBER ORDER
 T   300=  7.0914
```

PROBLEM E VARIATION: CORRELATION TO TEST DATA

The correlation (also called “calibration”) of any type of analytical model to test data is a time consuming task. It is typically performed by perturbing a single uncertain input parameter and then executing a run. Selected outputs (i.e. temperatures, pressures, etc.) are then compared to the test data. This comparison is often performed visually by plotting predictions and results together. Based upon the comparison, the analyst decides either to accept the current values of the input parameter, or to change it and execute another run and another comparison. This procedure can obviously become very complicated as the number of uncertain parameters increases, and the adequacy of the correlation becomes harder to determine.

In this problem, the simplified CPL model described earlier in this in section will be correlated to test data. Many of the concepts presented here also apply to any optimization problem, since data correlation is a specific application of optimization.

This problem was chosen to demonstrate the following SINDA/FLUINT features:

1. how to use the Solver to correlate/calibrate a model
2. how to formulate a correlation (or optimization) problem
3. how to define constraints
4. how to input test data

E.6 A SINDA/FLUINT Model

Several questions need to be answered in order to set up the automated calibration of a model using the Solver. These questions include:

1. What physical parameters are uncertain, by how much, and how can those uncertainties by related to specific input parameters?
2. What is the relationship between test points and model predictions? Is there a one to one relationship? Or must either the test data or the model be changed or mapped to enable a comparison?
3. How will the difference between model predictions and test results be calculated? Ultimately, a single figure of merit (the objective) must be used to expressed the worthiness of each attempted correlation.

The rest of this subsection will be devoted to answering these questions for this particular sample problem.

The most difficult and yet critical part of correlating a model is unrelated to SINDA/FLUINT: it is identifying the key uncertainties in the model. This is an important step because adding spurious uncertainties (i.e., ones that do not affect the correlation) can stall the progress of the Solver, and of course forgetting key uncertainties will produce misleading results.

The key uncertainties in the model were identified as (1) the power input into the evaporators, (2) the heat transfer coefficients in the condenser, (3) the resistance of the conductive pad between the canister lid and the condenser plate, and (4) the actual temperature of the reservoir.

Also difficult is deciding how uncertain each parameter was, and the final choices are somewhat arbitrary. Fortunately, unless these limits are actually constraining the final answer, their actual values are irrelevant. It was finally decided that the uncertainty in the power input was 5%, with an additional 5% allocated on the low end to account for heat leaks off the evaporators. The uncertainty in the film coefficients in the condenser were selected as 25%, and 50% uncertainty was selected for the bolted conductive pad between the condenser plate and the GAS canister lid. The reservoir temperature of 29˚C appeared to be low, being an initial value that didn't account for compressive heating during start-up (nor subsequent cooling after this initial compression), so the lower limit was selected as 28.5˚C but the upper limit as 31˚C. These parameters are summarized below:

Parameter	Lower Limit	Upper Limit	Comments
Input power	90% nominal	105% nominal	uncertain due to leaks, meas. methods
Condenser Heat Transfer Coefficient	75% nominal	125% nominal	correlation for condensation in grooves
Conductive Pad Conductance	50% nominal	150% nominal	highly uncertain: based on vendor data
Saturation Temperature	28.5˚C	31˚C	nominal: 29˚C; wasn't measured directly

These parameters and their respective uncertainties were chosen based on suspicions, experience, and other topics not relevant to the presentation of SINDA/FLUINT methodology, and hence a detailed discussion will be avoided.

However, how these uncertainties are applied to the model *is* relevant. It is rather easy to "retrofit" an existing model by applying unit multiplying factors to existing parameters. These "factors" are registers initialized to 1.0 that are declared to be design variables in DESIGN DATA, and then applied where needed within the model. "UNKPOW" was multiplied to the evaporator input power in USER DATA. "UNKHTC" was applied to the UAM factors of the condenser ties. "UNKCHO" was applied to the conductors between the plate and the lid. Strictly, "UNKHTC" applies not only to the two phase region but to also to the single phase region. Also, "UNKCHO" is not a true multiplying factor on the pad conductance since it is applied to an effective conductance based on fin efficiencies. Nonetheless, for correlation purposes the above simplifications are adequate. Finally, the saturation temperature of the reservoir was replaced (not multiplied) by UNKSAT whose initial value is 29.

Test data for the CPL is shown as the three dark (solid) lines in Figure E-5. There are three available temperature responses measured at different locations in the condenser plate. Fortunately, these locations correspond more or less directly to 3 SINDA nodes in the PLATE submodel. The first measurement is located at the inlet to the condenser plate and is represented by the node 1. Node 5 represents the second measurement located in the middle of the condenser. The third and last measurement is located at the outlet of the condenser plate, which is modeled by node 7.

The purpose of the correlation is to find the values of the four uncertain factors listed above that minimize the temperature difference between the model predictions and the test results. It is tempting to compare only the final values of temperatures at the end of the event (42 minutes) since that would greatly simplify the task at hand. Of course, comparing only one thermocouple would also simplify the tasks, at the cost of a much less trustworthy correlation. Therefore, all three data points will be compared at various intervals during the transient event, with the error accumulated weighing each time point equally. The selected interval for comparison will be the same as that used for output: two minutes. Thus, there will be a total of 3*42/2 = 63 comparisons made.

Two methods of producing a single objective value OBJECT from these 63 comparisons will be used. The first will employ a summation of the squared error (difference in temperatures) as the OBJECT to be minimized, in effect achieving a least squares fit. This fit will be preceded by a design space scan (DSCANLH) to locate a good starting point. This important step accelerates the subsequent SOLVER call, avoids scaling problems associated with poor initial conditions, and helps avoid local (vs. global) minima.

The second will minimize the maximum error ("MINIMAX"). Strictly, the OBJECT shouldn't be simply set equal to the maximum error since a discontinuity exists at the final answer since at least two data points will be limited by this maximum error.* Therefore, following the methods outlined in the main volume of the user's manual, a fifth design variable, ERRMAX, will be created and minimized, and it will be used as the upper and lower limit of 63 constraint variables, one for each comparison point.

Unfortunately, a design space prescan is not easily accomplished with a minimax method since the objective is also a design variable (ERRMAX). Combined with the extra difficulty in setting up such a calibration and its sensitivity to noise in the test data, the simpler least squares fit is recommended.

E.7 The Input File: Least Squares Method

Input blocks unchanged from the simplified CPL problem presented earlier will not be repeated here.

OPTIONS DATA—As with previous examples, a summary file is written to USER1 and USER2.

REGISTER DATA—In order to be used as correlating parameters (design variables), uncertainties must listed as real registers. The four unknown factors described above are identified and initialized.

SOLVER DATA—Data used to control the Solver is entered here. The method used by the Solver was chosen as the METHO=1. (For an unconstrained problem like this METHO=2 is the only other choice.) The default value of GOAL (-1.0E-30) is being used, hence OBJECT will be minimized. Since only defaults are used, there is actually no need for the SOLVER DATA block in this model.

---

* Unofficially, this "illegal" method actually works very well in this particular sample problem, even producing the best fit with a maximum error of 2.85 degrees. Some experimentation is clearly warranted.

DESIGN DATA—Uncertainty ranges are translated into mathematical expressions. Power was determined to be known within +5% and -10%, or “0.90 ≤ UNKPOW ≥ 1.05.” The uncertainty in the film coefficient correlation was estimated at 25%, or “0.75 ≤ UNKHTC ≥ 1.25.” Conductance through the interface pad had the largest uncertainty of 50%, or 0.50 ≤ UNKCHO ≥ 1.50. The saturation temperature will be allowed to vary from 28.5 to 31˚C, or 28.5 ≤ UNKSAT≥ 31.0. All of these variables were previously defined as registers.

CONTROL DATA—Input data is the same as that presented earlier, except for OUTUTF which is set to 120 since the fluid submodel’s OUTPUT CALLS block will be used for comparison calculations, which are to be performed at an interval of 2 minutes.

SOLOUTPUT CALLS—A call is made to DESTAB and CSTTAB to monitor the SOLVER’s progress.

USER DATA—Power input to the evaporator is defined. Note the UNKPOW factor used for “adjusting” the power during correlation.

ARRAY DATA—Array 10 is defines the node numbers that will be used for the comparison. This array makes the use of the PREPLIST routine possible. Array 20 defines array numbers where the complete set of test data is located (as defined a few lines later), which makes use of the PREPDAT1 routine possible. Space is created in arrays 20 and 25 to hold the current temperature values of nodes defined in array 10 and test results, respectively, as needed for the COMPARE routine. The last three doublet arrays 101, 105, and 107 contain test data.

OUTPUT CALLS—The correlation is only done for the transient portion of the run. NSOL is used as a flag to perform the necessary steps to perform the comparison. First PREPLIST is called to fill PLATE.A20 with temperatures of nodes defined in PLATE.A10. Next, PREPDAT1 is called to fill PLATE.A25 with test data for the current time. COMPARE is called to calculate the error between the analytical model and test data using a sum of the squared values algorithm (SUMSQR). The error is returned as DTEST and is summed with OBJECT. (To have placed OBJECT as the last argument would have caused previous calculations to have been overwritten.)

OPERATIONS—After building both the thermal submodels and the fluid submodel as one configuration, the first order of business is to write header information to the summary files. The enthalpy of junction 40 is held constant by calling HTRLMP as before. The initial temperatures for the thermal model are saved, by calling SVPART, in order to retrieve them for use as initial conditions since the transient solution will be executed many times in PROCEDURE. Note that care is taken not to save registers so as not to conflict with manipulations made with the Solver. A preliminary scan of 12 points is invoked using DSCANLH, then the best point found by that routine is passed to the subsequent call to SOLVER.

PROCEDURE DATA—First, temperature are reinitialized in a call to RESPAR using values stored via the previous call to SVPART. The solver control constant NERVUS is set to 3. The solver will continue even if a steady state routine fails to converge (FASTIC or “Steady” in this case, whose nonconvergence is irrelevant to the problem at hand). A steady state analysis is performed to obtain a set of initial conditions. OBJECT is reinitialized to 0 to allow error to be accumulated during the transient. If it were not set to zero prior to each loop through SOLVER, then the error calculated by COMPARE would carry over from previous transients.

NERVUS is set back to the default value of 0. This will cause SOLVER to abort if FWDBCK ("Transient") fails to convergence. FWDBCK is call next to perform a transient analysis. OBJECT is updated in OUTPUT CALLS to accumulate the squared error, but before leaving PROCEDURE the final sum is divided by 63 (the number of comparison points) and the square root is taken, yielding a true root mean square objective. There are two reasons for this action: (1) to yield an OBJECT that has intuitive meaning and dimensions, and (2) to reduce the scale of OBJECT variations, which as noted in the main volume of the manual has a positive effect on Solver operations.

E.8 The Input File: MINIMAX Method

Only changes to the input file needed to perform the MINMAX run are described.

REGISTER DATA—All registers are the same as discussed above except for the introduction of ERRMAX. ERRMAX is the maximum error, or the largest difference between the model predication and test data. It will be both a design variable and the objective to be minimized.*

SOLVER DATA—The Solver method is changed from the default method by setting METHO=3 (the modified method of feasible directions), which tends to do better with heavily constrained optimizations such as MINIMAX problems present. OBJECT is set equal to the register ERRMAX, which means that it will not need to be updated explicitly in logic blocks. Since the default value of GOAL (-1.0E-30) is used, the OBJECT will be minimized, and therefore ERRMAX will be minimized. The maximum number of loops (PROCEDURE calls) performed by SOLVER is increased from the default value of 100 to 200. RCACTO defines when a constraint becomes active; MINIMAX fits can be very sensitive to the value of this parameter.

DESIGN DATA—An additional design variable, ERRMAX, is added for the MINIMAX run.

CONSTRAINT DATA—The GEN options is used to define the 63 constraints that will be needed, one per comparison (21 comparisons per node times 3 nodes compared). The resulting names of the constraints will be CST01, CST02, ... through CST63. Note that if 100 or more had been generated, the names would have been CST001, CST002, etc.

USER DATA—IPTA20 and IPTA25 are defined as 0. These variables are pointers to the internal locations of array A20 and A25. They will be defined in OPERATIONS.

OUTPUT CALLS—The first generated constraint (CST01) and a dummy array (FAKE) are equivalenced. Since constraints are stored in the order in which they are input or generated, "FAKE" now provides a means in looking up a constraint via an index.

Correlation is only done for the transient portion of the run. NSOL is used as a flag to perform the necessary steps to perform the correlation. The current time is converted from seconds to minutes and stored in TTEST. An index for the constraints is calculated based on TTEST. First PREPLIST is called to fill PLATE.A20 with temperatures of nodes defined in PLATE.A10. Next, PREPDAT1 is called to fill PLATE.A25 with test data for the current time. COMPARE is called to calculate the

---

* One of the flaws of the MINIMAX method is its sensitivity to the initial value of ERRMAX. The value should be based on preliminary runs: it should be set just larger than the maximum error calculated using the initial values of the design variables.

error between the analytical model and test data using minimize the maximum error algorithm (MINIMAX), which in this case will store the error in the next three cells of the last argument.

The Fortran manipulates with the equivalenced “FAKE” array and the index are simply done to avoid a string of IF/THEN checks such as:

```
IF(TIMEN .GE. 41.99)THEN
         make the comparison at 42 seconds
ELSEIF(TIMEN .GE. 39.99)THEN
         make the comparison at 40 seconds
...
```

These manipulations are not recommended for most users since they can be dangerous if done improperly. In the above problem, PREPLIST, PREPDAT1 and even COMPARE are of minimal use but were preserved to maintain similarity with the previous least squares method. Nonetheless, the difficulty in working with many constraints is endemic to the MINIMAX method, and hence the above methods were used in this sample problem to highlight this point.

A much simpler variation is to simply minimize the maximum error directly without constraints. Such an approach would more closely resemble the simpler least squares method:

```
CALL COMPARE(A20, A25, 0, 0, 'MAXERR', DTEST)
OBJECT = MAX(OBJECT,DTEST)
```

Although strictly speaking the above approach cannot be formally recommended since it introduces a discontinuity in the objective function at the answer, it is much simpler to set up than a true MINIMAX method, and often works satisfactorily. In fact, in all the methods attempted in the generation of this sample problem, this “illegal” method provided the best fit (2.85 degrees error) in very few iterations (about 40). In other words, the Solver is actually somewhat tolerant of discontinuities, especially when the number of active constraints is large such that the *apparent* discontinuity is small.

OPERATIONS—The internal location for arrays A20 and A25 are obtained with a call to ARYTRN. See OUTPUT CALLS.

PROCEDURE DATA—For the MINIMAX analysis, OBJECT need not be initialized since it is defined via register expressions in SOLVER DATA.

E.9 Output Description

Selected printings from the OUTPUT files of the two runs are provided on the pages following the input listings.

Figure E-7 displays the results for both methods. About 30 to 50 procedure calls (including the 12 prescan calls using DSCANLH) were used to determine the final parameters: UNKPOW=1.05, UNKHTC=0.81 to 1.2 (see below), UNKCHO=0.85, and UNKSAT=29.8. The maximum deviation was about 2.5˚C, which occurred at node 7 (near the end of the condenser) at the end of the event. The RMS error (OBJECT) was about 1˚C.

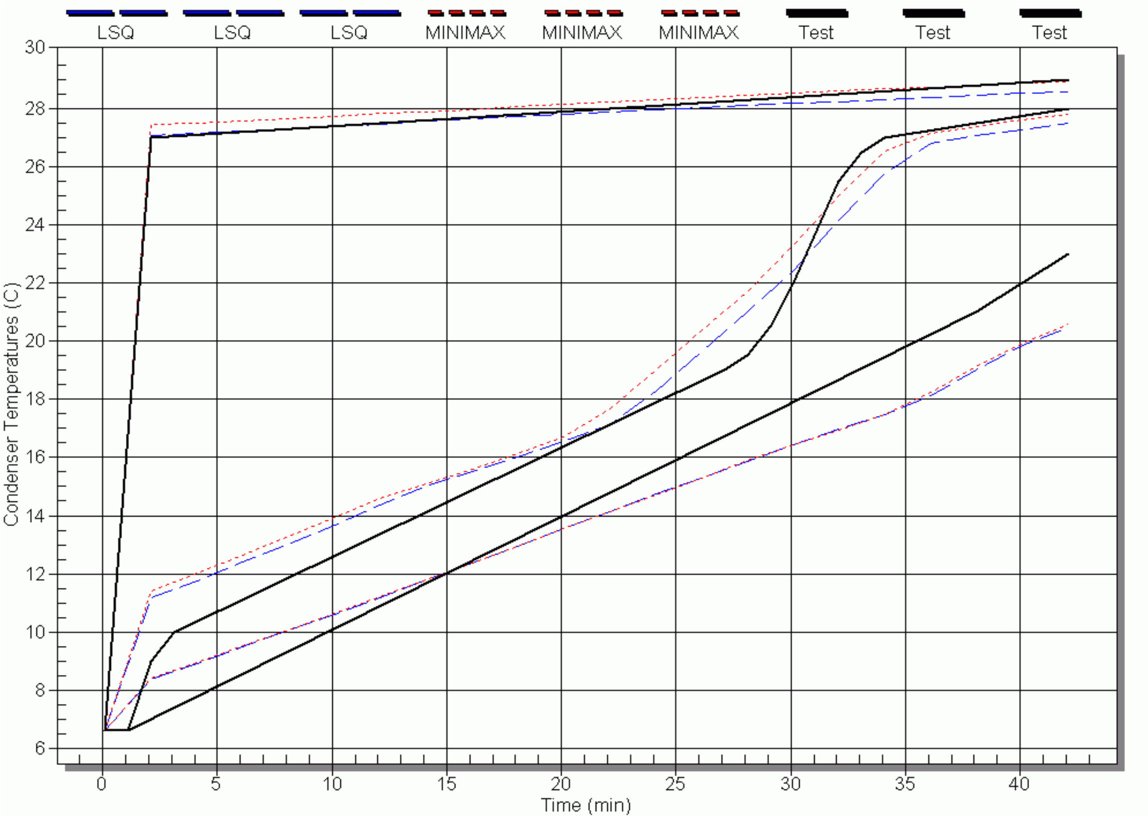

Figure E-7 Correlation Results for Both Methods

By comparison, the maximum error (MINIMAX) method requires between 30 to 100 PROCEDURE calls. (The exact number can be highly variable using MINIMAX methods.) The final parameters were: UNKPOW=1.03, UNKHTC=0.96 to 1.25 (see below), UNKCHO=0.79, and UNKSAT=30.2˚C. ERRMAX equals about 2.4˚C: about the same maximum error as the least squares method.

The value of UNKHTC turns out to vary significantly from run to run if minor changes to the inputs are made. The reason is that the underlying model is relatively insensitive to that parameter: changes in other design variables make a much bigger difference and so the Solver could (and does) end with a pseudo-random value for UNKHTC. This can be seen most clearly via a call to SOLCHECK, which results in the following information

```
SOLVER CONNECTIVITY AND SENSITIVITY CHECKER

                     UNKPOW       UNKHTC       UNKCHO       UNKSAT

      *OBJECT*     -3.562       0.1962        2.333        3.448
```

The above four numbers are slopes: partial derivatives of the objective function with respect to each design variable, taken about the starting point. Notice that the sensitivity of UNKHTC is an order of magnitude less than that of other design variables. In this case (and by no means to be taken as a global conclusion), UNKHTC could be removed as a design variable. The physical explanation for this insensitivity is that UNKHTC is multiplied by a conductance that is very large (that of condensation), and which is in series with other relatively low conductances.

The two methods produced the similar trends albeit different results. Both agreed that the conductive pad performance had been overestimated, and that the reservoir temperature had been underestimated. Neither produced a good comparison for node 7, suggesting that a critical unknown, perhaps effective plate capacitance or a single-phase heat transfer correction factor, is missing from the correlation, or that the model otherwise does not represent the real condition well enough at that point (e.g., perhaps a physical gap in the conductive pad exists locally). *Correlation can't fix an erroneous model, but it can improve a valid one.*

The MINIMAX method typical requires more set up time, defining constraints, call compare, etc. It is also more sensitive to noise in the data, and less amenable to prescans using DSCANLH. In some cases, however, it yields a better fit. In most real cases, however, it is not worth the effort involved.

Interestingly, one of the best fits was achieved using a method that is officially not recommended because it introduces discontinuities: the direct minimization of the maximum error (without using constraints). This fact is mentioned to reemphasize the point that some experimentation is recommended when using the Solver, especially when correlating data.

Input File for Sum of the Square Method

```
C        NOTE: HEADER SUBROUTINES IS NOT REPEATED BELOW
C
HEADER OPTIONS DATA
TITLE FLUINT SAMPLE MODEL - FIT FOR CPL GET AWAY SPECIAL (GAS) EXPERIMENT
SUMSQR
         OUTPUT   = cplfitls1.out
         USER1    = cplfitls1.usr
C
HEADER REGISTER DATA
C POWER TO THE EVAPORATOR
         UNKPOW   = 1.0
C HEAT TRANSFER COEF. IN THE CONDENSER PIPING
         UNKHTC   = 1.0
C CONTACT CONDUCTANCE BETWEEN PIPING AND CONDENSER PLATE
         UNKCHO   = 1.0
C RESERVOIR TEMPERATURE
         UNKSAT   = 29.0
C
HEADER SOLVER DATA
         METHO    = 1              $ SOLVER METHOD
C
HEADER DESIGN DATA
         0.9      <=      UNKPOW   <=      1.10
         0.75     <=      UNKHTC   <=      1.25
         0.5      <=      UNKCHO   <=      1.5
         28.5     <=      UNKSAT   <=      31.0
C
HEADER CONTROL CONSTANTS, GLOBAL
         UID      = SI
         ABSZRO   = -273.16
         OUTPUT   = 120.0                  $ OUTPUT EVERY 2 MINUTES
         OUTPTF   = 1.0E30
         DTMAXF   = 5.0                    $ MAX TIME STEP IN SECONDS
         NLOOPS   = 50
C
HEADER SOLOUTPUT CALLS
         CALL DESTAB
         CALL CSTTAB
C
HEADER USER DATA, GLOBAL
         POWER    = UNKPOW*2.0*255.0       $ 510.0 WATTS TOTAL
```

```
C
C GET FAST FLUID DESC. PRODUCED BY RAPPR FOR NH3 @ 29C
C
INSERT cplpdq.inc
C
HEADER ARRAY DATA,PLATE
C
                  10 = $ ARRAY OF NODE NUMBERS USED FOR COMPARISION
         1, 5, 7
C
                  15 = $ ARRAY OF ARRAY NUMBERS FOR TEST DATA
         101, 105, 107
C
                  20 = $ ARRAY TO HOLD THE PREDICTIONS
         SPACE,3
C
                  25 = $ ARRAY TO HOLD THE TEST DATA
         SPACE,3
C
C CPL TEST DATA
C
                  101 = $ CONDENSER INLET
         0.0,     6.6
         2.0,     27.
         42.,     29.
                  105 = $ CONDENSER MIDDLE
         0.0, 6.6
         1.0, 6.6
         2.0, 9.0
         3.0, 10.0
         2.7e+01, 1.9e+01
         2.8e+01, 1.95e+01
         2.9e+01, 2.05e+01
         3.0e+01, 2.2e+01
         3.2e+01, 2.55e+01
         3.3e+01, 2.65e+01
         3.4e+01, 2.7e+01
         4.2e+01, 2.8e+01
                  107 = $ CONDENSER EXIT
         0.0,     6.6
         1.0,     6.6
         38.,     21.
         42.,     23.
```

```
HEADER FLOW DATA,CPL,FID=6717$ START LOOP DESCRIPTION
C
C SET MODEL DEFAULTS
C SET PRESSURE FOR ALL LUMPS AT SATURATION FOR 29C
C
LU DEF,  TL = 6.6,PL = 1.1323E6, XL = 0.0
PA DEF,  FR = 0.0                  $ SHUT DOWN INITIALLY
C
C 0.0153 SQ IN TOTAL GROOVE AREA
C FOR 1-PHASE GROOVED LINE, USE HYD DIA ASSUM, AF = TOTAL
C PERIMETER = 16*3*0.034 + 16*0.014" = 1.856" = 4.71E-2 m
C FLOW AREA = 16.0*6.17E-7 + 0.25*PI*4.699E-3**2 = 2.72E-5
C
                  DH = 4.*2.72E-5/4.71E-2
                  AF = 2.72E-5
C
C DEFINE SINGLE SUBCOOLED TANK AS EVAPORATOR INLET
C
LU TANK,10,VOL = 125.0E-6  $ LIQUID HEADER (COLD)
                  COMP = 0.01/PL#this$ GUESS
C
C USE MFRSET AS PUMP
C
PA CONN,1040,10,40,DEV = MFRSET
C
C CONDENSER INLET (HEATER JUNCTION)
C SET AS SATURATED VAPOR
C
LU JUNC,40,XL = 1.0$ SAT VAPOR
                  PL = 1.0E30
                  TL = UNKSAT
C
C DEFINE CONDENSER: 9 CENTERED SEGMENTS OF 1.57 M TOTAL LENGTH
C WILL USE MODIFIED ROHSENOW CORRELATION FOR GROOVE HEAT TRANSFER
C IF APPROPRIATE AF IS USED
C
M HX,1,C,1,1,1,PLATE.1,40,10,NSEG = 9$ VAPOR LINE
         TLENT = 1.57
         DHS = 4.*2.72E-5/4.71E-2
         DEFF = 0.005
         AFS = 2.72E-5
         LU = JUNC,PA = STUBE$ LOW TEMPORAL RESOLUTION
         UAM      = UNKHTC
```

```
C
C FINALLY, ADD RESERVOIR AND LINE BETWEEN IT AND LIQUID HEADER
C INITIALIZE PLENUM AS TWO PHASE BUT USE LIQUID SUCTION
C (EASY WAY TO GET SATURATED LIQUID)
C
LU PLEN,99,XL = 0.1$ SAT LIQUID
                  TL = UNKSAT
C                 VOL = 2.8E-4                $ IF WERE TANK
C
PA CONN,99,10,99, STAT = RLS                  $ LIQ FROM PLEN SIDE
         DEV = STUBE,TLEN = 0.70              $ 70 CM
         DEFF = 0.005
C
HEADER NODE DATA, PLATE
C
C BOUNDARY
         -300,6.6,0.0
C
C PIPE NODES
C
C        GEN,1,9,1,6.6,85.9/9.0
         GEN,1,9,1,6.6,-1.0
C
C RADIATOR NODES
C
         11,6.6,           85.9/9.0 + 230.3 $ FIRST HALF PASS
         GEN,12,4,1,6.6,85.9/9.0 + 216.75$ NEXT TWO PASS
         GEN,16,4,1,6.6,85.9/9.0 + 289.0$ LENGTH TWO PASSES
C
HEADER CONDUCTOR DATA, PLATE
C
C BOUNDARY TO PLATE THROUGH COTHERM
C 63% and 51% FIN EFFICIENCIES
C
         301,11,300,25.6*0.63*UNKCHO
         GEN,302,4,1,12,1,300,0,24.4*0.63*UNKCHO
         GEN,306,4,1,16,1,300,0,32.4*0.51*UNKCHO
C
C RADIAL: TUBE WALL AND SADDLE WELD
C
         GEN,101,9,1,1,1,11,1,17.2
C
C AXIAL: ALONG FLOW DIRECTION
C
         423,12,13,0.85
         445,14,15,0.85
         467,16,17,0.85
         489,18,19,1.13
```

```
C
C SIDE: ACROSS FLOW DIRECTION
C
         212,11,12,5.28
         224,12,15,5.28
         235,13,14,5.28
         247,14,17,5.28
         256,15,16,5.28
         279,17,18,3.17
         268,16,19,3.17
C
HEADER FLOGIC 0, CPL
C
C MAKE SURE HEATER JUNCTION STAYS VAPOR
C
         CALL CHGLMP('CPL',40,'XL',1.0,'PL')
C
C SET MFRSET FOR CORRECT VOLUMETRIC FLOWRATE
C
         SMFR1040 = POWER/(HL40 - HL10)
C
HEADER VARIABLES 1, PLATE
C
C UPDATE SINK TEMPERATURE LINEARLY
         T300              = 6.6 + (17.0 - 6.6)*TIMEM/(42.0*60.0)
C
HEADER OUTPUT CALLS,CPL
HEADER OUTPUT CALLS,PLATE
         IF (NSTATO .EQ. 0) THEN
                  CALL TPRINT('ALL')
                  CALL LMPTAB('ALL')
                  CALL TIETAB('ALL')
                  CALL PTHTAB('ALL')
         ENDIF
         IF(NSOL .GT. 1)THEN
                  TTEST    = TIMEN/60.0
                  CALL PREPLIST('PLATE', 'T', A10, 0, A20)
                  CALL PREPDAT1(TTEST, 'PLATE', A15, 0, 0, A25)
                  CALL COMPARE(A20, A25, 0, 0, 'SUMSQR', DTEST)
                  OBJECT = OBJECT + DTEST
                  WRITE(NUSER1,11)TTEST,T1,A(25+1),T5,A(25+2),T7,A(25+3)
         ENDIF
11      FORMAT(1X,1PG11.4,4X,6G11.4)
```

```
HEADER OPERATIONS
C
BUILD GAS,PLATE
BUILDF GAS,CPL
C
C WRITE TRANSIENT HEADER
C
         WRITE(NUSER1,10)
10      FORMAT(/' CPL - RADIATOR TEMPERATURE RESPONSE TO STEP INPUT,'//
           .    '       TIME  (MIN)',5X,'T1',9X,'INLET',6X,'T5',9X,'MID-
DLE',5X,'T7',9X,'OUTLET')
DEFMOD PLATE
C
C HOLD HEATER JUNCTION ENTHALPY
C
         CALL HTRLMP('CPL',40)
C
C SAVE AWAY ONLY PLATE TEMPERATURES
C
         CALL SVPART('T',NTEST)
C START WITH PRESCAN
         NLOOPO = 12
         CALL DSCANLH
         NLOOPO = 100
         CALL SOLVER
C
HEADER PROCEDURE
         CALL RESPAR(NTEST)
         TIMEO    = 0.0
C
C RUN STEADY STATE TO GET FLUID INITIAL CONDITIONS HOLDING THERMAL
C HOLD TANK 10 TOO SINCE INITIALLY NO FLOW
C
         CALL DRPMOD('PLATE')
         CALL HLDLMP('CPL',10)
         NERVUS            = 3
         CALL FASTIC
         CALL ADDMOD('PLATE')
         CALL RELLMP('CPL',10)
C RUN TRANSIENT
         NERVUS            = 0
         OBJECT   = 0.0
         TIMEND   = 42.0*60.0       $ START 42 MINUTES TRANSIENT
         WRITE(NUSER1,*)' STARTING ',LOOPCO,'TH CALL TO PROC'
         CALL FWDBCK
         OBJECT            = SQRT(OBJECT/63.0)
         WRITE(NUSER1,*)' NSTATO = ',NSTATO
         WRITE(NUSER1,*)' OBJECT = ',OBJECT
```

Input File for the MINIMAX Method

```
C        NOTE: HEADER SUBROUTINES IS NOT REPEATED BELOW
C
HEADER OPTIONS DATA
TITLE FLUINT SAMPLE MODEL - FIT FOR CPL GET AWAY SPECIAL (GAS) EXPERIMENT
MINIMAX
         OUTPUT   = cplfitmnmx.out
         USER1    = cplfitmnmx.usr
C
HEADER REGISTER DATA
C POWER TO THE EVAPORATOR
         UNKPOW   = 1.0
C HEAT TRANSFER COEF. IN THE CONDENSER PIPING
         UNKHTC   = 1.0
C CONTACT CONDUCTANCE BETWEEN PIPING AND CONDENSER PLATE
         UNKCHO   = 1.0
C RESERVOIR TEMPERATURE
         UNKSAT   = 29.0
C ERROR OR DIFFERENCE BETWEEN MODEL PREDICTION AND TEST DATA
         ERRMAX   = 5.0
C
HEADER SOLVER DATA
C        METHO    = 1      $ SOLVER METHOD
         OBJECT   = ERRMAX $ OBJECT IS SET EQUAL TO MAX. ERROR
         NLOOPO   = 250    $ MAX. NUMBER OF LOOPS FOR SOLVER
         RCACTO   = 0.5    $ WHEN A CONSTRAINT BECOMES ACTIVE
C
HEADER DESIGN DATA
         0.9      <=       UNKPOW   <=      1.05
         0.75     <=       UNKHTC   <=      1.25
         0.5      <=       UNKCHO   <=      1.5
         28.5     <=       UNKSAT   <=      31.0
         0.0      <=       ERRMAX
C
HEADER CONSTRAINT DATA
         GEN CST, 01, 63, 1, -ERRMAX, ERRMAX
C
HEADER CONTROL CONSTANTS, GLOBAL
         UID      = SI
         ABSZRO   = -273.16
         OUTPUT   = 120.0  $ OUTPUT EVERY 2 MINUTES
         OUTPTF   = 1.0E30
         DTMAXF   = 5.0    $ MAX TIME STEP IN SECONDS
         NLOOPS   = 250
HEADER SOLOUTPUT CALLS
         CALL DESTAB
         CALL CSTTAB
```

```
HEADER USER DATA, GLOBAL
         POWER    = UNKPOW*2.0*255.0$ 510.0 WATTS TOTAL
         IPTA20   = 0               $ INTERNAL LOCATION OF ARRAY 20
         IPTA25   = 0               $ INTERNAL LOCATION OF ARRAY 25
C
C GET FAST FLUID DESC. PRODUCED BY RAPPR FOR NH3 @ 29C
C
INSERT cplpdq.inc
HEADER ARRAY DATA,PLATE
C
                  10 = $ ARRAY OF NODE NUMBERS USED FOR COMPARISION
         1, 5, 7
C
                  15 = $ ARRAY OF ARRAY NUMBERS FOR TEST DATA
         101, 105, 107
C
                  20 = $ ARRAY TO HOLD THE PREDICTIONS
         SPACE,3
C
                  25 = $ ARRAY TO HOLD THE TEST DATA
         SPACE,3
C
C CPL TEST DATA
C
                  101 = $ CONDENSER INLET
         0.0,     6.6
         2.0,     27.
         42.,     29.
                  105 = $ CONDENSER MIDDLE
         0.0, 6.6
         1.0, 6.6
         2.0, 9.0
         3.0, 10.0
         2.7e+01, 1.9e+01
         2.8e+01, 1.95e+01
         2.9e+01, 2.05e+01
         3.0e+01, 2.2e+01
         3.2e+01, 2.55e+01
         3.3e+01, 2.65e+01
         3.4e+01, 2.7e+01
         4.2e+01, 2.8e+01
                  107 = $ CONDENSER EXIT
         0.0,     6.6
         1.0,     6.6
         38.,     21.
         42.,     23.
C
```

```
HEADER FLOW DATA,CPL,FID=6717$ START LOOP DESCRIPTION
C
C SET MODEL DEFAULTS
C SET PRESSURE FOR ALL LUMPS AT SATURATION FOR 29C
C
LU DEF,  TL = 6.6,PL = 1.1323E6, XL = 0.0
PA DEF,  FR = 0.0                   $ SHUT DOWN INITIALLY
C
C 0.0153 SQ IN TOTAL GROOVE AREA
C FOR 1-PHASE GROOVED LINE, USE HYD DIA ASSUM, AF = TOTAL
C PERIMETER = 16*3*0.034 + 16*0.014" = 1.856" = 4.71E-2 m
C FLOW AREA = 16.0*6.17E-7 + 0.25*PI*4.699E-3**2 = 2.72E-5
C
                  DH = 4.*2.72E-5/4.71E-2
                  AF = 2.72E-5
C
C DEFINE SINGLE SUBCOOLED TANK AS EVAPORATOR INLET
C
LU TANK,10,VOL = 125.0E-6           $ LIQUID HEADER (COLD)
         COMP = 0.01/PL#this        $ GUESS
C
C USE MFRSET AS PUMP
C
PA CONN,1040,10,40,DEV = MFRSET
C
C CONDENSER INLET (HEATER JUNCTION)
C SET AS SATURATED VAPOR
C
LU JUNC,40,XL = 1.0$ SAT VAPOR
                  PL = 1.0E30
                  TL = UNKSAT
C
C DEFINE CONDENSER: 9 CENTERED SEGMENTS OF 1.57 M TOTAL LENGTH
C WILL USE MODIFIED ROHSENOW CORRELATION FOR GROOVE HEAT TRANSFER
C IF APPROPROPRIATE AF IS USED
C
M HX,1,C,1,1,1,PLATE.1,40,10,NSEG = 9        $ VAPOR LINE
         TLENT = 1.57
         DHS = 4.*2.72E-5/4.71E-2
         DEFF = 0.005
         AFS = 2.72E-5
         LU = JUNC,PA = STUBE       $ LOW TEMPORAL RESOLUTION
         UAM      = UNKHTC
C
C FINALLY, ADD RESERVOIR AND LINE BETWEEN IT AND LIQUID HEADER
C INITIALIZE PLENUM AS TWO PHASE BUT USE LIQUID SUCTION
C (EASY WAY TO GET SATURATED LIQUID)
C
```

```
LU PLEN,99,XL = 0.1$ SAT LIQUID
                  TL = UNKSAT
C                 VOL = 2.8E-4               $ IF WERE TANK
C
PA CONN,99,10,99, STAT = RLS         $ LIQ FROM PLEN SIDE
         DEV = STUBE,TLEN = 0.70     $ 70 CM
         DEFF = 0.005
C
HEADER NODE DATA, PLATE
C
C BOUNDARY
         -300,6.6,0.0
C
C PIPE NODES
C
C        GEN,1,9,1,6.6,85.9/9.0
         GEN,1,9,1,6.6,-1.0
C
C RADIATOR NODES
C
         11,6.6,           85.9/9.0 + 230.3 $ FIRST HALF PASS
         GEN,12,4,1,6.6,85.9/9.0 + 216.75$ NEXT TWO PASS
         GEN,16,4,1,6.6,85.9/9.0 + 289.0$ LENGTH TWO PASSES
C
HEADER CONDUCTOR DATA, PLATE
C
C BOUNDARY TO PLATE THROUGH COTHERM
C 63% and 51% FIN EFFICIENCIES
C
         301,11,300,25.6*0.63*UNKCHO
         GEN,302,4,1,12,1,300,0,24.4*0.63*UNKCHO
         GEN,306,4,1,16,1,300,0,32.4*0.51*UNKCHO
C
C RADIAL: TUBE WALL AND SADDLE WELD
C
         GEN,101,9,1,1,1,11,1,17.2
C
C AXIAL: ALONG FLOW DIRECTION
C
         423,12,13,0.85
         445,14,15,0.85
         467,16,17,0.85
         489,18,19,1.13
C
C SIDE: ACROSS FLOW DIRECTION
C
         212,11,12,5.28
         224,12,15,5.28
         235,13,14,5.28
```

```
         247,14,17,5.28
         256,15,16,5.28
         279,17,18,3.17
         268,16,19,3.17
C
HEADER FLOGIC 0, CPL
C
C MAKE SURE HEATER JUNCTION STAYS VAPOR
C
         CALL CHGLMP('CPL',40,'XL',1.0,'PL')
C
C SET MFRSET FOR CORRECT VOLUMETRIC FLOWRATE
C
         SMFR1040 = POWER/(HL40 - HL10)
C
HEADER VARIABLES 1, PLATE
C
C UPDATE SINK TEMPERATURE LINEARLY
         T300              = 6.6 + (17.0 - 6.6)*TIMEM/(42.0*60.0)
HEADER OUTPUT CALLS,PLATE
F        DIMENSION FAKE(1)
F        EQUIVALENCE (FAKE,CST01)
         IF (NSTATO .EQ. 0) THEN
                  CALL TPRINT('ALL')
                  CALL LMPTAB('ALL')
                  CALL TIETAB('ALL')
                  CALL PTHTAB('ALL')
         ENDIF
         IF(NSOL .GT. 1)THEN
                  TTEST    = TIMEN/60.0
                  JTEST    = (TTEST+1)/2.
                  IF(3*JTEST .GT. 63) CALL ABNORM('OOPS',0,'OOPS')
                  CALL PREPLIST('PLATE', 'T', A10, 0, A20)
                  CALL PREPDAT1(TTEST, 'PLATE', A15, 0, 0, A25)
F                 IF (JTEST .GT. 0)
F    +            CALL COMPARE(A(IPTA20),A(IPTA25),0,0,
     +                     'MINIMAX',FAKE(3*JTEST-2))
                  WRITE(NUSER1,11)TTEST,T1,A(25+1),T5,A(25+2),T7,A(25+3)
         ENDIF
11      FORMAT(1X,1PG11.4,4X,6G11.4)
C
HEADER OPERATIONS
C
BUILD GAS,PLATE
BUILDF GAS,CPL
C
C GET THE INTERNAL LOCATION OF ARRAY 20 AND 25
C
         CALL ARYTRN ('PLATE', 20, IPTA20)
```

```
         CALL ARYTRN ('PLATE', 25, IPTA25)
C
C WRITE TRANSIENT HEADER
C
         WRITE(NUSER1,10)
10      FORMAT(/' CPL - RADIATOR TEMPERATURE RESPONSE TO STEP INPUT,'//
         .     '        TIME   (MIN)',5X,'T1',9X,'INLET',6X,'T5',9X,'MID-
DLE',5X,'T7',9X,'OUTLET')
DEFMOD PLATE
C
C HOLD HEATER JUNCTION ENTHALPY
C
         CALL HTRLMP('CPL',40)
C
C SAVE AWAY ONLY PLATE TEMPERATURES
C
         CALL SVPART('T',NTEST)
         CALL SOLVER
C
HEADER PROCEDURE
         CALL RESPAR(NTEST)
         TIMEO    = 0.0
C
C RUN STEADY STATE TO GET FLUID INITIAL CONDITIONS HOLDING THERMAL
C HOLD TANK 10 TOO SINCE INITIALLY NO FLOW
C
         CALL DRPMOD('PLATE')
         CALL HLDLMP('CPL',10)
         NERVUS            = 3
         CALL FASTIC
         CALL ADDMOD('PLATE')
         CALL RELLMP('CPL',10)
C RUN TRANSIENT
         NERVUS            = 0
         TIMEND   = 42.0*60.0       $ START 42 MINUTES TRANSIENT
         WRITE(NUSER1,*)' STARTING ',LOOPCO,'TH CALL TO PROC'
         CALL FWDBCK
         WRITE(NUSER1,*)' NSTATO = ',NSTATO
         WRITE(NUSER1,*)' OBJECT = ',OBJECT
END OF DATA
```

Processor Output

```
LEAST SQUARES

 SOLVER CONVERGENCE CRITERIA MET AFTER    21 CALLS TO PROCEDURE


                          SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE  1163

MODEL = SINDA             FLUINT SAMPLE MODEL - FIT FOR CPL GET AWAY SPECIAL (GAS) EXPERIMEN


        NUMBER OF DESIGN VARIABLES =         4            TOTAL NO. OF CONSTRAINTS =           0
        CALLS TO PROCEDURE (LOOPCO) =       21            VS. MAXIMUM (NLOOPO) =             100  (   0   FINISHED    )
        CURRENT OBJECTIVE VALUE (OBJECT) =   1.02192      VS. TARGET (GOAL) = -1.000000E+30 (MINIMIZE)
        METHO = 1, NERVUS = 0, RCACTO =  0.100000    , RCERRO =  3.000000E-03, DELOBJ = -3.079176E-04

                                   DESIGN VARIABLE TABULATION

NAME AND STATUS       LOWER LIMIT AND STATUS          VALUE          UPPER LIMIT AND STATUS

UNKPOW   (ACTIVE)      0.90000     (FIXED)             1.0500          1.0500     (LIMITING)
UNKHTC   (ACTIVE)      0.75000     (FIXED)            0.80689          1.2500     (FIXED)
UNKCHO   (ACTIVE)      0.50000     (FIXED)            0.84827          1.5000     (FIXED)
UNKSAT   (ACTIVE)       28.500     (FIXED)             31.000          31.000     (LIMITING)~
```

```
   MINIMAX

SOLVER CONVERGENCE CRITERIA MET AFTER   31 CALLS TO PROCEDURE

                           SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE   234

MODEL = SINDA             FLUINT SAMPLE MODEL - FIT FOR CPL GET AWAY SPECIAL (GAS) EXPERIMEN


        NUMBER OF DESIGN VARIABLES =         5            TOTAL NO. OF CONSTRAINTS =         126
        CALLS TO PROCEDURE (LOOPCO) =       31            VS. MAXIMUM (NLOOPO) =             200  (   0   FINISHED    )
        CURRENT OBJECTIVE VALUE (OBJECT) =   1.91906      VS. TARGET (GOAL) = -1.000000E+30 (MINIMIZE)
        METHO = 3, NERVUS = 0, RCACTO =  3.000000E-02, RCERRO =  3.000000E-03, DELOBJ =   0.00000

                                   DESIGN VARIABLE TABULATION

NAME AND STATUS       LOWER LIMIT AND STATUS          VALUE          UPPER LIMIT AND STATUS

UNKPOW   (ACTIVE)      0.90000     (FIXED)             1.0275          1.0500     (FIXED)
UNKHTC   (ACTIVE)      0.75000     (FIXED)            0.97490          1.2500     (FIXED)
UNKCHO   (ACTIVE)      0.50000     (FIXED)            0.84851          1.5000     (FIXED)
UNKSAT   (ACTIVE)       28.500     (FIXED)             29.725          31.000     (FIXED)
ERRMAX   (ACTIVE)       0.0000     (FIXED)             1.9191         1.00000E+30 (FIXED)
```

```
                                    NAMED CONSTRAINT VARIABLE TABULATION

NAME AND STATUS       LOWER LIMIT AND STATUS          VALUE          UPPER LIMIT AND STATUS       DEFINING EXPRESSION (IF UNNAMED)

CST01    (UNHELD)     -1.9191      (FORMULA)        -0.28918          1.9191      (FORMULA)         (NONE)
CST02    (UNHELD)     -1.9191      (FORMULA)          2.1975          1.9191      (VIOLATED)        (NONE)
CST03    (UNHELD)     -1.9191      (FORMULA)          1.3089          1.9191      (FORMULA)         (NONE)
CST04    (UNHELD)     -1.9191      (FORMULA)        -0.31399          1.9191      (FORMULA)         (NONE)
CST05    (UNHELD)     -1.9191      (FORMULA)          1.3980          1.9191      (FORMULA)         (NONE)
CST06    (UNHELD)     -1.9191      (FORMULA)          1.0611          1.9191      (FORMULA)         (NONE)
CST07    (UNHELD)     -1.9191      (FORMULA)        -0.33135          1.9191      (FORMULA)         (NONE)
CST08    (UNHELD)     -1.9191      (FORMULA)          1.2675          1.9191      (FORMULA)         (NONE)
CST09    (UNHELD)     -1.9191      (FORMULA)         0.83153          1.9191      (FORMULA)         (NONE)
CST10    (UNHELD)     -1.9191      (FORMULA)        -0.34462          1.9191      (FORMULA)         (NONE)
CST11    (UNHELD)     -1.9191      (FORMULA)          1.1932          1.9191      (FORMULA)         (NONE)
CST12    (UNHELD)     -1.9191      (FORMULA)         0.61833          1.9191      (FORMULA)         (NONE)
CST13    (UNHELD)     -1.9191      (FORMULA)        -0.35663          1.9191      (FORMULA)         (NONE)
CST14    (UNHELD)     -1.9191      (FORMULA)          1.1222          1.9191      (FORMULA)         (NONE)
CST15    (UNHELD)     -1.9191      (FORMULA)         0.39687          1.9191      (FORMULA)         (NONE)
CST16    (UNHELD)     -1.9191      (FORMULA)        -0.36896          1.9191      (FORMULA)         (NONE)
CST17    (UNHELD)     -1.9191      (FORMULA)         0.90848          1.9191      (FORMULA)         (NONE)
CST18    (UNHELD)     -1.9191      (FORMULA)         0.20257          1.9191      (FORMULA)         (NONE)
CST19    (UNHELD)     -1.9191      (FORMULA)        -0.38064          1.9191      (FORMULA)         (NONE)
CST20    (UNHELD)     -1.9191      (FORMULA)         0.65823          1.9191      (FORMULA)         (NONE)
CST21    (UNHELD)     -1.9191      (FORMULA)        -5.98717E-03      1.9191      (FORMULA)         (NONE)
CST22    (UNHELD)     -1.9191      (FORMULA)        -0.39360          1.9191      (FORMULA)         (NONE)
CST23    (UNHELD)     -1.9191      (FORMULA)         0.41971          1.9191      (FORMULA)         (NONE)
CST24    (UNHELD)     -1.9191      (FORMULA)        -0.20795          1.9191      (FORMULA)         (NONE)
CST25    (UNHELD)     -1.9191      (FORMULA)        -0.40629          1.9191      (FORMULA)         (NONE)
CST26    (UNHELD)     -1.9191      (FORMULA)         0.20322          1.9191      (FORMULA)         (NONE)
CST27    (UNHELD)     -1.9191      (FORMULA)        -0.40893          1.9191      (FORMULA)         (NONE)
CST28    (UNHELD)     -1.9191      (FORMULA)        -0.42023          1.9191      (FORMULA)         (NONE)
CST29    (UNHELD)     -1.9191      (FORMULA)         9.30176E-02      1.9191      (FORMULA)         (NONE)
```

```
NAME AND STATUS       LOWER LIMIT AND STATUS          VALUE          UPPER LIMIT AND STATUS       DEFINING EXPRESSION (IF UNNAMED)

CST30    (UNHELD)     -1.9191      (FORMULA)        -0.59951          1.9191      (FORMULA)         (NONE)
CST31    (UNHELD)     -1.9191      (FORMULA)        -0.43274          1.9191      (FORMULA)         (NONE)
CST32    (UNHELD)     -1.9191      (FORMULA)         0.56601          1.9191      (FORMULA)         (NONE)
CST33    (UNHELD)     -1.9191      (FORMULA)        -0.79226          1.9191      (FORMULA)         (NONE)
CST34    (UNHELD)     -1.9191      (FORMULA)        -0.44500          1.9191      (FORMULA)         (NONE)
CST35    (UNHELD)     -1.9191      (FORMULA)          1.1298          1.9191      (FORMULA)         (NONE)
CST36    (UNHELD)     -1.9191      (FORMULA)        -0.97890          1.9191      (FORMULA)         (NONE)
CST37    (UNHELD)     -1.9191      (FORMULA)        -0.45803          1.9191      (FORMULA)         (NONE)
CST38    (UNHELD)     -1.9191      (FORMULA)          1.7012          1.9191      (FORMULA)         (NONE)
CST39    (UNHELD)     -1.9191      (FORMULA)         -1.1748          1.9191      (FORMULA)         (NONE)
CST40    (UNHELD)     -1.9191      (FORMULA)        -0.47145          1.9191      (FORMULA)         (NONE)
CST41    (UNHELD)     -1.9191      (FORMULA)          2.2762          1.9191      (VIOLATED)        (NONE)
CST42    (UNHELD)     -1.9191      (FORMULA)         -1.3750          1.9191      (FORMULA)         (NONE)
CST43    (UNHELD)     -1.9191      (FORMULA)        -0.48481          1.9191      (FORMULA)         (NONE)
CST44    (UNHELD)     -1.9191      (FORMULA)          1.4582          1.9191      (FORMULA)         (NONE)
CST45    (UNHELD)     -1.9191      (FORMULA)         -1.6520          1.9191      (FORMULA)         (NONE)
CST46    (UNHELD)     -1.9191      (FORMULA)        -0.49908          1.9191      (FORMULA)         (NONE)
CST47    (UNHELD)     -1.9191      (FORMULA)        -0.40164          1.9191      (FORMULA)         (NONE)
CST48    (UNHELD)     -1.9191      (CONSTRAINING)    -1.8985          1.9191      (FORMULA)         (NONE)
CST49    (UNHELD)     -1.9191      (FORMULA)        -0.51489          1.9191      (FORMULA)         (NONE)
CST50    (UNHELD)     -1.9191      (FORMULA)        -0.71375          1.9191      (FORMULA)         (NONE)
CST51    (UNHELD)     -1.9191      (VIOLATED)        -2.0472          1.9191      (FORMULA)         (NONE)
CST52    (UNHELD)     -1.9191      (FORMULA)        -0.57613          1.9191      (FORMULA)         (NONE)
CST53    (UNHELD)     -1.9191      (FORMULA)        -0.69873          1.9191      (FORMULA)         (NONE)
CST54    (UNHELD)     -1.9191      (VIOLATED)        -1.9584          1.9191      (FORMULA)         (NONE)
CST55    (UNHELD)     -1.9191      (FORMULA)        -0.59816          1.9191      (FORMULA)         (NONE)
CST56    (UNHELD)     -1.9191      (FORMULA)        -0.72018          1.9191      (FORMULA)         (NONE)
CST57    (UNHELD)     -1.9191      (FORMULA)         -1.8614          1.9191      (FORMULA)         (NONE)
CST58    (UNHELD)     -1.9191      (FORMULA)        -0.62122          1.9191      (FORMULA)         (NONE)
CST59    (UNHELD)     -1.9191      (FORMULA)        -0.73950          1.9191      (FORMULA)         (NONE)
CST60    (UNHELD)     -1.9191      (VIOLATED)        -2.2167          1.9191      (FORMULA)         (NONE)
CST61    (UNHELD)     -1.9191      (FORMULA)        -0.64542          1.9191      (FORMULA)         (NONE)
CST62    (UNHELD)     -1.9191      (FORMULA)        -0.77756          1.9191      (FORMULA)         (NONE)
CST63    (UNHELD)     -1.9191      (VIOLATED)        -2.5420          1.9191      (FORMULA)         (NONE)
```

PROBLEM F: LH$_2$ STORAGE TANK

This problem simulates a liquid hydrogen storage tank with a thermodynamic vent system (TVS), and includes both steady-state TVS sizing and transient filling. This problem was chosen to demonstrate the following FLUINT features:

1. nonequilibrium in tanks (imperfect mixing) with twinned tanks
2. 7000 series fluid descriptions
3. user-supplied heat transfer coefficients
4. steady-state sizing logic vs. transient simulation logic
5. use of heater junctions to simplify heat exchanger simulations
6. moveable ties

F.1 Problem Description

To minimize resupply launches and to maximize spacecraft life, long term storage of cryogenic propellants, sensor coolants, and fuels in space requires absolute minimal boil-off. With this requirement in mind, a liquid hydrogen ground test system (Figure F-1) was built and tested.[*] The test system consists of a four foot diameter storage tank that is blanketed by multi-layer insulation (MLI), and uses a TVS to minimize losses. The tank is suspended from above using low conductivity filaments. Liquid is drained from the bottom of the tank, flashed through a pressure regulator, and passed back through a heat exchanger that is completely submerged in the liquid that is inside of the tank. Within this internal heat exchanger, the remaining liquid (now at significantly reduced pressure and several degrees colder) is boiled, absorbing energy from the tank. The heat exchanger discharges vapor to a vapor cooled shield (VCS), which is a thin aluminum shell located within the MLI. Aluminum piping is attached to the VCS shell in an upward spiral, with approximately constant spacing between coils. This vapor passing through this pipe cools the shield, reducing heat leaks into the system. The warmed vapor hydrogen is then vented to vacuum through a control valve.

The goals of this analysis are to (1) calculate the performance of a half-full tank at the optimum TVS flowrate, and (2) simulate the transient no-vent filling of the tank from a colder, higher pressure source.

---

[*] John E. Anderson et al, *Evaluation of Long-term Cryogenic Storage System,* Cryogenic Engineering Conference, July 1989.

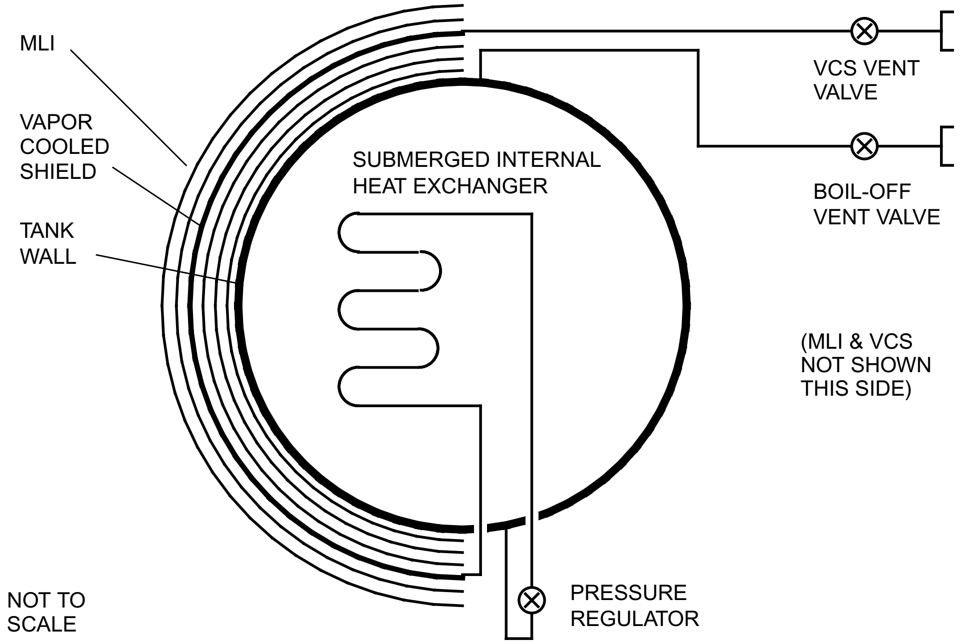

Figure F-1 Schematic of Storage Tank with Thermodynamic Vent System

The parameters of the system are:

Tank:

Inner diameter	42 in
Volume	22.45 ft^3
Thickness	0.3 in
Conductance at top from environment	1.24E-2 BTU/°F
Material	Steel
Conductivity	8.33 BTU/hr-ft-°F
Specific Heat	0.11 BTU/lb_m-°F

Submerged Internal Heat Exchanger:

Piping inner diameter	0.18 in
T-shaped Fin, each of 2 sections	2in x 1/16in
Total pipe length	160 in.
Material	Copper
Conductivity	500. BTU/hr-ft-°F

VCS:

Thickness	0.045 in
Conductance at top from environment	1.86E-4 BTU/°F
Material	Aluminum
Conductivity	133. BTU/hr-ft-°F
Specific Heat	0.21 BTU/lb_m-°F

VCS Piping:

Diameter	0.313 in
Thickness	0.035 in
Total Length (Spiral)	80. ft
Material	Aluminum
Conductivity	133. BTU/hr-ft-°F

MLI:

Outer Diameter	51 in
Tank to VCS effective emissivity (ε^*)	0.008
VCS to skin effective emissivity (ε^*)	0.007
Skin emissivity	0.1
Chamber temperature	540 R

Internal tank heat transfer:

Liquid to subcooled walls	20 BTH/hr-ft^2-°F
Liquid to superheated walls	Pool boiling (Sample Problem C)
Vapor to subcooled walls	20 BTH/hr-ft^2-°F (condensing)
Vapor to superheated walls	4 BTH/hr-ft^2-°F

TVS:

Flowrate (initial)	0.0382 lb_m/hr
Nominal pressure	4 psia

Fill Source:

Temperature	Minimum (near freezing)
Pressure	60 psia

Some of the above parameters were calculated by analyses that are not documented in this section, but that merit some discussion.

The MLI performance was estimated from test data—effective MLI emissivities are notoriously difficult to predict *a priori*, and their prediction is not relevant to this problem in any case. To calibrate these factors, data from a boil-off (vented vapor, constant pressure) test were used. Only two values are needed from such a test: the VCS temperature and the rate of boil-off. Data from other tests with zero and excess TVS flowrate provided an independent confirmation of these values and of the model in general.

One of the primary purposes of such a model is to help predict the required TVS flowrate, which is a significant inverse figure of merit for such a storage system: a lower value indicates better insulation and less valuable liquid lost. Because of the long time scales involved in such testing (it takes a full week to reach equilibrium), it is extremely difficult to experimentally determine the minimum (and therefore optimum) TVS flowrate required to keep the tank pressure from rising. By the time such tests have been completed, the LH_2 fill level has changed so drastically (perhaps the tank has drained completely) that the results may be indeterminate—*a steady value is required from an inherently unsteady system*. Analytically, arriving at a design value for the TVS flowrate is much more tenable: the TVS flowrate is equal to the heat rate that enters the tank divided by the heat of vaporization. Unfortunately, this heat rate and the TVS flowrate are very tightly coupled.

Complicated iterative logic could be created to guide a model toward the design flowrate in the course of a steady state run, but tight coupling noted above would make convergence very elusive. The Solver could be used in goal seeking mode, with the TVS flowrate being the sole design variable, the GOAL set to be zero and the OBJECT set to be the mismatch between the net heat leak and the product of TVS flowrate and the heat of vaporization.*

However, this sample problem predates the advent of the Solver, so instead a parametric sweep of steady-state system response versus TVS flowrate were produced, the results of which are depicted in Figure F-2. This method predicts a TVS flowrate of about 0.0382 lb_m/hr corresponding to a heat leak into the tank of about 7 BTU/hr. As the bonus of using this method, the system response to off-design conditions can also be seen in this same chart. For example, it is evident from this figure that at zero TVS flowrate the heat leak into the tank would be almost five times greater than at the design flowrate, with a proportional increase in the amount of liquid lost due to boil-off: there is a substantial benefit derived from the incorporation of the TVS.

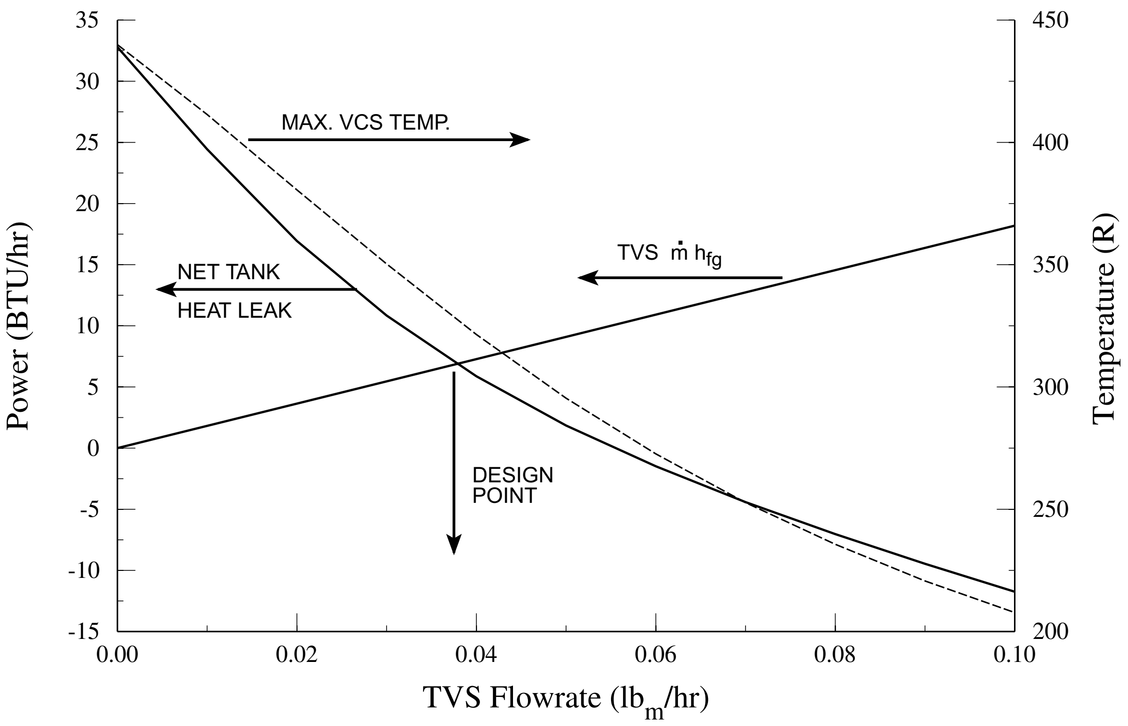

Figure F-2 Parametric Results to Predict Optimum TVS Flowrate

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* Or the TVS flowrate itself could be minimized subject to the constraint (CONSTRAINT DATA) that the net heat into the tank is zero, an equality constraint.

F.2 A SINDA/FLUINT Model

The modeling approach is governed by the goals of the analysis: to capture the behavior of the whole system, not to provide detailed point-design analyses of its constituent components. The tank wall, VCS, and MLI were each divided equally by area into nine horizontal sections. Figure F-3 shows the schematic of the mathematical model.

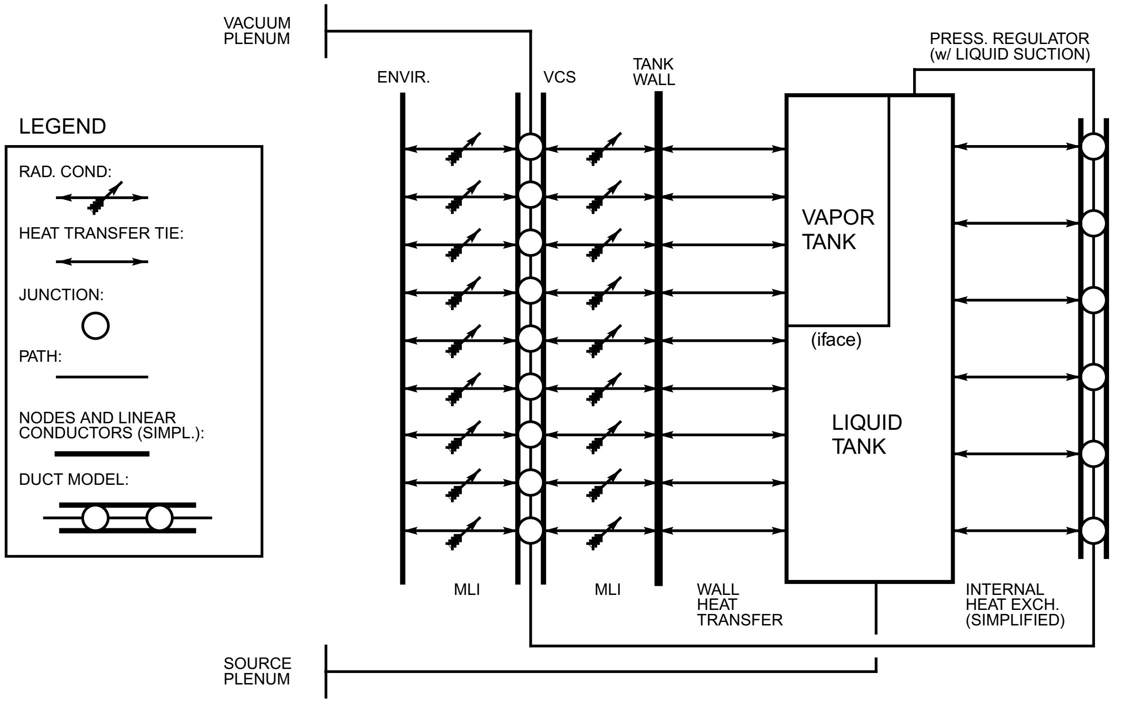

Figure F-3 Schematic of Storage Tank Math Model

The decision to divide the model into nine sections was driven by the need to resolve the heat transfer (1) within the VCS and (2) between the tank wall and its fluid with adequate spatial resolution. Actually, because of the relatively large conductivities in the VCS and tank walls, fewer sections would probably suffice—the system can be characterized by fewer temperatures. Because of the large temperature variations in the aluminum VCS, temperature-varying conductivities and specific heats might be appropriate, and are easily included if the property information is readily available. However, these quantities were assumed constant in this analysis for simplicity. While each node in the tank wall has the same mass, the conductivities between them vary according to the spherical geometry. The same is true for the VCS shell nodes. These variations are estimated based on rough KA/L style calculations.

A single FLUINT control volume (or "tank") could be used to simulate the storage tank itself. This decision precludes thermal stratification, which is valid because of the relatively large conductivity of the thick tank wall and of the surrounding VCS. However, the use of a single (untwinned) tank would imply perfect mixing, which would lead to sudden collapse of the vapor volume when the fill transient began. The fluid is not well stirred: twinned tanks will be used, one for the vapor phase and another for the liquid, with a default FLAT iface between them. If thermal stratification *were* important in either the liquid or vapor regions, these regions could have been further subdivided using ifaces, with twinned tanks only being used where the liquid/vapor interface existed.

The heat transfer between the phases is difficult to predict with any certainty, but can be assumed to be less than the heat transfer to the wall due to the lack of shear at the interface. The default value multipliers (negative values of UVT, ULT) were used to input these coefficients, which are influenced by the presence of natural convection in the vapor side and the stirring effect of injected fluid in the liquid side. For this example, values of ULT and UVT are input as -4.0 and -2.0, meaning four times the liquid solid conduction value and two times the vapor conduction value, both of which are dependent only on the shape of the volumes. The reader is welcome to investigate the transient fill problem by parametrically varying these values. However, note that using zero heat and mass transfer at the interface (UVT=ULT=0.) changes the results very little: the majority of the exchange is with the wall, not between the liquid and vapor phases.

On the other hand, the interface area (AST) *is* known with a high degree of certainty, and is updated in the logic blocks accordingly.

The heat transfer between the tank wall and the fluid within is dependent not only on the phase of the adjacent fluid, but also on effective "state" of the wall (i.e., is it cold enough to cause local condensation, or warm enough to cause local boiling?). At different fill levels, the fixed wall nodes will be adjacent to a different FLUINT tank. This difficulty is overcome by the use of the PUTTIE routine, which allows the ties to be reattached as the tank fills or empties.*

For this system, there is no true time-independent state unless the insulation is perfect: the tank must eventually empty. However, the fill level varies slowly (by definition—otherwise the storage system is a failure). A pseudo-steady solution may be found by using HLDLMP on the tank during steady-state solutions, which is equivalent to treating them like plena. The tank will be subsequently "released" (using RELLMP) to simulate transient filling.

A path with liquid suction is used to extract only liquid from the liquid tank, which would otherwise be assumed to be homogeneously distributed. While two-phase flow *can* occur within such a divided-phase (nonequilibrium) model, the importance of the liquid suction is minimal in this case: no bubbles form in the liquid. The effect of gravity (i.e., fill level) on this pipe penetration is minimal because of the low density of hydrogen. Otherwise, the elevation of the liquid tank could be set the be the height of the interface over the bottom of the tank, such that the liquid tank's pressure represented the pressure at the interface.

This same path, a DPRVLV downstream pressure regulator, will be used to simulate the pressure regulator. The set-point (PSET) of the back-pressure (i.e., that of the TVS line) is set to 4 psia. During the steady-state run, the K-factor of that valve will be varied as needed to achieve the desired results. But since it is desired to use a fixed valve position during the transient, the K-factor is held fixed before the transient by setting its upper and lower limits (FKH and FKL, respectively) to be equal to the resulting FK from the steady state run. This operation is performed in OPERATIONS.

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* Neither Sinaps*Plus* nor FloCAD postprocessing accept dynamic network re-wiring such as PUTTIE performs.

Similarly, the exhaust to “vacuum” needs to be represented by a fixed flowrate during steady-state, but during the transient event a fixed K-factor is desired. In other words, an MFRSET connector is ideal for the steady-state run, but a LOSS connector is desired during the transient. In this case, both paths are input in parallel, and only one is used at a time. The paths are switched using DUP factors. The FK for the LOSS element is sized from the MFRSET-caused pressure drop resulting from the steady-state prediction.

At both the TVS entrance and exit, pressure drops are large and choking is possible. At the backpressure regulator, the default of MCH=-2 (nonequilibrium expansion) is realistic, but the throat pressures would be below that available in the simplified fluid description. Therefore, equilibrium expansion (MCH=2) is chosen instead. Such a choice may underestimate the critical flow rate, but in this case the TVS flowrate is limited by the MFRSET, which itself represents choked flow by design: an orifice or control valve to be sized, perhaps.

Because of the relative sizes and time scales, nearly all of the fluid model employed time-independent junctions and connectors, while the thermal model included capacitance lags of the tank and VCS. In other words, the hydrodynamic response was assumed instantaneous compared to the thermal response.

The liquid tank is tied via HTU ties to the fins of the internal heat exchanger. Initial models showed that this internal heat exchanger is greatly oversized because of the small flowrate needed to balance the small heat leak into the tank. The inlet fluid, initially at a quality of about 0.18, boils quickly in the first few inches of the twelve foot long heat exchanger. Furthermore, for all flowrates of interest, the vapor exits at the temperature of the liquid in the tank—the effectiveness of the heat exchanger is unity. To capture the boiling would require a very fine mesh network at the inlet. Such detail is really only needed to help design the heat exchanger itself, and is unimportant to the operation of the system. Therefore, a modeling “trick” is employed to greatly simplify the heat exchanger model without sacrificing its hydrodynamic or thermodynamic behavior. The trick is to use a “heater junction” (via HTRLMP) in the first leg of the heat exchanger to decouple the thermodynamic solution without disrupting the hydrodynamic solution: the heater junction is used to convert the flow into vapor without considering the heat transfer process involved. Energy is conserved because the energy required to perform this evaporation is extracted from the tied node. Because of the complexity of the internal heat exchanger design and its lack of relative importance, further discussions of this portion of the model are not necessary.

The description of the working fluid itself deserves attention. FLUINT contains a “library” of properties for 20 room temperature refrigerants. To analyze a fluid such as hydrogen, the user must provide a description in the input file using an FPROP block. In this example, a simplified two-phase (7000 series) description of hydrogen was developed using handbook values for the properties of each phase and for the properties of the saturation dome. From these values, FLUINT develops a thermodynamically consistent internal description of hydrogen. Tabular descriptions (input as 6000 series fluids) also exist, and would normally represent a better choice because they are faster, more accurate, and valid over a wider range than a 7000 series fluid.

F.3 The Input File

The input file is listed immediately following the last section.

OPTIONS DATA—As with previous examples, a user file (USER1) is named that will contain a summary listing of the output file. A restart file is used to save the results of the steady-state analysis for future use.

CONTROL DATA—English units are chosen, with units of °R and psia. SIGMA is set equal to the built-in constant sbcon (0.1713E-8). 500 steady-state iterations (NLOOPS) are allowed. The value of OUTPTF is given as 1 minute versus 6 minutes for the value of OUTPUT; the fluid submodel OUTPUT CALLS block is used for frequent printing the USER1 file, while the thermal submodel OUTPUT CALLS block is used for standard output calls.

USER DATA—One variable, PTEST, is declared for use in logic as a unit conversion constant. A register could have been used equivalently if renamed (ATEST through ZTEST are reserved names for USER DATA).

REGISTER DATA—Variables to be used in the data blocks and logic blocks are declared and initialized. Among them are heat transfer coefficients, and various geometric properties. Some, such as TSAT, are simply being declared in REGISTER DATA but will be initialized and used in logic blocks. Most others are simply used to centralize key variables used in data blocks, perhaps to enable future sensitivity studies, correlations, etc.

"PIE" is used to fetch the value of the built-in constant "pi" and enable its use within Fortran logic blocks, since "pi" is otherwise only available within input expressions. (This is a fairly common "trick" in SINDA/FLUINT.)

NODE DATA—Four thermal submodels are input: (1) *IHX*, the internal heat exchanger consisting of 6 arithmetic nodes along the copper pipe and fin (#1-6) and four more nodes at other locations lacking a pipe, (2) *TANK*, the model of the nine vertical sections of steel wall, (3) *VCS*, a similar model for the aluminum VCS shell, and (4) *MLI*, a corresponding model of the outer layer of MLI, which is assumed massless. The MLI model also contains the boundary node representing the chamber source.

CONDUCTOR DATA—For the IHX model, conductors are input for the axial terms. In the VCS and TANK models, linear conductors are used for vertical conduction with varying KA/L, where A and L are only roughly approximated. The MLI submodel contains the effective radiation conductances linking the tank, the VCS, the MLI, and the chamber. These conductors assume nearly planar radiation between the vertical segments as a first order approximation.

ARRAY DATA—Arrays of void fractions versus segment position are input. These arrays are used in the FLOGIC 0 block to locate the liquid surface with respect to the wall nodes.

FLOW DATA—One fluid submodel named HYDRO is used. The working fluid is “7702”, meaning the simplified user-input two-phase parahydrogen description discussed below. The names and types of the major elements are as follows:

- Tank model:
    - TANK 1 ....liquid side of tank (primary twin) (stagnant)
    - TANK 2 ....vapor side of tank (secondary twin) (stagnant)
    - FLAT iface, CONSTQ ftie, and superpaths are generated by default for twins
    - HTU ties 201-255 ....ties to *outside* of internal heat exchanger
    - HTU ties 301-309 ....ties to tank wall
- Throttle and internal heat exchanger (IHX) model:
    - DPRVLV 100..................pressure regulator (throttle)
    - HTN ties 101-106 ....ties to *inside* of internal heat exchanger
    - STUBEs 101-106 ....IHX line
    - JUNCs 101-106.............IHX line
- VCS model:
    - HTNC ties 401-409........ties to VCS plate with fin efficiency term
    - STUBEs 401-410 ....VCS line
    - JUNCs 401-409.............VCS line
- Flow boundary conditions:
    - MFRSET 998.................outlet valve to “vacuum”
    - LOSS 999......................replaces above MFRSET during transient
    - PLEN 999......................”vacuum” (1 psia, warm vapor, stagnant)
    - PLEN 1999....................fill source (60 psia, cold liquid, stagnant)
    - STUBE 1999 ....fill line (invisible during steady state)

FLOGIC 0—This routine updates the somewhat detailed model of the tank wall heat transfer. The heat transfer model adjusts the 300 series ties according to fill level and the temperature of the wall compared to the saturation point. The logic loops through these ties from bottom to top, locating the position of the interface compared to the wall segments, which have equal heat transfer area but unequal depths due to the spherical geometry of the storage tank.

If the tank wall is at least partially covered and is warmer than the saturation temperature, then pool boiling heat transfer is included by a call to POOLBOIL (see Section 7 of the main volume). For colder submerged walls, a single-phase conduction value is assumed. Similarly, for vapor segments the heat transfer coefficient is a function of whether the wall temperature is above or below saturation. If the wall temperature is below saturation, an estimated condensation coefficient is used. Note that as the liquid level rises or recedes, a single wall node will “see” a different tank. This change is effected via the PUTTIE routine, which can also be used to tie to other nodes or to move ties completely.

Finally, the interface area AST is calculated as a function of fill level, which is related to the size of the vapor volume (Tank #2). An internal FLUINT routine is used to calculate a cube root; to prevent the debug feature from flagging out the name “CUROOT” as an unidentified variable, an ’F’ is placed in column 1 to prevent attempted translation and therefore validation. Alternatively, the spell checker feature may be turned off locally with a SPELLOFF command, or globally with a SPELLOFF command in OPTIONS DATA. (Note use of SPELLOFF is not recommended since simple spelling errors can then lead to errors that are difficult to detect.)

OUTPUT CALLS—The infrequently called block for the MLI submodel contained calls to the standard FLUINT tabulation routines as well as TPRINT. During transients, the block for HYDRO will be called more frequently, printing a single line of tailored information to the user file with each call.

OPERATIONS—The twinned tank volumes are initially set on the basis of the input value of quality. This is corrected using calls to CHGVOL to make each tank initially use half the available volume. Next, the configuration is built, containing all input submodels. Because NSOL=0 by default, this BUILDF command has the side effect of combining the twinned tanks (deactivating the secondary tank). The main tank is then held (e.g., put in a boundary state) by HLDLMP for FASTIC ("STEADY"), and will be released before the transient via calls to RELLMP. Similarly, the inlet of the internal heat exchanger, Junction #101, is turned into a saturated vapor heater junction by calls to CHGLMP and to HTRLMP, which causes the enthalpy to become fixed. The energy required to boil all of the liquid (entering at a quality of about 0.18) in #101 is automatically extracted from the tied node IHX.1. This represents heat transfer by a nonphysical process, but prevents the program from requiring finer spatial resolution to discern the boiling process, which occurs within a few inches of pipe. Because the remainder of the heat exchanger brings the TVS flow up to the temperature of the liquid temperature by the exit, the entire heat exchanger could be replaced by one such tie to a HTRLMP junction—a simple representation of a perfect heat exchanger.

The pressure regulator is modeled as a DPRVLV, but after the steady state the value of its resistance is fixed by setting the upper and lower limits (FKH and FKL, respectively) on FK to be the current value of FK (i.e., the value returned by the steady-state run).

To model the exhaust valve, an MFRSET is used during steady-states to simplify the model (again, this is easier than trying to dynamically size a LOSS factor. Replacing the MFRSET with an equivalent LOSS allows the TVS flowrate to vary with upstream tank pressure during the transient. DUP options are used to turn off one path and turn on another. Recall that a path with DUPI=DUPJ=0 still exists, it is simply ignored by the adjacent lumps. The lumps will affect the path, but not vice versa.

DUP factors are similarly exploited to make the fill line (STUBE 1999) "appear" suddenly at the start of a transient. A CTLVLV in series with the STUBE would accomplish the same, but would require an additional junction if it did not replace the STUBE completely, and would add a small pressure drop which might be undesirable.

FPROP DATA—Two-phase parahydrogen may be adequately described by a simple 7000 series fluid as long as the vapor pressures never exceed a fraction of the critical point. This particular description contains arrays instead of single values and point-slope properties. It is very accurate along the isobar representing one atmosphere, and is reasonably accurate for slightly higher pressures. The second DOME input line could be replaced by the commented line for even greater accuracy within the tank itself, but the accuracy at lower pressures (e.g., within the TVS) would suffer slightly.

F.4 Output Description

The user summary file and the selected portions of the OUTPUT file are listed following the input file. Figure F-4 contains a plot detailing the fill event.

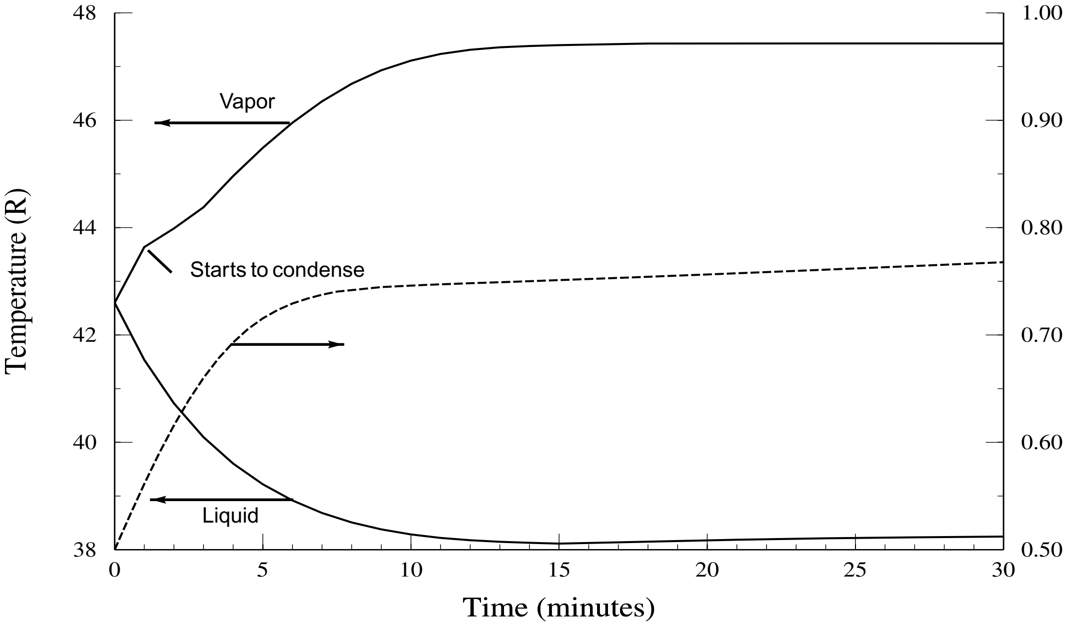

Figure F-4 Temperature Response During Fill

Because the liquid entering the tank is colder than the initial tank state, a perfect mixing assumption would cause an immediate collapse of the tank pressure (as happens in the pressure cooker sample problem), and this lowered pressure would persist until the liquid tank became hard-filled within a few minutes, at which time the pressure in the tank would suddenly jump up to the source pressure of 60 psia. Modeling the storage tank with a single FLUINT tank will result in such behavior (see also the pressure cooker sample problem presented earlier).

With interphase heat and mass transfer reduced to finite time scales, the cold fluid entering the tank compresses the vapor, causing an increase rather than a decrease in tank pressure. Even for very large heat transfer coefficients (i.e., nearer to perfect mixing), the initial influx of liquid is so swift compared to the condensation rate that the vapor compresses rather than collapses. The influx thus leads a decrease in the flowrate: a negative feedback loop exists. Because the liquid is colder, the vapor will begin to condense. Actually, the vapor condenses against the wall much more readily, essentially staying very close to saturation.

After about 15 minutes, the system is quasi-steady even though the tank is not full: the pressures have equilibrated and the influx rate is matched by the condensation rate within the vapor: any decrease in vapor volume is offset by further addition of cold liquid at the bottom. Because the liquid tank gains more cold liquid than warm condensate (which is essentially negligible), the temperature would continue to drop if no wall model were included. In this analysis, the liquid eventually starts to warm because of energy absorbed from the environment. The TVS flowrate has increased due to the increased tank pressure, but either this increase is negligible or, more likely, the VCS temperature is decreasing very slowly and thus has not intercepted much additional energy. (The more pressure in the tank, the *less* equilibrium TVS flowrate is required to maintain that saturation condition. However, such a system would be unstable: a transient increase in pressure needs to be offset by a transient *increase* in TVS flowrate.)

Input File

```
HEADER OPTIONS DATA
TITLE LH2 STORAGE TANK WITH INTERNAL HX AND VAPOR COOLED SHIELD
C
         MLINE    = 52
         MODEL    = TVS
         OUTPUT   = tvs.out
         RSO      = tvs.rso
         RSI      = tvs.rsi
         USER1    = tvs.usr
C        USER2    = tvs.us2
C
HEADER CONTROL DATA, GLOBAL
         UID      = ENG              $ ENGLISH UNITS
         ABSZRO   = 0.0              $ DEGREES RANKINE
         PATMOS   = 0.0              $ PSIA
         NLOOPS   = 500
         SIGMA    = sbcon            $ S-B CONSTANT IN ENGLISH UNITS
         OUTPUT   = 0.1
         OUTPTF   = 1.0/60.0         $ OUTPUT EACH MINUTE
C
HEADER USER DATA, GLOBAL
         PTEST          = 144.*grav$ UNIT CONVERSION CONSTANT
HEADER REGISTER DATA
         HTLIQ    = 20.0             $ TANK TO BULK LIQ HTC
         HTVAP    = 4.0              $ TANK TO BULK VAP HTC, SINGLE PHASE
         HTCON    = 20.0             $ TANK TO BULK VAP HTC, CONDENSATION
C        ABOVE MAY SEEM LOW BUT DOMINATED BY HTVAP: MUST GET TO WALL FIRST.
         TSAT     = 1.0              $ SAT TEMP: TEMP VALUE
         RESOL    = 9                $ RESOLUTION
         RTANK    = 0.5*42./12.      $ TANK RADIUS (FT)
         AWALL    = 4*pi*Rtank^2/RESOL$ AREA OF WALL, EACH SEGMENT
         VTANK    = 4*pi/3*Rtank^3   $ TOTAL TANK VOLUME
         RVCS     = 0.5*48./12.      $ VCS RADIUS (FT)
         AVCS     = 4*pi*RVCS^2/RESOL$ AREA OF VCS, EACH SEGMENT
         VCSOD    = 0.313/12.        $ OD of VCS pipes
         VCSID    = VCSOD - 2*0.035/12$ ID of VCS pipes
         RMLI     = 0.5*51./12.      $ VCS RADIUS (FT)
         AMLI     = 4*pi*RMLI^2/RESOL$ AREA OF VCS, EACH SEGMENT
         PIE      = pi               $ get value of PI for logic
         IHXpipeO = 0.25/12.$ INTERNAL HX PIPE X-SECTION Outer Diam
         IHXpipeD = 0.18/12.$ INTERNAL HX PIPE X-SECTION Inner Diam
         IHXpipeL = 160./12.$ INTERNAL HX PIPE X-SECTION Length
         IHXpipeA = pi/4*(IHXpipeO^2-IHXpipeD^2)$ INTERNAL HX PIPE X-SEC
         IHXfinA = 2*2.*(1/16)/144$ INTERNAL HX fin X-SECTION AREA
         IHXfinS = 2*2*2./12$ INTERNAL HX fin SURFACE AREA per unit length
         CuCond   = 500.0            $ Copper conductivity
```

```
         VCScond  = 133.            $ VCS conductivity
         VCSthick = 0.045/12        $ VCS thickness
         WallCond = 8.33            $ Tank wall conductivity
         WallThk  = 0.3/12          $ Wall thickness of tank
C Angles useful for wall breakdown (see below)
         theta1   = pi*38.94/180
         theta2   = pi*56.25/180
         theta3   = pi*70.53/180
         theta4   = pi*83.62/180
C
HEADER NODE DATA,IHX
C INTERNAL HEAT EXCHANGER: ALL ARITHMETIC NODES; NEGLECT CAPACITANCE OF
C 1/16” COPPER FINS. (DOWNSTREAM DISCRETIZED IN FLUINT MODEL)
C
C ALMOST ALL BOILING HAPPENS QUICKLY IN FIRST FOOT
C TOTAL LENGTH IS 160” WITH ELBOWS EVERY APPROX 27”
C DIVIDE INTO 6 SEGMENTS 2.22’  EACH
C
         GEN 1,6,1,43.,-1.0         $ PIPE/FIN NODES (@ ROOT OF FINS)
         201,43.,-1.0               $ MIDDLE OF UNPIPED SECTIONS
         202,43.,-1.0               $ MIDDLE OF UNPIPED SECTIONS
         204,43.,-1.0               $ MIDDLE OF UNPIPED SECTIONS
         205,43.,-1.0               $ MIDDLE OF UNPIPED SECTIONS
C
HEADER CONDUCTOR DATA,IHX
C INTERNAL HEAT EXCHANGER: AXIAL CONDUCTION TERMS
C                          pipe A    fin A     K  L $ TWEEN PIPE NODES
         GEN 1,5,1,1,1,2,1,(IHXpipeA+IHXfinA)*CuCond/(IHXpipeL/6)
         100,1,TANK.1,IHXpipeA*CuCond/1.0$ TO TANK BASE (SAY 1 FT PIPE)
C ACTUALLY, #6 AND TANK.1 ARE NEARLY CO-LOCATED
         101,6,TANK.1,IHXpipeA*CuCond*12.0$ TO TANK BASE (SAY 1 IN PIPE)
         201,1,201,IHXfinA*CuCond/1.25       $ TO UNPIPED SECTIONS
         202,2,202,IHXfinA*CuCond/1.25       $ TO UNPIPED SECTIONS
         204,4,204,IHXfinA*CuCond/1.25       $ TO UNPIPED SECTIONS
         205,5,205,IHXfinA*CuCond/1.25       $ TO UNPIPED SECTIONS
         203,201,202,IHXfinA*CuCond/2.5      $ TWEEN UNPIPED NODES
         206,204,205,IHXfinA*CuCond/2.5      $ TWEEN UNPIPED NODES
C
```

```
HEADER NODE DATA,TANK
C
C TANK WALL NODES: DIVIDE TANK INTO 9 SECTIONS REPRESENTING
C EQUAL AREA PORTIONS COVERED BY VCS.  HORIZONTAL SLICES.
C
C        V of SPHERICAL SECTION= 1/3*PI*H^2*(3R-H)
C        A of SPHERICAL SECTION= 2*PI*R*H
C
C        NODE     h/R              THETA BOTTOM/TOPALPHA BOTTOM/TOP
C        ---------------------------------------------------------------
---
C        1        0.-.222          0./38.94     1./.9657
C        2        .222-.44438.94/56.25       .9657/.8738
C        3        .444-.66756.25/70.53       .8738/.7408
C        4        .667-.88970.53/83.62       .7408/.5830
C        5        .889-1.11183.62/96.38      .5830/.4170
C        6        1.111-1.33396.38/109.47    .4170/.2592
C        7        1.333-1.556109.47/123.75   .2592/.1262
C        8        1.556-1.778 123.75/141.06  .1262/.0343
C        9        1.7778-2.0141.06/180.      .0343/0.
C
C                    DEN=487,CP=0.11
         GEN 1,9,1,43.,AWALL*WallThk*487.*.11$ FROM BASE UP
C
C        theta1   = pi*38.94/180
C        theta2   = pi*56.25/180
C        theta3   = pi*70.53/180
C        theta4   = pi*83.62/180
C
HEADER CONDUCTOR DATA,TANK
C                 K*THK * R * 2PI * SINE(THETA) /LENGTH (= R DELTA THETA)
         1,1,2,WallCond*WallThk* 2.*pi*sin(theta1)/(0.5*(theta2-0))
         8,8,9,WallCond*WallThk* 2.*pi*sin(theta1)/(0.5*(theta2-0))
         7,7,8,WallCond*WallThk* 2.*pi*sin(theta2)/(0.5*(theta3-theta1))
         2,2,3,WallCond*WallThk* 2.*pi*sin(theta2)/(0.5*(theta3-theta1))
         6,6,7,WallCond*WallThk* 2.*pi*sin(theta3)/(0.5*(theta4-theta2))
         3,3,4,WallCond*WallThk* 2.*pi*sin(theta3)/(0.5*(theta4-theta2))
         5,5,6,WallCond*WallThk* 2.*pi*sin(theta4)/(2.0*(pi/2-theta4))
         4,4,5,WallCond*WallThk* 2.*pi*sin(theta4)/(2.0*(pi/2-theta4))
C
C VCS: FOLLOW TANK NODAL SCHEME
C
HEADER NODE DATA,VCS
C
C                    DEN=174,CP=0.21
         GEN 1,9,1,350.,AVCS*VCSthick*174.*.21$ FROM BASE UP
C
```

```
HEADER CONDUCTOR DATA,VCS
C                 K*THK * R * 2PI * SINE(THETA) /LENGTH (= R DELTA THETA)
         1,1,2,VCScond*VCSthick* 2.*pi*sin(theta1)/(0.5*(theta2-0))
         8,8,9,VCScond*VCSthick* 2.*pi*sin(theta1)/(0.5*(theta2-0))
         7,7,8,VCScond*VCSthick* 2.*pi*sin(theta2)/(0.5*(theta3-theta1))
         2,2,3,VCScond*VCSthick* 2.*pi*sin(theta2)/(0.5*(theta3-theta1))
         6,6,7,VCScond*VCSthick* 2.*pi*sin(theta3)/(0.5*(theta4-theta2))
         3,3,4,VCScond*VCSthick* 2.*pi*sin(theta3)/(0.5*(theta4-theta2))
         5,5,6,VCScond*VCSthick* 2.*pi*sin(theta4)/(2.0*(pi/2-theta4))
         4,4,5,VCScond*VCSthick* 2.*pi*sin(theta4)/(2.0*(pi/2-theta4))
C
C CONNECT VCS.1 TO TANK.1 WITH .313” .035wall 9 to 12”
C
         10,1,TANK.1,8.33*pi*0.25*(VCSOD^2-VCSID^2)/1.
C
HEADER ARRAY DATA, HYDRO
C
C ARRAY 1: VOID FRACTION AT TOP OF EACH SEGMENT
         1= .9657, .8738, .7408, .5830, .4170, .2592, .1262, .0343, 0.
C ARRAY 2: VOID FRACTION AT BOTTOM OF EACH SEGMENT
         2= 1.0,  .9657, .8738, .7408, .5830, .4170, .2592, .1262, .0343
C
C OUTER SHELL MLI PLUS ALL MLI CONDUCTANCES AND CHAMBER BDY NODE
C
HEADER NODE DATA,MLI
         GEN 1,9,1,530.,-1.0        $ FROM BASE UP
         -999,540.,0.0              $ VACUUM CHAMBER BDY NODE
C
HEADER CONDUCTOR DATA,MLI
C CONDUCTORS BETWEEN CHAMBER AND OUTER LAYER
C SAY 51” DIA @ 0.04 e, CHAMBER 72” DIA @ 0.3 e: eff e = 0.034
C BUT KNOW FROM TESTS THAT EXCHANGE IS GOOD HERE: SAY e = 0.1
         GEN,-1,9,1,1,1,999,0,AMLI*0.1
C CONDUCTORS BETWEEN OUTER LAYER AND VCS (24 LAYERS MLI) say e* = .007
         GEN,-11,9,1,VCS.1,1,1,1,AVCS*.007
C CONDUCTORS BETWEEN VCS AND TANK (48 LAYERS MLI) say e* = .008
         GEN,-21,9,1,VCS.1,1,TANK.1,1,AVCS*.008
C
C NOW LINEAR CONDUCTORS TO VCS AND TO TANK:
C (ALL AT TOP OF TANK AND VCS FOR SIMPLICITY)
C
         100,999,TANK.9,1.24E-2
         200,999, VCS.9,1.86E-4
C
C 7000 USER FLUID: PARA HYDROGEN
```

```
HEADER FLOW DATA,HYDRO,FID=7702
C
C
C THIS INCLUDES ALL FLUID IN SYSTEM
C
C THIS IS TANK ITSELF: TWINNED TANKS FOR NONEQ
C INITIAL CONDITIONS: HALF FULL. SATURATED AT 42.6R
C
LU TANK,1                          $ LIQUID HALF
         LTWIN     = 2             $ VAPOR HALF
         VOL       = VTANK
         XL        = 0.001         $ FAKE: WILL BE OVERWRITTEN IN OPER
         TL        = 42.6
         PL        = 0.0           $ FAKE: FLUINT WILL OVERWRITE
         LSTAT     = STAG
C USE UVT=-2.0 (INCLUDES NATURAL CONVECTION) AND ULT=-4.0 (INCLUDES STIR-
RING
C CAUSED BY INGRESS). AST CALCULATED LATER
         UVT       = -2.0
         ULT       = -4.0
C
C DEFAULT PRESSURE IS HEREAFTER 4.0 PSIA
C
LU DEF, XL= 1.0
         PL!       = 4.0
         TL        = 42.6
C
PA DEF,  FR        = 0.0382,WRF    = 1.0E-5
C
C PRESSURE REGULATOR
C
PA CONN,100,1,100,STAT = LS,DEV    = DPRVLV
         PSET      = 4.            $ NEED DOWNSTREAM PRESSURE 4 PSIA
         AF        = 0.25*pi*IHXpipeD^2
         MCH       = 2             $ allow flashing in throat
LU JUNC,100,       XL       = .1,  TL       = 80.0
C
C GENERATE INTERNAL HEAT EXCHANGER
C
M HX,1,D,101,101,101,IHX.1,100,NSEG=6
         TLENT     = IHXpipeL,DHS  = IHXpipeD
         TL        = 28.,          TLINC    = 2.
         XL        = 0.18,         XLINC    = 1.0
         LU        = JUNC,         PA       = STUBE
C
C GENERATE TIES TO INTERNAL HEAT EXCHANGER
C INCLUDE FIN EFFECTIVENESSES
C
M GENT,2,HTU,201,1,IHX.1,N=6
```

```
         UA       = HTLIQ*0.9*(IHXpipeL/6)*IHXfinS
         LUINC    = 0
T HTU,251,1,IHX.201,UA= HTLIQ*0.9*2.5*IHXfinS
T HTU,252,1,IHX.202,UA= HTLIQ*0.9*2.5*IHXfinS
T HTU,254,1,IHX.204,UA= HTLIQ*0.9*2.5*IHXfinS
T HTU,255,1,IHX.205,UA= HTLIQ*0.9*2.5*IHXfinS
C
C GENERATE TIES TO TANK WALL
C WILL OVERRIDE UA LATER ACCORDING TO FILL LEVEL AND BOILING
C
M GENT,3,HTU,301,1,TANK.1,N=9
         UA       = HTLIQ*AWALL     $ initial guess only
         AHT      = AWALL           $ FOR UB FORM: UA = AHT*UB*dT**UEDT
         LUINC    = 0
C
C NOW GENERATE VCS PIPING
C
PA DEF, DH= VCSID
M HX,4,C,401,401,401,VCS.1,106,998,NSEG=9
         TLENT    = 80.,            DHS      = VCSID
         TL       = 325.,           TLINC    = 2.0,             XL
= 1.0
         LU       = JUNC,           PA       = STUBE
C VCS NODE IS ACTUALLY PLATE NOT PIPE, SO INCLUDE
C FIN EFFICIENCY HERE AS AREA FRACTION
         AFRACT   = 0.9
C
C FINALLY, EXHAUST TO “VACUUM”
C THIS IS MAIN CONTROL VALVE TO BALANCE SYSTEM
C
LU JUNC,998,PL!   = 2.0,   TL       = 400.
PA CONN,998,998,999,DEV= MFRSET
PA CONN,999,998,999,DUP= 0.0
                           DEV      = LOSS, FK= 1000.0
C
LU PLEN,999,TL    = 500.0  $ EXHAUST TO NEAR VACUUM
         PL!      = 1.0    $ STATE IRRELEVANT SINCE CONNECTED BY MFRSET
         LSTAT    = STAG
C        THIS PRESSURE IS INTENTIONALLY LOW AND WILL CAUSE ONE WARNING
C        AT THE BEGINNING OF THE PROCESSOR EXECUTION, WHEN THE PRESSURE
C        WILL BE RAISED TO THE MINIMUM ALLOWABLE.
C
C ADD SUBCOOLED FILL LINE AND SOURCE
C
LU PLEN,1999,TL   = 20.0
         PL       = 60.0
         LSTAT    = STAG
         XL       = 0.0
C        THIS TEMPERATURE IS INTENTIONALLY LOW AND WILL CAUSE ONE WARNING
```

```
C        AT THE BEGINNING OF THE PROCESSOR EXECUTION, WHEN THE TEMP.
C        WILL BE RAISED TO THE MINIMUM ALLOWABLE.
C
C 10 FOOT BY 0.18” DIA TUBING, INITIALLY MISSING (DUP=0.0 TO TANK #1)
C
PA CONN,1999,1999,1,DUPJ= 0.0, STAT = DLS
         DEV      = STUBE
         DH       = IHXpipeD
         TLEN     = 10.0
         MCH      = 0               $ Turn off choking
C
C
HEADER OPERATIONS
C
C INITIALIZE TWINS BEFORE THE BUILDF HOMOGENIZES THEM
C
         CALL CHGVOL(‘HYDRO’,1,0.5*VTANK)
         CALL CHGVOL(‘HYDRO’,2,0.5*VTANK)
C
BUILD ALL
BUILDF ALL
C
C INITIALIZE TANK STATE AND HOLD: APPROX 1/2 FULL
C
DEFMOD HYDRO
         CALL HLDLMP(‘HYDRO’,1)
C
C NEGLECT NUCLEATE BOILING RESOLUTION: USE HTRLMP
C TO CONVERT ALL FLOW INTO VAPOR IN FIRST TIE.  THIS
C DUMPS APPROPRIATE AMOUNT OF ENERGY INTO IHX.1
C
         CALL CHGLMP(‘HYDRO’,101,’XL’,1.0,’PL’)
         CALL HTRLMP(‘HYDRO’,101)
C
C FIND “STEADY STATE” WITH FIXED TANK STATE
C
         CALL REGTAB
         CALL GPRINT(‘ALL’)
         CALL CPRINT(‘ALL’)
         CALL FASTIC
         CALL RESAVE(‘ALL’)
         HTEST    = VHFG(PL1-PATMOS,TL1-ABSZRO,1.0/DL2,HYDRO.FI)
         WRITE(NUSER1,999)FR998*HTEST,QDOT1+QDOT2
F999     FORMAT(‘ BOIL-OFF ENERGY  = ‘,1PG13.5,’, VS. LEAKAGE: ‘,G13.5/)
         WRITE(NUSER1,1000)
1000     FORMAT(‘ TIME (MIN)’,T16,’PERC. LIQ’,T30,’LIQ TEMP’,T45
     .   ,’LIQ QUAL’,T57,’VAP TEMP’,T69,’VAP QUAL’,T84,’TVS FR’,T95
     .  ,’FILL RATE’,T107,’TANK PRES’/)
C
```

```
C SWITCH FROM PRESSURE REGULATION TO EQUIVALENT HEAD LOSS
C
         FKH100            = FK100
         FKL100            = FK100
C
C SWITCH FROM CONSTANT FLOWRATE EXIT VALVE TO EQUIV HEAD LOSS
C
         DUPI998           = 0.0
         DUPJ998           = 0.0
         DUPI999           = 1.0
         DUPJ999           = 1.0
         FK999    = 2.0*DL998*(AF999/FR998)**2*PTEST*SNGL(PL998-PL999)
         FR999             = FR998
C
C TURN ON FILL LINE (IT APPEARS SUDDENLY TO TANK #1)
C
         DUPJ1999 = 1.0
C
C RELEASE STORAGE TANK FROM BOUNDARY STATE
C
         CALL RELLMP(‘HYDRO’,1)
C
         TIMEND            = 1.0
         CALL FWDBCK
C
HEADER OUTPUT CALLS, MLI
         IF(NSOL .LE. 1 .AND. LOOPCT .EQ. 0) RETURN
C STEADY STATE AND INFREQUENT TRANSIENT
         CALL LMPTAB(‘ALL’)
         CALL L2TAB(‘ALL’)
         CALL TIETAB(‘ALL’)
         CALL PTHTAB(‘ALL’)
         CALL TPRINT(‘ALL’)
HEADER OUTPUT CALLS, HYDRO
C FREQUENT TRANSIENT (ONE-LINE TO USER FILE)
         IF(NSOL .LE. 1) RETURN
         WRITE(NUSER1,10)TIMEN*60.0,VOL1/
VTANK,TL1,XL1,TL2,XL2,FR100,FR1999,PL1
10       FORMAT(1X,1P,9G13.5)
C
C IF GREATER THAN 15 MINUTES, PRINT EVERY 3 MINUTES
         IF(TIMEN .GE. 0.2499) OUTPTF= 3.0/60.0
C IF GREATER THAN 30 MINUTES, PRINT EVERY 5 MINUTES
         IF(TIMEN .GE. 0.4999) OUTPTF= 5.0/60.0
C
```

```
HEADER FLOGIC 0, HYDRO
         IF(LOOPCT .GT. 0.98*NLOOPS) MLI.ITEROT= 1
C
C REPROPORTION TANK WALL TIES ACCORDING TO FILL LEVEL
C USE POOL BOILING IN LIQUID SIDE IF WALL HOTTER
C
         ATEST              = VOL2/VTANK
C
C LOOP THROUGH TIES TO THE WALL
C
         DO 10 ITEST = 0,8
C ESTIMATE FRACTION OF VAPOR
C ARRAY 1: VOID FRACTION AT TOP OF SEGMENT
C ARRAY 2: VOID FRACTION AT BOTTOM OF SEGMENT
                  JTEST             = ITEST + 1
                  RTEST             = (ATEST-A(1+JTEST))
     .                              /(A(2+JTEST)-A(1+JTEST))
                  RTEST             = MIN(1.0,MAX(0.0,RTEST))
C
C CALC SATURATION POINT
                  TSAT              = VTS(PL2-PATMOS,HYDRO.FI) + ABSZRO
C
C IF ALL WITHIN VAPOR TANK: MOVE TIE TO VAPOR, ELSE MOVE TO LIQUID TANK
C
                  MTEST             = INTNOD(‘TANK’,1+ITEST)
                  NTEST             = INTTIE(‘HYDRO’,301+ITEST)
FSTART
                  IF(RTEST .GE. 1.0)THEN
                           CALL PUTTIE(‘HYDRO’,301+ITEST,2,’TANK’,0)
                           IF(T(MTEST) .GE. TSAT)THEN
                                    UB(NTEST)= HTVAP
                                    UEDT(NTEST)= 0.0
                           ELSE
                                    UB(NTEST)= HTCON
                                    UEDT(NTEST)= 0.0
                           ENDIF
                  ELSE
                           CALL PUTTIE(‘HYDRO’,301+ITEST,1,’TANK’,0)
                           IF(T(MTEST) .LE. TSAT)THEN
                                    UB(NTEST)= HTLIQ*(1.0-RTEST)
     .                                          + RTEST*HTVAP
                                    UEDT(NTEST)= 0.0
                           ELSE
                                    CALL POOLBOIL(UTEST,BTEST,DTEST,
     .                               QTEST,TTEST,STEST,ETEST,
     .                               T(MTEST),TSAT,
FSTOP
     .                               0.01,1.0,0.0,HYDRO.FI)
FSTART
```

```
                                    IF(HTLIQ .GT. UTESTT)THEN
                                        UB(NTEST)= HTLIQ*(1.0-RTEST)
     .                                          + RTEST*HTVAP
                                        UEDT(NTEST)= 0.0
                                    ELSE
                                        UB(NTEST)= BTEST*(1.0-RTEST)
     .                                          + RTEST*HTVAP
C APPORTION TEMP COEFFICIENT ACCORDING TO RELATIVE STRENGTH OF U:
                                        UEDT(NTEST)=DTEST*
     .                                       (1.0-RTEST)*BTEST
     .                                          /((1.0-RTEST)*BTEST
     .                                          + RTEST*HTVAP)
                                    ENDIF
                           ENDIF
                  ENDIF
FSTOP
10       CONTINUE
C
C USE VOL OF TANK TO CALCULATE SURFACE AREA
C (GROUND TEST: FLAT INTERFACE DUE TO GRAVITY)
C V = PI*H**2/3 * (3R - H), H IS HEIGHT OF SPHERICAL SEGMENT (DEPTH)
C CUBIC FUNCTION OF H:    PI/3 *H**3 - PI*R *H**2 + 0 + V
C USE CUROOT (CHEAT: INTERNAL FLUINT FUNCTION).
C V = PI*H/6 * (3*A**2 + H**2), A IS RADIUS OF AST
C RADIUS OF TANK IS RTANK
C
SPELLOFF
         HTEST    = CUROOT(PIE/3.,-PIE*RTANK,0.0,VOL2,RTANK,.FALSE.)
SPELLON
         AST1     = 2.*VOL2/HTEST - PIE*HTEST*HTEST/3.
C------------------------------
```

```
HEADER FPROP DATA,7702,SI,0.0
C
C MORE COMPLETE PARA H2 TWO-PHASE (FROM 13.8 TO 30K, NEAR 20 K)
C VAPOR PROPERTIES ARE FOR SUPERHEATED VAPOR (1 ATM)
C (EXCEPT CP WHICH MUST BE FOR LOW PRESSURE GAS)
C
         RGAS     = 8314.34/2.0159
         TCRIT    = 32.938
         PCRIT    = 1.2838E6
         ST       = 2.172E-3
         TMIN     = 13.80
         PGMAX    = 1.0E6
         TGMAX    = 500.0
         DIFV     = 6.12
         WSRK     = -0.2324
C *** ALTERNATE INPUTS FOR SATURATED VAPOR PROPERTIES
C IF RUNNING ANALYSES FOR SATURATION CONDITIONS
C THEN USE THE FOLLOWING LINES INSTEAD
C        PGMAX            = 1.0E6
C        TGMAX            = 32.0
CAT,VG,  14.0,0.748E-6,18.0,0.988E-6,20.27,1.128E-6,22.0,1.238E-6
C        26.0,1.519E-6,30.0,1.917E-6,32.0,2.379E-6
CAT,KG,  14.0,0.01254,18.0,0.01497,20.27,0.01694,24.0,0.02181
C        28.0,0.02991,30.0,0.03787,32.0,0.06677
C *** END ALTERNATE INPUTS
AT,DOME, 13.80,   0.007042E6,139.75E3 + 309.10E3
C ELSE            24.0,    0.26424E6,203.16E3 + 213.94E3
                  20.28,   0.101325E6,189.11E3 + 256.33E3
AT,VL,   14.0,24.8E-6,16.0,19.42E-6,18.0,15.93E-6,20.0,13.48E-6,
         22.0,11.61E-6,24.0,10.1E-6,26.0,8.8E-6,28.0,7.62E-6,
         30.0,6.46E-6,32.0,5.13E-6,32.98,3.54E-6
AT,VG,   14.0,0.748E-6,18.0,0.988E-6,20.27,1.128E-6,22.0,1.219E-6
         26.0,1.424E-6,30.0,1.621E-6,35.0,1.856E-6,40.0,2.02E-6
         50.0,2.498E-6,60.0,2.884E-6,80.0,3.585E-6,100.0,4.574E-6
         120.0,5.408E-6,160.0,6.3E-6,200.0,6.901E-6,240.0,7.419E-6
         300.0,8.141E-6,350.0,8.723E-6,400.0,9.297E-6,500.0,10.426E-6
AT,KL,   14.0,0.07462,16.0,0.08886,18.0,0.09543,20.0,0.0984
         22.0,0.10095,24.0,0.10084,26.0,0.09843,28.0,0.09378
         30.0,0.08657,32.98,0.09146
AT,KG,   14.0,0.01254,18.0,0.01497,20.27,0.01694,24.0,0.0195
         28.0,0.02247,32.0,0.02534,35.0,0.02741,40.0,0.03088
         50.0,0.03781,60.0,0.04481,80.0,0.06027,100.0,0.08954
         140.0,0.13613,180.0,0.15565,220.0,0.16341,260.0,0.16914,
         300.0,0.17591,400.0,0.19745,500.0,0.22128
AT,CPG,  14.0,10.54E3,20.0,10.43E3,24.0,10.39E3,32.0,10.35E3
         40.0,10.36E3,50.0,10.49E3,60.0,10.62E3,80.0,11.72E3
         100.0,13.4E3,160.0,16.34E3,200.0,16.07E3,280.0,15.0E3
         350.0,14.63E3,400.0,14.55E3,500.0,14.52E3
```

```
AT,DL,   13.80,77.04,17.0,74.19,20.28,70.80,23.0,67.41
         25.0,64.47,27.0,60.97,29.0,56.59,31.0,50.46
         32.0,45.70,32.938,31.36
END OF DATA
```

Processor Output

```
BOIL-OFF ENERGY  =    6.9467    , VS. LEAKAGE:    6.7274

TIME (MIN)    PERC. LIQ    LIQ TEMP     LIQ QUAL    VAP TEMP    VAP QUAL      TVS FR     FILL RATE   TANK PRES

   0.0000      0.50000      42.600      0.0000      42.600       1.0000     3.82000E-02  206.52      34.642
   1.0000      0.52907      41.590      0.0000      43.813       1.0000     4.01684E-02  192.94      37.685
   2.0000      0.55739      40.813      0.0000      44.239       1.0000     4.17251E-02  181.22      40.150
   3.0000      0.58445      40.197      0.0000      44.270      0.99986     4.30413E-02  170.35      42.304
   4.0000      0.60976      39.709      0.0000      44.815      0.99966     4.45941E-02  155.56      45.040
   5.0000      0.63286      39.320      0.0000      45.317      0.99965     4.60471E-02  140.01      47.675
   6.0000      0.65355      39.011      0.0000      45.772      0.99949     4.73542E-02  123.97      50.147
   7.0000      0.67164      38.767      0.0000      46.169      0.99937     4.85060E-02  107.84      52.380
   8.0000      0.68731      38.576      0.0000      46.510      0.99957     4.95320E-02  91.319      54.371
   9.0000      0.70043      38.429      0.0000      46.786      0.99958     5.03474E-02  75.719      56.008
   10.000      0.71120      38.320      0.0000      46.998      0.99968     5.09903E-02  61.018      57.301
   11.000      0.71983      38.240      0.0000      47.152      0.99973     5.14566E-02  48.047      58.252
   12.000      0.72660      38.184      0.0000      47.257      0.99979     5.17756E-02  37.116      58.902
   13.000      0.73187      38.145      0.0000      47.323      0.99982     5.19803E-02  28.437      59.320
   14.000      0.73596      38.118      0.0000      47.363      0.99986     5.21044E-02  21.964      59.572
   15.000      0.73919      38.098      0.0000      47.387      0.99989     5.21787E-02  17.266      59.721
   18.000      0.74410      38.110      0.0000      47.428      0.99997     5.22986E-02  4.0775      59.978
   21.000      0.74590      38.147      0.0000      47.430      0.99999     5.22982E-02  2.1960      59.992
   24.000      0.74701      38.175      0.0000      47.430      0.99999     5.22923E-02  1.5229      59.997
   27.000      0.74802      38.193      0.0000      47.430      0.99998     5.22865E-02  1.5769      59.997
   30.000      0.74906      38.205      0.0000      47.430      0.99999     5.22821E-02  1.8162      59.995
   35.000      0.75095      38.215      0.0000      47.430      0.99999     5.22772E-02  2.1746      59.993
   40.000      0.75299      38.217      0.0000      47.430      0.99999     5.22758E-02  2.3459      59.991
   45.000      0.75513      38.213      0.0000      47.430      0.99999     5.22760E-02  2.4642      59.991
   50.000      0.75735      38.207      0.0000      47.429      0.99998     5.22775E-02  2.5355      59.990
   55.000      0.75961      38.198      0.0000      47.430      0.99998     5.22802E-02  2.6464      59.989
   60.000      0.76191      38.187      0.0000      47.430      0.99999     5.22820E-02  2.7020      59.989
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                         SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE     3

MODEL = TVS                  LH2 STORAGE TANK WITH INTERNAL HX AND VAPOR COOLED SHIELD


                                  NAMED CALCULATOR REGISTER TABULATION

 NAME        VALUE       EXPRESSION ......

HTLIQ        20.000      20.0
HTVAP        4.0000      4.0
HTCON        20.000      20.0
TSAT         1.0000      1.0
RESOL        9.0000      9
RTANK        1.7500      0.5*42./12.
AWALL        4.2761      4*PI*RTANK^2/RESOL
VTANK        22.449      4*PI/3*RTANK^3
RVCS         2.0000      0.5*48./12.
AVCS         5.5851      4*PI*RVCS^2/RESOL
VCSOD       2.60833E-02  0.313/12.
VCSID       2.02500E-02  VCSOD - 2*0.035/12
RMLI         2.1250      0.5*51./12.
AMLI         6.3050      4*PI*RMLI^2/RESOL
PIE          3.1416      PI
IHXPIPEO    2.08333E-02  0.25/12.
IHXPIPED    1.50000E-02  0.18/12.
IHXPIPEL     13.333      160./12.
IHXPIPEA    1.64170E-04  PI/4*(IHXPIPEO^2-IHXPIPED^2)
IHXFINA     1.73611E-03  2*2.*(1/16)/144
IHXFINS     0.66667      2*2*2./12
CUCOND       500.00      500.0
VCSCOND      133.00      133.
VCSTHICK    3.75000E-03  0.045/12
WALLCOND     8.3300      8.33
WALLTHK     2.50000E-02  0.3/12
THETA1      0.67963      PI*38.94/180
THETA2      0.98175      PI*56.25/180
THETA3       1.2310      PI*70.53/180
THETA4       1.4594      PI*83.62/180
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                           SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR          PAGE    13

MODEL = TVS                  LH2 STORAGE TANK WITH INTERNAL HX AND VAPOR COOLED SHIELD
  FASTIC


 FLUID SUBMODEL NAME = HYDRO   ; FLUID NO. = 7702


        LOOPCT =     91
        CONVERGENCE STATUS = SUBMODEL CONVERGED AS OF      90 ITERATIONS. ENERGY STABLE BUT UNBALANCED


                                    LUMP PARAMETER TABULATION FOR SUBMODEL HYDRO

  LUMP  TYPE     TEMP       PRESSURE      QUALITY      VOID FRACT.  DENSITY      ENTHALPY      HEAT RATE     MASS RATE     ENERGY RATE

     1  TANK    42.60        34.64      4.0998E-02   0.5000         2.162       -79.86         6.727       -3.8200E-02    10.06
   100  JUNC    29.80        4.000      0.1821       0.9755       0.1396        -87.32         0.000          0.000        0.000
   101  JUNC    29.80        4.000       1.000        1.000       2.6064E-02     73.76         6.153          0.000        0.000
   102  JUNC    39.22        4.000       1.000        1.000       1.9512E-02     97.81        0.9185          0.000       -5.9605E-08
   103  JUNC    41.73        4.000       1.000        1.000       1.8296E-02     104.1        0.2421          0.000       -1.1921E-07
   104  JUNC    42.38        3.999       1.000        1.000       1.8006E-02     105.8       6.2233E-02       0.000        6.1430E-06
   105  JUNC    42.54        3.999       1.000        1.000       1.7933E-02     106.2       1.5897E-02       0.000        8.1435E-06
   106  JUNC    42.59        3.999       1.000        1.000       1.7914E-02     106.3       4.0859E-03       0.000        4.6371E-06
   401  JUNC    307.5        3.997       1.000        1.000       2.4439E-03     934.3         31.63          0.000       -4.9591E-05
   402  JUNC    318.3        3.988       1.000        1.000       2.3563E-03     975.9         1.589          0.000        1.2493E-04
   403  JUNC    321.1        3.978       1.000        1.000       2.3299E-03     987.0        0.4231          0.000       -5.0068E-05
   404  JUNC    322.9        3.969       1.000        1.000       2.3113E-03     994.0        0.2678          0.000        3.5763E-06
   405  JUNC    324.3        3.959       1.000        1.000       2.2963E-03     999.1        0.1971          0.000        5.4836E-05
   406  JUNC    325.3        3.950       1.000        1.000       2.2833E-03     1003.        0.1571          0.000       -1.4973E-04
   407  JUNC    326.2        3.940       1.000        1.000       2.2714E-03     1007.        0.1313          0.000       -1.5237E-03
   408  JUNC    327.0        3.931       1.000        1.000       2.2604E-03     1010.        0.1154          0.000        8.6546E-05
   409  JUNC    327.9        3.921       1.000        1.000       2.2486E-03     1013.        0.1341          0.000       -1.4305E-06
   998  JUNC    327.9        3.916       1.000        1.000       2.2457E-03     1013.         0.000          0.000       -2.5940E-03
   999  PLEN    500.0        1.022       1.000        1.000       3.8439E-04     1657.         0.000       3.8200E-02     38.71
  1999  PLEN    24.84        60.00       0.000        0.000         4.809       -128.0         0.000        -206.5        2.6433E+04
```

```
                                    TIE PARAMETER TABULATION FOR SUBMODEL HYDRO

  TIE   TYPE      UA          QTIE         LUMP     TEF           NODE                   TEMP.    2P   PATH 1     FRACT    PATH 2     FRACT

   101  HTN    0.2470        6.153         101     29.80      IHX.1                    42.38           101     1.0000
   102  HTN    0.2748       0.9185         102     39.22      IHX.2                    42.56           102     1.0000
   103  HTN    0.2820       0.2421         103     41.73      IHX.3                    42.59           103     1.0000
   104  HTN    0.2838      6.2233E-02      104     42.38      IHX.4                    42.60           104     1.0000
   105  HTN    0.2843      1.5897E-02      105     42.54      IHX.5                    42.60           105     1.0000
   106  HTN    0.2844      4.0859E-03      106     42.59      IHX.6                    42.60           106     1.0000
   201  HTU     26.67       -5.905            1     42.60      IHX.1                    42.38
   202  HTU     26.67      -0.9619            1     42.60      IHX.2                    42.56
   203  HTU     26.67      -0.2505            1     42.60      IHX.3                    42.59
   204  HTU     26.67     -6.2880E-02        1     42.60      IHX.4                    42.60
   205  HTU     26.67     -1.5849E-02        1     42.60      IHX.5                    42.60
   206  HTU     26.67      8.5268E-03        1     42.60      IHX.6                    42.60
   251  HTU     30.00      -0.1489           1     42.60      IHX.201                  42.60
   252  HTU     30.00     -2.5874E-02        1     42.60      IHX.202                  42.60
   254  HTU     30.00     -1.5867E-03        1     42.60      IHX.204                  42.60
   255  HTU     30.00     -4.1663E-04        1     42.60      IHX.205                  42.60
   301  HTU     85.52        1.156           1     42.60      TANK.1                   42.61
   302  HTU     85.52       0.7946           1     42.60      TANK.2                   42.61
   303  HTU     85.52       0.8141           1     42.60      TANK.3                   42.61
   304  HTU     85.52       0.8320           1     42.60      TANK.4                   42.61
   305  HTU     85.52       0.8458           1     42.60      TANK.5                   42.61
   306  HTU     85.52       0.8571           1     42.60      TANK.6                   42.61
   307  HTU     85.52       0.8710           1     42.60      TANK.7                   42.61
   308  HTU     85.52       0.9860           1     42.60      TANK.8                   42.61
   309  HTU     85.52        6.935           1     42.60      TANK.9                   42.68
   401  HTNC    8.062        31.63         401     307.5      VCS.1                    311.5           401     0.9000    402      0.4500
   402  HTNC    8.190        1.589         402     318.3      VCS.2                    318.5           402     0.4500    403      0.4500
   403  HTNC    8.230       0.4231         403     321.1      VCS.3                    321.2           403     0.4500    404      0.4500
   404  HTNC    8.256       0.2678         404     322.9      VCS.4                    323.0           404     0.4500    405      0.4500
   405  HTNC    8.273       0.1971         405     324.3      VCS.5                    324.3           405     0.4500    406      0.4500
   406  HTNC    8.279       0.1571         406     325.3      VCS.6                    325.3           406     0.4500    407      0.4500
   407  HTNC    8.284       0.1313         407     326.2      VCS.7                    326.2           407     0.4500    408      0.4500
   408  HTNC    8.289       0.1154         408     327.0      VCS.8                    327.0           408     0.4500    409      0.4500
   409  HTNC    8.294       0.1341         409     327.9      VCS.9                    327.9           409     0.4500    410      0.9000
```

```
                              PATH PARAMETER TABULATION FOR SUBMODEL HYDRO

  PATH  TYPE    LMP 1   LMP 2   DUP I      DUP J    STAT   XL UPSTRM    FLOWRATE     DELTA PRES    REYNOLDS     MACH     REGIME

  100   DPRVLV      1     100    1.0        1.0     LS       0.000      3.8200E-02    30.64                   0.000
  101   STUBE     100     101    1.0        1.0     NORM    0.1821      3.8200E-02   1.1611E-04    330.2      0.001    ANNULAR
  102   STUBE     101     102    1.0        1.0     NORM     1.000      3.8200E-02   1.4284E-04    1487.      0.002    1 PHASE
  103   STUBE     102     103    1.0        1.0     NORM     1.000      3.8200E-02   1.8414E-04    1110.      0.003    1 PHASE
  104   STUBE     103     104    1.0        1.0     NORM     1.000      3.8200E-02   1.9618E-04    1047.      0.003    1 PHASE
  105   STUBE     104     105    1.0        1.0     NORM     1.000      3.8200E-02   1.9939E-04    1032.      0.003    1 PHASE
  106   STUBE     105     106    1.0        1.0     NORM     1.000      3.8200E-02   2.0019E-04    1029.      0.003    1 PHASE
  401   STUBE     106     401    1.0        1.0     NORM     1.000      3.8200E-02   2.3351E-03    761.3      0.002    1 PHASE
  402   STUBE     401     402    1.0        1.0     NORM     1.000      3.8200E-02   8.9975E-03    153.6      0.004    1 PHASE
  403   STUBE     402     403    1.0        1.0     NORM     1.000      3.8200E-02   9.2906E-03    151.5      0.004    1 PHASE
  404   STUBE     403     404    1.0        1.0     NORM     1.000      3.8200E-02   9.4076E-03    151.0      0.004    1 PHASE
  405   STUBE     404     405    1.0        1.0     NORM     1.000      3.8200E-02   9.4948E-03    150.6      0.005    1 PHASE
  406   STUBE     405     406    1.0        1.0     NORM     1.000      3.8200E-02   9.5673E-03    150.4      0.005    1 PHASE
  407   STUBE     406     407    1.0        1.0     NORM     1.000      3.8200E-02   9.6314E-03    150.2      0.005    1 PHASE
  408   STUBE     407     408    1.0        1.0     NORM     1.000      3.8200E-02   9.6902E-03    150.0      0.005    1 PHASE
  409   STUBE     408     409    1.0        1.0     NORM     1.000      3.8200E-02   9.7496E-03    149.8      0.005    1 PHASE
  410   STUBE     409     998    1.0        1.0     NORM     1.000      3.8200E-02   4.8934E-03    149.7      0.005    1 PHASE
  998   MFRSET    998     999    1.0        1.0     NORM     1.000      3.8200E-02    2.894                   0.005
  999   LOSS      998     999    0.0        0.0     NORM     1.000      0.2845        2.894                   0.034
 1999   STUBE    1999       1    1.0        0.0     DLS      0.000       206.5        25.36       2.8596E+05  0.012x   1 PHASE
```

```
SUBMODEL NAME = IHX


                                      CALCULATED                                  ALLOWED
       MAX DIFF DELTA T PER ITER      DRLXCC(                0)=  0.00000      VS. DRLXCA= 1.000000E-02
       MAX ARITH DELTA T PER ITER     ARLXCC(IHX           205)=-3.814697E-06 VS. ARLXCA= 1.000000E-02
       MAX SYSTEM ENERGY BALANCE      EBALSC                   = 1.412463E-04 VS. EBALSA * ESUMIS       = 7.372558E-02
                                                                                  EBALSA= 1.000000E-02
       ENERGY INTO AND OUT OF SYS     ESUMIS                   =  7.37256         ESUMOS=  7.40470
       MAX NODAL ENERGY BALANCE       EBALNC(IHX             5)= 5.483512E-05 VS. EBALNA=  0.00000
       NUMBER OF ITERATIONS           LOOPCT                   =       91      VS. NLOOPS=      500
       PROBLEM TIME                   TIMEN                    =  0.00000      VS. TIMEND=  0.00000

                                    DIFFUSION NODES IN INPUT NODE NUMBER ORDER
                                                       ++NONE++
                                    ARITHMETIC NODES IN INPUT NODE NUMBER ORDER
 T      1=  42.379      T      2=  42.564      T      3=  42.591      T      4=  42.598      T      5=  42.599      T      6=  42.600
 T    201=  42.595      T    202=  42.599      T    204=  42.600      T    205=  42.600




 SUBMODEL NAME = TANK


                                      CALCULATED                                  ALLOWED
       MAX DIFF DELTA T PER ITER      DRLXCC(TANK            8)=-3.814697E-06 VS. DRLXCA= 1.000000E-02
       MAX ARITH DELTA T PER ITER     ARLXCC(                0)=  0.00000      VS. ARLXCA= 1.000000E-02
       MAX SYSTEM ENERGY BALANCE      EBALSC                   =-7.076589E-04 VS. EBALSA * ESUMIS       =  0.00000
                                                                                  EBALSA= 1.000000E-02
       ENERGY INTO AND OUT OF SYS     ESUMIS                   =  0.00000         ESUMOS=  14.0901
       MAX NODAL ENERGY BALANCE       EBALNC(TANK            7)=-9.451767E-05 VS. EBALNA=  0.00000
       NUMBER OF ITERATIONS           LOOPCT                   =       91      VS. NLOOPS=      500
       PROBLEM TIME                   TIMEN                    =  0.00000      VS. TIMEND=  0.00000

                                    DIFFUSION NODES IN INPUT NODE NUMBER ORDER
 T      1=  42.614      T      2=  42.609      T      3=  42.610      T      4=  42.610      T      5=  42.610      T      6=  42.610
 T      7=  42.610      T      8=  42.612      T      9=  42.681
```

```
SUBMODEL NAME = VCS

                                     CALCULATED                              ALLOWED
       MAX DIFF DELTA T PER ITER     DRLXCC(VCS           9)=-9.399414E-03 VS. DRLXCA= 1.000000E-02
       MAX ARITH DELTA T PER ITER    ARLXCC(              0)=  0.00000     VS. ARLXCA= 1.000000E-02
       MAX SYSTEM ENERGY BALANCE     EBALSC                 =-0.279587     VS. EBALSA * ESUMIS       =  0.00000
                                                                                EBALSA= 1.000000E-02
       ENERGY INTO AND OUT OF SYS    ESUMIS                 =  0.00000         ESUMOS=  34.4300
       MAX NODAL ENERGY BALANCE      EBALNC(VCS           5)=-5.487376E-02 VS. EBALNA=  0.00000
       NUMBER OF ITERATIONS          LOOPCT                 =       91      VS. NLOOPS=     500
       PROBLEM TIME                  TIMEN                  =  0.00000     VS. TIMEND=  0.00000

                                   DIFFUSION NODES IN INPUT NODE NUMBER ORDER
 T     1=  311.47     T     2=  318.46     T     3=  321.17     T     4=  322.96     T     5=  324.29     T     6=  325.35
 T     7=  326.24     T     8=  327.02     T     9=  327.93
                                   ARITHMETIC NODES IN INPUT NODE NUMBER ORDER
                                                      ++NONE++
                                   HEATER NODES IN INPUT NODE NUMBER ORDER
                                                      ++NONE++
                                   BOUNDARY NODES IN INPUT NODE NUMBER ORDER
                                                      ++NONE++

SUBMODEL NAME = MLI


                                     CALCULATED                              ALLOWED
       MAX DIFF DELTA T PER ITER     DRLXCC(              0)=  0.00000     VS. DRLXCA= 1.000000E-02
       MAX ARITH DELTA T PER ITER    ARLXCC(MLI           7)=-3.080374E-04 VS. ARLXCA= 1.000000E-02
       MAX SYSTEM ENERGY BALANCE     EBALSC                 =-1.371460E-12 VS. EBALSA * ESUMIS       = 0.482721
                                                                                EBALSA= 1.000000E-02
       ENERGY INTO AND OUT OF SYS    ESUMIS                 =  48.2721         ESUMOS=  0.00000
       MAX NODAL ENERGY BALANCE      EBALNC(MLI           4)=-5.485840E-13 VS. EBALNA=  0.00000
       NUMBER OF ITERATIONS          LOOPCT                 =       91      VS. NLOOPS=     500
       PROBLEM TIME                  TIMEN                  =  0.00000     VS. TIMEND=  0.00000

                                   DIFFUSION NODES IN INPUT NODE NUMBER ORDER
                                                      ++NONE++
                                   ARITHMETIC NODES IN INPUT NODE NUMBER ORDER
 T     1=  532.85     T     2=  532.93     T     3=  532.97     T     4=  532.99     T     5=  533.01     T     6=  533.02
 T     7=  533.03     T     8=  533.04     T     9=  533.06
                                   HEATER NODES IN INPUT NODE NUMBER ORDER
                                                      ++NONE++
                                   BOUNDARY NODES IN INPUT NODE NUMBER ORDER
 T   999=  540.00


 RESTART RECORD NUMBER        231 WRITTEN FOR TIMEN =    0.00000     , LOOPCT/O/R =         88/         0/         0
```

PROBLEM G: VAPOR COMPRESSION CYCLE

Vapor compression (reverse Rankine) cycles are the basis of most air conditioning systems. Compressed (and therefore heated) gas is cooled and condensed at a high temperature, rejecting heat from the loop to the environment. The condensate is expanded to a low pressure through a valve, orifice, capillary tube, or other throttling device. Two-phase flow enters the low temperature evaporator, which acquires heat from the source (house, vehicle cabin, food compartment, etc.). The chilled air will often be cooled below its dew point, and perhaps below its freezing point. Figure G-1 depicts a simplified loop.

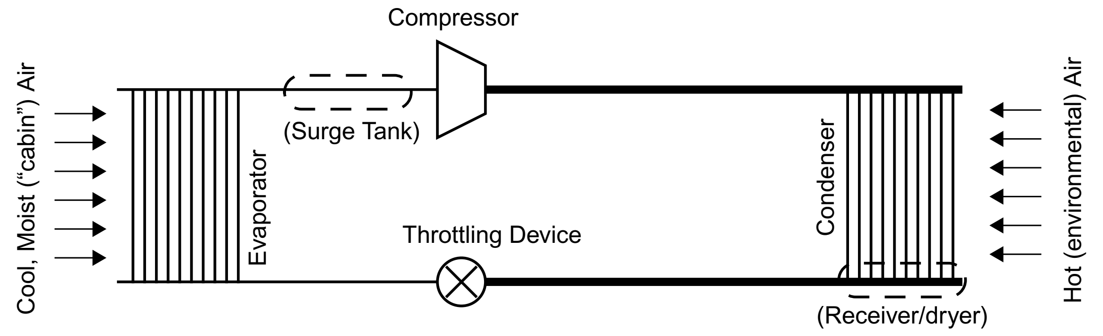

Figure G-1 Simplified Vapor Compression Cycle

For maximum performance (coefficient of performance COP = Qevap/Qcompr), the evaporator will yield 100% saturated vapor: no superheat. However, most compressors do not tolerate liquid, at least not very much nor for very long. Therefore, for maximum design life a minimum superheat is desired: on the order of perhaps 10°F despite variations in operating conditions such as compressor shaft speed (or input power if electric), environmental and cabin conditions, etc. A surge tank, with gravitational or other barriers to trap and contain liquid refrigerant, is sometimes used at the inlet of the compressor for handling off-design conditions, but such tanks can only offer transient protection. For various reasons, control of the evaporator superheat set-point is traditionally performed by the expansion device rather than the compressor. Simple fixed expansion devices such as orifices do not offer much control, although others (orifice tubes* and capillary tubes) are better. Active control is common via a passively actuated valve: a TXV (thermostatic expansion valve), which has a servo line (also called a "capillary tube," not to be confused with the throttling device of the same name) connected to a remote bulb that is placed on the evaporator outlet.

This problem analyzes a fictitious R134a automotive vapor compression cycle air conditioner. The likelihood of a fixed expansion device (sharp-edged orifice) providing adequate superheat pro-

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* Note: the ELLD (L/D) factor in the ORIFICE connector ("long orifice") is appropriate for incompressible flows only, and is *not* an appropriate model of an "orifice tube" (L/D on the order of 20-25) used as a liquid throttling device. See Section G.1 side notes.

tection is investigated statistically. Then, the transient control behavior of a replacement, a fictitious TXV, is investigated.

This problem was chosen to demonstrate the following FLUINT features:

1. realistic compressor modeling
2. orifice and TXV modeling
3. wet air psychrometrics
4. charge mass conservation in vapor compression cycles
5. statistical analysis approaches
6. dealing with reasonable nonconvergence
7. differential equation co-solvers for modeling mechanical motions

This problem is worked as both a system-level model and as a detailed evaporator model (substituting a TXV for a fixed orifice). The system-level model is solved hundreds of times at different steady state conditions to gain statistical performance information. The evaporator-level model is solved primarily in a transient mode to investigate control stability.

The Constant Charge Issue—In undergraduate texts, Rankine and other power cycles are taught as series of thermodynamic state points, with at least one pressure "given." In reality, the pressures in the system are largely self-determining. Usually, the more working fluid charge mass in a given system, the higher all pressures become. This means that when designing a system, if the pressure is chosen at any point, then a certain amount of charge has also been implicitly selected.

Therefore, it is important to be able to assess the variation of performance associated with a variable charge mass. For example, if a parametric sweep of compressor shaft speed is made assuming a constant suction pressure, then each speed investigated is a actually a different system: in order to keep suction pressure constant: each point investigated will have a different charge. A more realistic sweep would keep charge mass constant instead. This phenomena is illustrated by Figure G-2, which compares the two assumptions.

Furthermore, transient analyses can *only* be done if pressures are not prescribed; to predict transient performance, the solution must conserve the total working fluid mass and allow the pressures to change as needed.

In FLUINT, if one or more vapor- and/or gas-containing tanks are present in the system and plena (or HLDLMP tanks or junctions) are absent, then the pressures will self-determine *during a transient analysis* or an STDSTL run. However, in FASTIC ("Steady") tank volumes are "lost" since tanks are treated like junctions in that solution, and so a reference pressure must be supplied. Mathematically, junction states have meaning only in relationship to one or more tanks or plena.

This means that in most steady state solutions, FLUINT reverts to the undergraduate treatment of "pick a pressure, let mass self-determine." To actually perform the reverse ("pick mass, let pressure self-determine") means that either a parametric sweep on some reference pressure must be made, or the Solver or some other search or iterative closure must be invoked to find the reference pressure that yields the desired mass. To express the problem mathematically, a FLUINT steady state solution

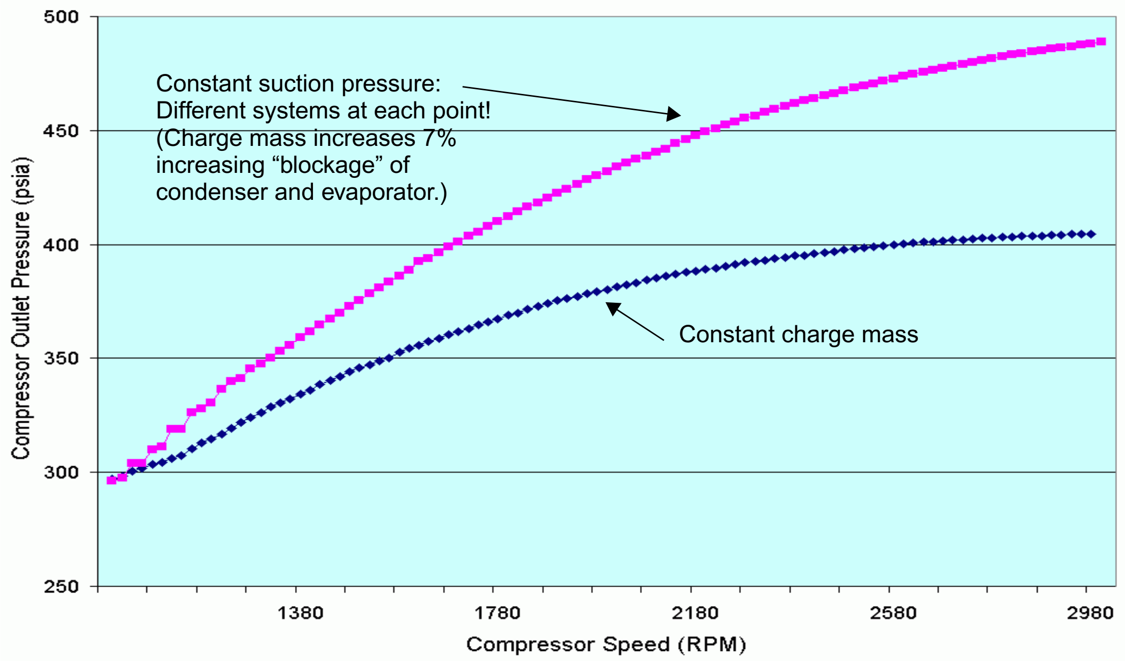

Figure G-2 Two Parametric Sweeps Illustrating the Importance of Conserving Mass

yields mass as a function of pressure, M(P), whereas pressure as a function of mass, P(M), is desired. This fact has important repercussions on vapor compression loop modeling in general, and on this sample problem in particular.

One final note should be made regarding surge tanks and receiver/dryers. These components essentially "disappear" in steady state analyses (except perhaps if they cause an oscillation instead of a true time-independent answer). In other words, they only "appear" in a transient mode by storing and releasing liquid, and therefore attenuating the sensitivity of a real system to changes in boundary conditions and compressor speeds. While FLUINT is capable of modeling such components, these transient effects are neglected in the system-level model and disregarded in the TXV transient model to preserve a tighter focus.

G.1 Part 1 Problem Description: System Model

The parameters for this R134a air conditioning system are listed below:

Compressor:	
Input shaft speed	1000 to 4000 RPM
(probability distribution function provided below)	
Isentropic efficiency	equation:
$\eta_i = 1 - 1.623371/(P*R) + 0.93049/P + 0.67806/R - 0.333806*R/P - 0.400297 - 0.052482*P/R$, where P is the pressure ratio and R is RPM/1000	
Volumetric efficiency	equation:
$\eta_v = 1 + 0.08469/R + 0.31711 - 0.085057*P/R - 0.153835*R - 0.014169*P$ where P is the pressure ratio and R is RPM/1000	
Displacement	20 cc
Charge mass:	0.2 lbm
(Gaussian distribution about this mean, with a 10% coefficient of variance[*])	
Condenser:	
Hydraulic Diameter	0.06 in.
Flow area factor (times $0.25*\pi*DH^2$)	2.0
Length	4 ft.
Number of parallel passages	30
Mass (aluminum C_p = 0.21 BTU/lbm-˚F)	5 lbm
Environmental (cooling) Air:	
Temperature	80 to 110˚F
(triangular probability distribution function peaks at 100˚F)	
Conductance to sink, overall	90 BTU/hr-˚F
Cabin (cooled) Air:	
Flow rate (counterflow)	300 CFM (ft^3/min)
Hydraulic diameter	0.25 in.
Flow area factor (times $0.25*\pi*DH^2$)	8.0 (fins)
Temperature	65 to 80˚F
(triangular probability distribution function peaks at 70˚F)	
Relative humidity	0 to 100%
(flat or uniform distribution: equal probability of any value)	
Fin effectiveness	0.8
Evaporator:	
Hydraulic Diameter	0.06 in.
Flow area factor (times $0.25*\pi*DH^2$)	2.0
Length	2 ft.
Number of parallel passages	24
Mass (aluminum C_p = 0.21 BTU/lbm-˚F)	5 lbm
Receiver/Dryer	neglected/absent
Surge Tank volume	300 cc
Hot (vapor) Transport Section (adiabatic)	
Diameter	0.15 in.
Length	10 ft.

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[*] The coefficient of variance is the standard deviation normalized to the mean, and is therefore unitless.

Cold (liquid) Transport Section (adiabatic)
  Diameter . . . . 0.10 in.
  Length . . . . 10 ft.
Throttling Orifice (fixed)
  Sharp-edged hole diameter . . . . 0.018 in.
    (Gaussian distribution about this mean, with a 3% coefficient of variance)

The probability distribution function for the compressor speed is based on a direct link to the motor speed for an automotive application: it represents the probability of being at any particular engine speed based on time, with more time spent at idle and full speed than in transition.* This function is plotted at the right. Keep in mind the shape of the curve is what is important: the overall probability (the area underneath the curve) will be normalized to unity by the program such the values of each peak can be chosen arbitrarily as long as they are consistent relative to each other.

As was noted above, sharp-edged orifices provide no active evaporator outlet superheat control: there are no provisions to prevent liquid from exiting the evaporator (and perhaps entering the compressor) other than transient storage within the surge tank. Therefore, the design question relevant to Part 1 of this sample problem is as follows: ***What are the chances that the minimum desired superheat (10˚F) will be achieved given variations in environmental temperature, cabin temperature, cabin relative humidity, compressor speed, orifice hole size, and charge mass?*** Note that the first few uncertainties are variations in usage scenario, while the latter two (orifice hole and charge mass) represent unit-to-unit manufacturing and installation uncertainties/tolerances.

To answer this question, only steady state effects will be considered for simplicity and conservatism, essentially neglecting surge tank and receiver/dryer responses.

Side Note: Other Expansion Devices—The sharp-edged orifice or fixed position throttling valve (for which an orifice might be considered a reasonable model) are not common choices. Other more typical devices include orifice tubes, capillary tubes, and thermostatic expansion valves (TXVs).

TXVs may be modeled at a system-level by using a DPRVLV connector whose PSET (downstream set-point pressure) is calculated to preserve the desired superheat, although Part 2 of this sample problem explores a more detailed dynamic model.

Capillary tube throttling devices may be modeled with duct macros with adequate axial resolution, choosing junctions and tubes due to the small diameters and long lengths of capillary tubes. HX macros are particularly useful for diabatic capillary tubes, and are a "must" if heat is regeneratively exchanged with the suction line.

Orifice tubes, on the other hand, cannot be readily modeled using built-in component models because of the complex physics involved. Specifically, they are not the same as "long orifices" and

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* And, as usual, this is fictitious or at least "cleansed" from real applications to avoid both unnecessary complications as well as proprietary sensitivities.

so the ORIFICE model in FLUINT is inappropriate. Good results for orifice tubes have been obtained using test data as performance maps, perhaps implemented using TABULAR connectors.

G.2 Part 1 SINDA/FLUINT Model

The compressor and the orifice divide the loop into two pressure levels, whereas the condenser and evaporator divide the loop by phase.

The evaporator and condenser both have many parallel legs that can be assumed to be identical. This assumption allows a single HX macro to be used to represent the entire evaporator, and a second HX macro to represent the condenser. Each such macro represents a single leg which should be finely divided due to the large gradients in phase and temperature that can be expected. DUPI/DUPJ and DUPN/DUPL path and tie duplication factors are used to magnify these effects at the system level according to the number of parallel passages. For example, the DUPI for the first path of the evaporator is set to 24, as is the DUPJ of the last path of that macro. From the macro's perspective, only one leg exists, but from the system's perspective it is as if 24 such passages existed.

The evaporator wall is represented as 1/24th of the total, so DUPN=DUPL=1.0 for the R134a side as well as the air/water side of that counterflow heat exchanger. Again, DUPI and DUPJ factors are used in the air flow submodel to model 24 identical parallel passages. This is to be contrasted with the condenser model, where the nodes represent the whole heat exchanger, and therefore the symmetry of the condenser is returned to the system level using *tie* duplication factors (DUPN=30).[*]

The cross sections of the condenser, evaporator, and air-side flow passages are not circular, and are in fact undefined in this problem: a flow area multiplier is used instead.[†] In a more realistic case, AF would be input faithfully, as would DH (based on the wetted perimeter so that heat transfer calculations are correct). Then if DH were inappropriate (a far-from-circular case such as triangular cross sections or slots), the DEFF factor would also be input.

The condenser is built using tanks while the evaporator uses junctions. In the latter case, the junctions have been assigned the correct volume (despite the fact that the solution ignores this input) for two important reasons: (1) so that this "tank vs. junction" decision can be easily revoked, and (2) so that routines such as SUMFLO and SUMDFLO can calculate the mass the system *would* contain, whether or not the element can actually store or release mass transiently. The model is only executed with FASTIC ("Steady") anyhow, so the distinction between tanks and junctions is irrelevant until a transient is invoked. But this leaves the basic question of why tanks are chosen in one component (the condenser) but not the other (the evaporator). Tanks, of course, are computationally more expensive in transients. Therefore, they are avoided where possible: in the evaporator, which volumetrically contains little liquid and therefore little mass. Neglecting mass, the tracking of which

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[*] While powerful, duplication factors can be confusing. Furthermore, they can cause energy flow imbalances that require extra steady-state iterations to confirm. They can be avoided in this case by using the diameter (DH and perhaps DEFF) of *each* passage, yet the flow area (AF) of *all* passages. However, since there are many situations were symmetry can be exploited to reduce model size, and duplication factors have other uses too, they are used and documented in this sample problem.

[†] Detailed geometries of the evaporator and condenser are purposely neglected since they would distract from the important conclusions of this sample. Many options are available for such hardware, and detailed models can be time-consuming to construct (especially without the help of codes such as FloCAD) but are not conceptually difficult.

is relevant to the charge/pressure self-determination problem described above, is not as easy in the condenser because it will contain much more liquid.

Homogeneous flow has been assumed in the evaporator and condenser for speed of solution, although some users report more accurate results using slip flow (twinned paths) due to the enhanced prediction of void fraction: due to the importance of the conservation of charge mass on the prediction of operating pressures.

The transport sections are rather long, but have been assumed to be insulated so coarse discretization can be used to simulate them. In effect, they represent only pressure drops and a small amount of volume for the charge mass tally.

The orifice model is rather simple from a user perspective: the built-in correlations are applied for the K-factor and vena contracta (choking) prediction. This election is possible despite the fact that flashing will occur as long as the upstream condition is liquid and not two-phase flow. In that (single-phase inlet) case, the losses in the built-in correlation are still relevant since they are dominated by the constriction[*] process and the calculation of the size of the vena contracta. *Then* the flashing can be presumed to occur in the downstream section as a separate process. In effect, the orifice is single-phase upstream of the vena contracta and two-phase downstream of it. This assumption is mimicked in the default assumptions for choked flow (MCH=-2), which neglect phase change in the constriction zone. In a nutshell, the fluid simply doesn't have *time* to flash at the inlet since the transit time is so small.[†]

The surge tank is simply a FLUINT tank with a vapor-specific suction applied to the outlet path (the compressor), which permits liquid to accumulate but only vapor to exit. However, such accumulation can only occur during a transient: in FASTIC ("Steady") the tank becomes a junction and therefore loses the ability to store or release mass. If liquid enters the junction (i.e., if there is incomplete boiling in the evaporator), then the liquid fraction in the surge tank jumps up instantly and the liquid from the evaporator flows into the compressor despite the request for vapor only: the junction has no place to store the liquid. Therefore, the surge tank model is a bit problematic for steady-states, and in fact its ability to store liquid is ignored in the charge calculation: each time the charge mass is tallied (via a call to SUMDFLO), the surge tank quality is first reset to 100% vapor (quality XL of 1.0). The purpose of even having such a surge tank model in this sample problem is to illustrate such effects and their choices. This point having been made with the surge tank, it won't be repeated for the analogous receiver/dryer, which is therefore omitted completely.[‡]

A compressor with a known power input and isentropic efficiency could perhaps be modeled by building a NULL connector and then calling the simulation routine COMPRS within FLOGIC 1 to take over manipulation of the NULL connector, which is otherwise a very advanced path to use.

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[*] "Constriction" geometrically represents "expansion" from the viewpoint of the accelerated fluid, if it is compressible.

[†] In either an orifice tube or capillary tube, this statement is no longer true: the fluid *does* flash before reaching the effective throat state.

[‡] In realistic transient models, the phase suction of the surge tank (if even present!) and the receiver/dryer tanks are manipulated in logic (via calls to CHGSUC) as functions of the void fraction (ALn for lump n). The real complication occurs when there is no steady state, and instead an oscillation about an average occurs. In such cases the user is forced to use STDSTL or a transient routine with a corresponding tremendous increase in computational cost.

However, the input power is *not* known. Instead, the shaft speed, displacement, and volumetric efficiencies are known instead. The mass flow rate is calculated by multiplying these three quantities together along with a fourth quantity: the current suction (compressor inlet) density. Both the volumetric and isentropic efficiencies are given as performance maps (equations, in this instance) as functions of speed and pressure ratio.

Future releases of SINDA/FLUINT will feature the ability to specify such performance maps directly for turbomachinery. In the meantime, user logic will be used to read these maps and apply them to a NULL connector and to an outlet lump temperature.

This logic is divided into two steps: (1) specification of the current outlet temperature given the current speed and pressure ratio (and therefore isentropic efficiency), and (2) specification of the current mass flow rate given the same data (to calculate the volumetric efficiency) along with the compressor inlet density. The first part will be placed in FLOGIC 0 and the second in FLOGIC 1 (although it too could have been placed in FLOGIC 0 if needed).

This logic will be described in the next section. For now, two details are important to note. First, the power is not specified directly, but rather indirectly: the compressor outlet lump is set to be a heater junction (via a call to HTRLMP) whose temperature is set by the user and whose heat rate QDOT is calculated by SINDA/FLUINT to maintain that temperature (or at least enthalpy) over the solution interval. This means that if the flow rate changes during each iteration or time step, a rather unrelenting assumption of constant heat load will be avoided in favor of an assumption of constant temperature.

Second, instead of using an MFRSET (or VFRSET) to set the compressor flow rate, a more implicit and therefore stable and forgiving method is used: a NULL connector. A NULL connector with zero GK is equivalent to an MFRSET or VFRSET, and allows no adjustment of flow rate within the solution interval despite changes to pressure ratios. Such a rigid device model would therefore be less likely to converge in steady-states (i.e., be more prone to oscillations) and would take small time steps in transients. Adding a nonzero GK term (the derivative of flow rate with respect to changes in pressure gradient) avoids these problems, and therefore justifies the use of the more advanced and abstract NULL over the simpler and more intuitive MFRSET and VFRSET components.[*] To calculate this term, the volumetric efficiency map must be explored beyond the current design point: the derivative with respect to pressure ratio is required. In this problem, the performance map is an equation and so the derivative could be obtained in a closed form solution. However, in other cases the maps are tables, so a more generalized if messy approach will be taken in this model: a finite difference perturbation of pressures.[†]

Finding Pressure as a Function of Charge Mass—Recall that while system mass is conserved in a transient analysis, the charge level cannot be specified directly in a steady state (FASTIC or Steady) solution. Instead, a reference pressure must be found that results in the correct charge for each scenario. In this sample problem, the discharge pressure (*PHI*, the pressure in HLDLMP junction 9000) is chosen as a reference.

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[*] Adding nonzero EI would further enhance the model by allowing the inlet temperature changes to be accounted for implicitly (meaning *within*, rather than *between*, solution intervals).

[†] This method has the further advantage of including variations in suction density if the inlet pressure is the one perturbed.

This inversion [calculating P(M) given M(P)] can be performed using (1) a parametric sweep with subsequent interpolation, (2) the Solver in a single-variable goal-seeking mode, (3) a binary search, or (4) internal iterative logic in FLOGIC 0 or 2 within a single steady state solution.

One example of the parametric sweep option (#1 above) is illustrated at the bottom of OPERATIONS, but is not used by this sample problem since *isolve*=3. A DO LOOP (or perhaps a PSWEEP call) is made from the lowest to highest expected pressures, with the results stored away in an array. Then, a interpolation (D1DEG1) is made on that array to estimate the pressure that would yield the correct charge, followed by a final steady state solution performed using this interpolated pressure. One of the disadvantages of the parametric sweep option is that it must test both the high and low extremes of pressure, at which points an inviable system is most likely to be found.

The second method (the Solver) could also be used in this case: the optimizer could be nested under the statistical design module. Each time a new random point is sampled (see commented lines in RELPROCEDURE), the Solver would shift the compressor outlet pressure until the current charge (*ChargeC*, the OBJECT) equals the desired charge (*ChargeD*, the GOAL) using the goal-seeking mode. This can require up to 20 or so iterations, with each iteration being a full steady-state solution. Also, the Solver can be confused by inconsistent results and false trends (i.e., “computational noise”): it demands good accuracy in the underlying solution, upon which it bases its decisions.

In this sample problem, the binary search method (#3) works best, and is very simple to implement. A reasonable maximum and minimum pressure are chosen, then a DO LOOP is repeated *NClevels* times (*NClevels* is an integer register set to 6), each time halving the range of possible pressures by testing the middle (mean) value to see whether it is too high or too low via a call to STEADY (see RELPROCEDURE). The effectiveness of the binary search algorithm lies in the fact that its accuracy is inversely proportional to $2^{(\mathrm{NClevels}+1)}$. In this case, the pressure will be found to an accuracy of $(500\text{-}200)/2^7 = 2.3$ psi with only 7 steady state solutions, and the final solution doesn’t count towards the cost since it is the one needed by DSAMPLE to estimate superheat. In other words, the binary search method costs 6 solutions, the Solver method about 10 to 20, and the parametric sweep option about 7 with coarse resolution.

All of the above methods require multiple steady-state solutions to achieve their result. These underlying solutions need to be accurate enough to avoid computational noise (especially for the Solver), but do not necessarily need to converge if the answers are “good enough.” Path duplication factors, for example, tend to require extra iterations to confirm even though the answers will not change appreciably in the final iteration. Therefore, a limit of 100 (NLOOPS) iterations will be allowed and the answers at that point accepted. A limit of *NClevels*=6 is also chosen to keep the run as fast as possible.

The accuracy of these “short cuts” will be double-checked by comparing the statistical spread of actual charge (*ChargeC*) with that of the specified charge (*ChargeD*). In other words, neither STEADY nor the binary search will be allowed the luxury of completely converged solutions in the interest of producing answers quickly, but this compromise is acceptable since the answers are reviewed (and, as will be shown, found to be adequately accurate).

The final method (#4) involves a *iterating* PHI *within a single steady state run.* Such an approach is possible, but it can take a lot of user logic and can easily suffer from convergence difficulties. Therefore, unlike the other options, it is not demonstrated within the input file nor discussed further.

G.3 Part 1 Inputs: System Model

[Because of the complexities of the model involved, full documentation is not provided here. Many diagrams were created in Sinaps*Plus*, and the sample model is available in that format as part of the install set. Temporary licenses are available to run Sinaps*Plus* as needed. Also, alternate solution approaches used in the development of this sample problem have been left in the input file but, with the exception of a brief descriptions in this subsection, they are largely undocumented. For the main run described in this chapter, the reliability assessment, the integer register *isolve* is equal to 3. Where necessary for clarity, comments regarding alternate solution approaches are denoted, like this one, in square brackets.]

The input file is listed immediately following the last section.

CONTROL DATA—English units are chosen, with units of °F and psia. A tight tolerance (0.3%) is specified for changes between steady state iterations (RERRF), and a lump-by-lump energy balance check is signaled with a negative value of REBALF because of the adverse influence of path duplication factors on system-level energy balances. As is usual with thermal models completely dominated by their connection to fluid submodels, no extra damping or acceleration is needed nor helpful, so EXTLIM is set to zero.

REGISTER DATA—As usual, various dimensions, efficiencies, etc. are defined up-front in register data so that registers can be used as a central control panel for model changes or parametric sweeps, and also as design variables and random variables. This includes the resolution (number of nodes and lumps) in the lengths of transport and heat exchange sections (e.g., *EvapRes*, *CondRes*), although if these two parameters were to change, then the network would also need to change,* but the expressions defining each element would remain invariant.

The factors in the compressor maps are listed (CI* for isentropic efficiency coefficients, CV* for volumetric efficiency). The volumetric efficiency *eVol* and isentropic efficiency *eIsen* are both calculated based on *Prat* (the ratio of compressor discharge to suction pressure) and *RPMF* (equal to *RPM* divided by 1000).

NODE AND CONDUCTOR DATA—Two thermal submodels are built, one for the hot air environment at the condenser end, and the other for the cold air heat exchanger at the evaporator end. The total mass of each node in the evaporator submodel, AirE, represents one part of one passage out of *EvapNum*. In the condenser submodel, AirC, each node represents the mass of all passages at the same flow-wise point: the condenser tie duplication factors assure that each of these nodes sees all the condenser passages that actually exist ("*CondNum*"). In both cases axial conductances are ignored or at least set very small (and so essentially ignored). The network diagram for submodel "AirC" is given in Figure G-3 as an example.

FLOW DATA—Two fluid submodels are used: one to represent the wet air in the "cabin" and one to represent the r134a loop.

The cabin model (Figure G-4) is a very simple one: moist air counterflowing over the nodes in thermal submodel AirE. Path duplication factors divide and recombine the 300 CFM air from the

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* Unlike Sinaps*Plus*, FloCAD "knows" about the geometry and therefore makes such resolution changes easily.

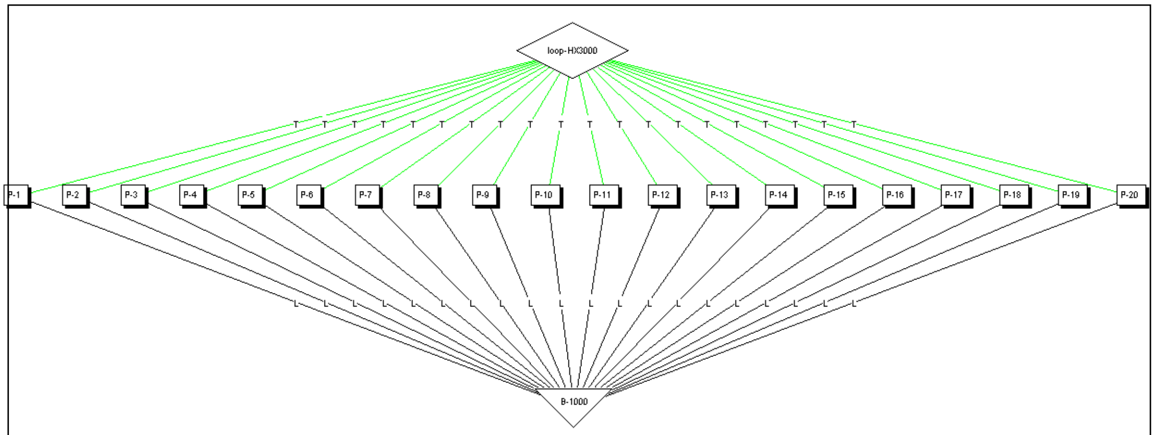

Figure G-3 Condenser Thermal Model “AirC” (Sinaps*Plus* Network Diagram)

VFRSET connector into *EvapNum* parallel sections. The fin effectiveness is applied as the tie UAM factor. The relative humidity, *RelHum*, of air is set in OPERATIONS via a call to HUMR2X. The working fluids are air (as an 8000 series file) as species “A” and the library description of water as species “W.”

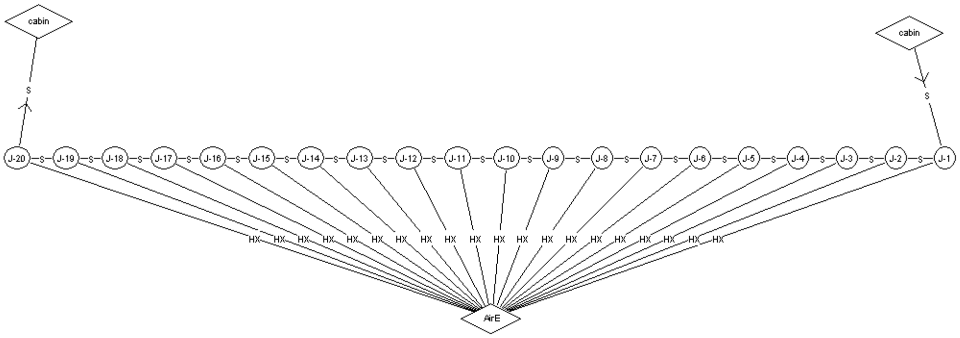

Figure G-4 Cabin Fluid Model “cabin” (Sinaps*Plus* Network Diagram)

The vapor compression cycle itself is placed into a fluid submodel named “loop” (Figure G-5). The working fluid properties are taken from the full pressure/temperature table description created from NIST’s REFPROP program, the converter for which arbitrarily assigned the table ID to be “6049.” Such tabular full-range descriptions for various fluids are available from www.crtech.com or by request.

The names and types of the major elements in fluid submodel “loop” are as follows:

Compressor:

TANK 1000	compressor inlet: Surge Tank
NULL 1000	for compressor simulation
JUNC 2000	compressor outlet
JUNC 9000	reference pressure *PHI* (held during steady states)

Condenser:
    HX 3000 (tanks 3001-3020, STUBEs 3000-3020, etc.)
Throttling orifice:
    JUNC 5000 . . . . Outlet of liquid line, inlet of orifice
    ORIF 5000 . . . . Throttle
    JUNC 6000 . . . . Outlet of throttle, inlet to evaporator
Evaporator:
    HX 6000 (junctions 6001-6020, STUBEs 6000-6020, etc.)
    Connects to cabin submodel via the thermal submodel AirE

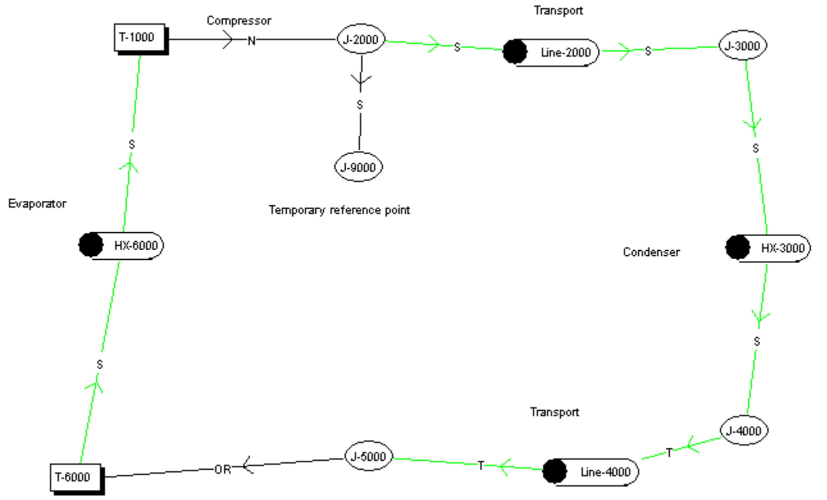

Figure G-5 R134A Fluid Model “loop” (Sinaps*Plus* Network Diagram)

OUTPUT CALLS—This block calls standard output routines LMPTAB, TIETAB, and PTHTAB, and SAVE. However, this block is only used if any transient runs are made, since otherwise it would generate too much data. If any submodel fails to converge (LOOPCT=NLOOPS), however, a snapshot is output and data saved to a different file (the RSO file via the RESAVE routine) to permit investigation.

RELIABILITY ENGINEERING BLOCKS—The reliability engineering blocks (RANDOM DATA, RELPROCEDURE, RELCONSTRAINT DATA, etc.) define the main purpose of the model when *isolve*=3: find the probability that the fixed-size orifice design will satisfy the compressor inlet superheat requirements given variations in environment, sizes, refrigerant charge, etc.

First, the uncertain variables are input as registers, then they are identified as uncertainties within the RANDOM DATA block. Two variables (charge and orifice hole) follow bell curve (normal) distributions as a result of the fact that they represent installation uncertainties and manufacturing tolerances.* The cabin relative humidity follows a uniform distribution: equal probability of any

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* Be careful not to define the mean as “Ohole” or “ChargeD” since those *are* the random variables: otherwise the mean itself would drift since the reliability engineering module will vary the values of these variables as it operates.

value between 0% and 100%. The remaining variables follow irregular probability distribution functions that are input in ARRAY DATA for submodel LOOP.

Next, reliability constraints ("failure limits") are defined. The first three constraints are not limits but rather requests for information: they will provide some knowledge of how the charge actually varied as a double-check, how the COP of the device varied, and what the chances are of ice build-up on the air side of the evaporator. These three limits are specified by equation, and so are "unnamed" constraints. The "real" reliability constraint is provided by SHEAT10, a named reliability constraint whose value will be set at the end of RELPROCEDURE to the temperature difference across the evaporator. This limit will then be compared to 10 ˚F. A second named reliability constraint, SHEAT20, is compared to 20˚F to gain a little more information about the resulting probability distribution function for superheat. Note that this second constraint is identical to the first except that it has different limits. Nonetheless, this requires the generation of a new unique name. (Using EZXY® histograms, the user can "interrogate" a predicted distribution function by specifying new constraint limits after the analysis is complete.)

A call to the output routine RANTAB in OPERATIONS will make sure that the random variables have been defined correctly, and a call to RCSTTAB in OPERATIONS will be used to summarize results. A call to SAVEDB in RELOUTPUT saves each data point away in the REDB file for use in plotting (or perhaps for appending future runs).

The prediction of the superheat probability distribution function itself is made via a call to DSAMPLE in OPERATIONS. DSAMPLE, the latin hypercube descriptive sampling routine, will be allowed an affordable number of calls: 100 (equal to NLOOPR). DSAMPLE will therefore call RELPROCEDURE 100 times, each with unique values of *RPM*, *ChargeD*, *TairE, RelHum, TairC*, and *Ohole*.

All that is theoretically needed for the RELPROCEDURE is a single steady state solution producing a single value of the current compressor inlet superheat. However, as has been noted above, the procedure must first adjust the pressure to get the correct charge. A binary search method (described above) accomplishes this inversion. Once the charge is reasonably matched, a final steady state is called within RELPROCEDURE to calculate the actual superheat, which is stored in SHEAT10 and SHEAT20 for post-processing.

SOLVER BLOCKS—The solver blocks (SOLVER DATA, DESIGN DATA, etc.) are a bit complicated since there are two potential uses of the Solver in this model. *Actually, the Solver is not used at all by the provided settings: it is documented only.* When the reliability runs are being made (*isolve*=3), the Solver can be used to perform the pressure/charge calculation, except that this has been commented out in RELPROCEDURE in favor of the binary search method. Otherwise, the Solver would be invoked use just a single design variable, *PHI*, and is set to a goal-seeking mode: find the value of *PHI* that yields *ChargeC* (actual charge) equal to *ChargeD* (desired or specified charge).

[When *isolve*=1, the Solver becomes the main solution, and not just a potential nested adjunct solution to DSAMPLE. In this sizing mode, the loop is designed such that the COP is maximized. Extra design variables are activated (see Sinaps*Plus:* inactivated design variables are not visible in the input file); in addition to *PHI*, design variables include *EvapDia*, *CondDia*, *EvapNum*, *CondNum*, *Ohole*, and *CompDisp*. The values of these variables found by the Solver roughly correspond to those used as “fixed” values in this sample problem, with a resulting COP of about 2. In the sizing mode, several optimization constraints are also applied: adequate cooling shall be produced, freezing should be avoided at the evaporator inlet, and superheat shall not be less than 20˚F: greater than 10˚F to allow margin for uncertainties. If 10˚F had been used instead and if the resulting optimum resided along this constraint, then since inputs are statistical rather than deterministic the minimum superheat constraint would have been violated roughly half the time. See “Robust Design” in Chapter 5 of the main volume for similar examples.]

OPERATIONS—The configuration is built (BUILD ALL and BUILDF ALL could have been used equivalently in this case) then the cabin air humidity is set. FLUINT expects absolute humidity as a gas mass fraction (cabin.XGW1000, the fraction of mass of species W in cabin plenum 1000), while the problem statement uses relative humidity (register *RelHum*). A call to HUMR2X finds equivalent absolute humidity, and a call to CHGLMP sets XGW for lump 1000. Other calls to CHGLMP make sure that the PL, TL, and XL of the cabin air are correct.

Next, the outlet of the compressor is set to constant enthalpy with a call to HTRLMP: compressor modeling logic in FLOGIC 0 will update the temperature of this lump (loop.2000) and SINDA/FLUINT will update its total heat rate QDOT as needed to achieve this temperature.

The thermodynamic state of junction loop.9000 is held constant next via a call to HLDLMP: it is turned into a plenum temporarily. Actually, for the entire series of analyses this action is never reversed, so one might wonder why a plenum wasn’t chosen instead. The reason that lump 9000 is a junction is because if a transient ever *were* run, then this HLDLMP action would be reversed (see the commented call to RELLMP at the bottom of OPERATIONS) such that the tanks in the loop would determine their own pressure as needed to conserve mass. For steady state analyses, it is more convenient to set this point as a reference pressure and, if necessary, adjust it to get the right loop mass.

When *isolve*=3, the main purpose of this model is effected: a statistical analysis using DSAMPLE descriptive sampling. A call to RANTAB precedes this analysis to check inputs, and a call to RCSTTAB follows the call to DSAMPLE to summarize findings. A header for the user file (USER1) is written; the contents will be filled from RELOUTPUT CALLS.

[When *isolve*=0, the IF checks all “fail” and logic falls through to the bottom of the loop, where a “manual” (non PSWEEP) parametric sweep of charge mass vs. pressure is run. (See the bottom of OPERATIONS.) This is an alternative to using the binary search algorithm or calling the Solver, and has the benefit of producing sensitivity information: a plot of mass vs. pressure. Note the DO LOOP operates on an integer variable then converts to a real variable to avoid round-off problems. It also re-uses PROC: the small sequence of operations already defined in the Solver’s PROCEDURE block. Data from the parametric is stored in an array (loop.a100) such that the correct pressure can be found using an interpolation routine, D1DEG1. This value is used for a final steady state, which hopefully yields an answer close to the right mass, and the results of *that* steady state can be used as initial conditions for a transient, which is currently commented out.]

[If a transient *were* run, NSOL would be greater than 1. This triggers variables such as *RPM* and *TairE* to change as functions of time via calls to D1DEG1 in FLOGIC 0, which look up prestored profiles in the ARRAY DATA for fluid submodel “loop.”]

[When *isolve*=1, a sizing mode is used. The Solver is used to select values of *PHI* (and therefore charge), the compressor displacement, orifice hole diameter, and evaporator and condenser sizes such that *COP* is maximized, subject to a constraint of a minimum of 20°F superheat at the compressor inlet (allowing margin for uncertainties to be explored when isolve=3). Other constraints include avoiding freezing and excessive pressure drops on the air side, and providing a minimum degree of cold production. Refer to the Sinaps*Plus* model, since these design variables and constraints are inactivated and therefore don't appear in the generated input file. The Solver achieves a COP of 2 or so for the given conditions, yet, as will be seen below, when the system is subject to a wider spectrum of conditions in the statistical analysis, the COP can range from about 1.4 to 2.6[*]]

[When *isolve*=2, a series of parametric sweeps are run, all invoking the Solver's PROCEDURE block. These sweeps make sure that the model can endure the wide range of conditions to which a later DSAMPLE run will subject it to. Hence the use of "2" for the number of steps in most cases: highest and lowest points only. Nonetheless, some cases that DSAMPLE tries don't converge, a subject that has been dealt with above. More importantly, however, is that none of them fail (run into a condition for which the model was not designed and cannot handle or at least survive).]

COMPRESSOR LOGIC (FLOGIC 0 and FLOGIC 1)—The compressor maps are "consulted" and their results (registers *eVol*, *eIsen*) are used to update the compressor mode in FLOGIC 0 and FLOGIC 1.[†] The compressor "model" consists simply of calculating three values: the outlet temperature (set as loop.tl2000), the current flow rate (set as the HK of the NULL connector), and the "flow conductance" of the compressor (the slope of the pressure/flow rate curve, set as the GK of the NULL connector).

The first value (the outlet temperature) is calculated in FLOGIC 0 using the current isentropic efficiency. Since the model cannot handle liquid in the surge tank during steady-states, that liquid is manually "erased" by setting the quality of loop.1000 equal to unity via a call to CHGLMP before continuing. Otherwise, the enthalpy of the inlet is calculated via a call to VS (which, like all property routines, expects temperatures and pressures in absolute user units), and the temperature and specific volume that the outlet *would* have at that entropy is calculated via a call to VTAV1. This temperature and specific volume are then used to calculate the enthalpy at that hypothetical discharge state via a call to VH. Given the isentropic efficiency, the actual outlet enthalpy can now be calculated. However, while the outlet enthalpy will be held constant (each interval) via the prior call to HTRLMP in OPERATIONS, it cannot be specified directly: "HL" is not a valid input to CHGLMP. So instead, the temperature corresponding to that enthalpy is calculated using a call to VTAV2, and *that* value is passed to CHGLMP as "TL."

The other two values (HK and GK: the flow characteristics of the compressor) are calculated in FLOGIC 1 using the current volumetric efficiency. These values are both based on the registers *Prat* (containing the pressure ratio across the compressor) and *RPMF* (*RPM* divided by 1000), which in turn are used to calculate the isentropic and volumetric efficiencies. The mass flow rate *CompEM* is then calculated using the volumetric efficiency, the current RPM, and also the current inlet suction density (loop.DG1000: the density of the vapor/gas phase in the surge tank). As FLOGIC 1 starts,

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[*] All of these COPs should not be taken as representative: this sample problem is fictitious, after all.

[†] Future versions are planned which will eliminate the need for this logic by accepting performance maps directly for both compressors and turbines.

the next compressor flow rate is already available as *CompEM*, so that HK can easily be calculated as the difference between it and the current compressor flow rate, loop.fr1000.

The calculation of GK, the partial of mass flow rate with respect to differences in pressure gradient (i.e., the slope of the local curve), however, is more complicated: the current *Prat* needs to be perturbed along with the DG1000 used in the *CompEM* equation. In other words, the GK factor will be estimated using a finite difference method: perturb the suction pressure slightly, and let the spreadsheet functions update *CompEM* accordingly. (This could have been replaced with a closed form derivative using the chain rule since the equations are known algebraically, but such an approach is the exception rather than the rule, so a more general-purpose method is used instead.) The only "finesse" involved is this: if pressures are to be perturbed, then it is desirable to "remember" their original double precision value and make sure that it is restored completely, and not its single precision equivalent. This restoration is accomplished by introducing a couple of new double precision variables while working around the facts that CHGLMP works only in single precision, and yet the SINDA/FLUINT preprocessor attempts to stop direct setting of variables like PL.

G.4 Part 1 Output Description: System Model

Selected printings from the OUTPUT file are provided on the pages following the input listings.

Warnings about steady state nonconvergence are discussed elsewhere as acceptable expediencies. Other warnings include "TEMPERATURE TOO HIGH" cautions, which can occur while the steady state solution is searching for a solution. If these warnings don't persist in the final answers, they can be ignored.

Before describing predictions, a validation of the "short cuts" employed must first be made. These "short cuts" include (1) limited accuracy of the binary search for the pressure that yields the correct charge, and (2) tolerating occasional nonconvergence. Scanning the USER1 file "vcAir.usr," reveals that the percentage error (*ChargeC* differing from *ChargeD*) was less than about 3%. More importantly, the statistics of the actual charge (*ChargeC*) were tracked as the first (unnamed) reliability constraint. *ChargeC* had almost the same mean as the specified *ChargeD* profile, with about the same coefficient of variance (10%): the short-cuts were valid. (If the coefficient of variance or standard deviation were larger than that of the specified distribution function, then the inaccuracies would be conservative: a larger range of charges would have been tested than was required.)

The results of the RCSTTAB routine can be seen at the end of the OUTPUT file, and represent the main results of the lengthy analysis: the chances of going below the 10˚F superheat limit are 0% by tally and ~0.01% using a Gaussian profile. The first value is the fraction of DSAMPLE runs that yielded insufficient superheat (0 out of 100), while the second value represents a calculation based on a fit of all calculated superheat data to a Gaussian (normal) profile. Thus, the system is better than 99% reliable, not counting the safety margin provided by the surge tank.

As a second check, there is less than 1% (by tally) chance of getting less than 20˚F superheat, or ~0.3% chance using a Gaussian profile. This is provided by the SHEAT20 variable, or via EZXY calculations within histograms.

Note: Being a statistical analysis that employs randomized variables, *repeated analysis will yield similar but not identical results*. Repeated runs of this model can yield up to 1% chance by tally and up to 0.1% chance by normal distribution of not providing 10˚F superheat: 99% reliability.

Figure G-6 presents two EZXY histograms of the SHEAT10 named constraint variable: the compressor inlet superheat. These plots were produced from the results of the SAVEDB call, which was placed in the REDB file (VCair.savdb in this case). The plot on the left shows each of the 100 points sampled by DSAMPLE, whereas the plot on the right shows the same data collected into fewer "buckets" (specifically, 10 groupings) so that trends are easier to see. The results visually confirm the numbers printed by RCSTTAB, as well as showing clearly that the skew is towards higher, not lower, superheat values.

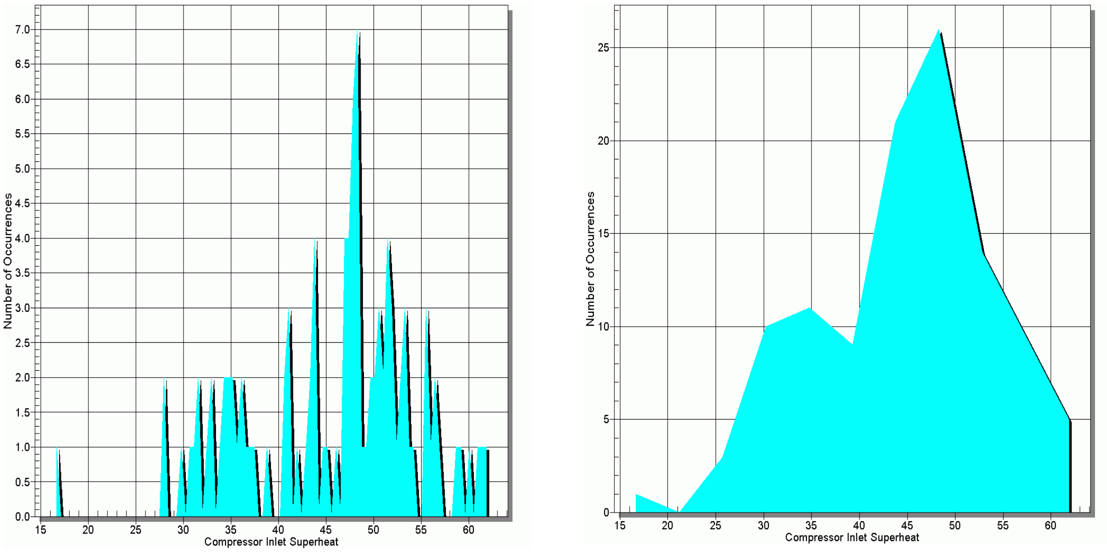

Figure G-6 Fine and Coarse Histograms of Compressor Inlet Superheat

In fact, the extent to which the system has be "over-designed" is also apparent: typical superheats are on the order of 50˚F. This represents waste: a much higher performing unit could be built if only the amount of superheat could be regulated according to current conditions. This enhanced performance is precisely the incentive to use more complicated active controls such as the thermostatic expansion valve (TXV) explored in the second part of this example problem. Note also that the high superheat corresponds to a cold evaporator inlet condition: the chances of building up ice on the air side at that point are 50 to 60% (based on the second unnamed reliability constraint)!

Two-phase Heat Transfer Notes: Perusal of the output file shows mark-ups in the '2P" column of the TIETAB outputs. In the condenser and in the air side of the evaporator, an occasional "S" indicates superheated condensation: superheated fluid but subsaturated wall. The "T" in the evaporator means transition boiling: the fluxes are high enough in that element to exceed the critical heat flux (CHF). The prediction of both the CHF and the post-CHF regimes (film and transition boiling) have large uncertainties as noted in the main volume. Sensitivity studies using the CHFF tie factors are recommended.

G.5 Part 2 Background: TXVs

The use of the orifice in the prior example problem successfully avoided liquid entering the compressor, but at a cost of overexpansion such that variations in manufacturing and environments are accommodated. Overexpansion translates into high superheat, which is inefficient thermodynamically, and also results in excessively cold evaporator inlets, which can lead to build-up of ice.

One alternative is to actively regulate the throttling such that more of the evaporator is active (boiling). TXVs (thermostatic expansion valves) adjust the flow through the loop to achieve complete vaporization with minimal superheat: typically about 10˚F. TXVs "sense" the differential in temperature between the inlet and outlet of the evaporator. The inlet of the evaporator is presumed to be saturated since it is downstream of the flashing that occurred within the throttling device (the TXV itself). The outlet of the evaporator should contain superheated vapor. If there is insufficient superheat at the outlet, the TXV closes down and restricts the flow. If there is too much superheat, the TXV opens up to allow more liquid (actually, two-phase fluid) to enter the evaporator.

Unfortunately, there is a lag between the sensing of this temperature and the adjustment. For example, assume there is too much superheat, so the TXV begins to open. In addition to lags and finite time constants in the sensing mechanism and valve pin motion, the newly released fluid must traverse the length of the evaporator, quenching heated sections as it does. By the time cooler vapor reaches the outlet, the system may overshoot and "hunt" for a stable set point. This difficulty in arriving at a stable set point is therefore termed evaporator or TXV "hunting." Many time constants and lags are involved, making detailed modeling necessary. Hunting is undesirable not only from an efficiency viewpoint, but also because it leads to increased wear of the valve and compressor.

A typical TXV is depicted in Figure G-7. Fluid flows past a bottleneck created by a gap between valve pin and the valve seat, and pressure is reduced. The low-pressure port is connected to one side of a diaphragm via an equalization tube, either external or (as shown in the figure) internal. The other side of the diaphragm is connected hydrodynamically via a long "capillary tube" to a bulb, which is itself attached thermally to the suction line at the outlet of the evaporator. The diaphragm therefore senses the difference

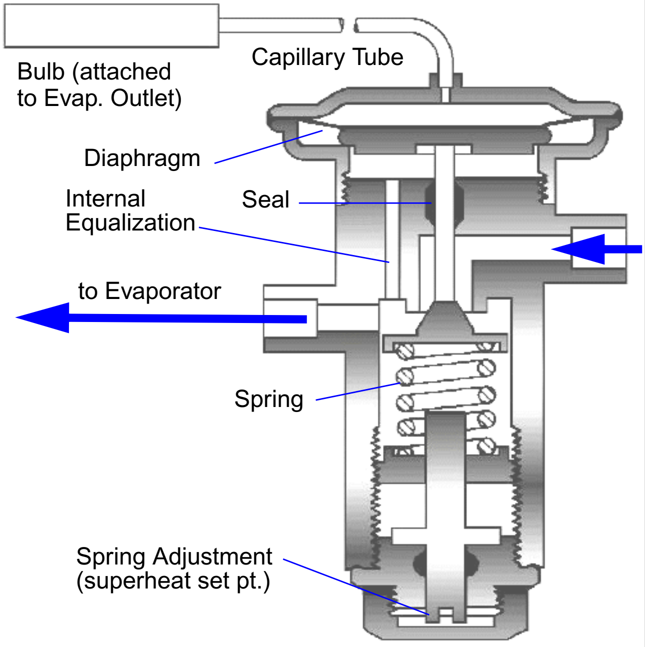

Figure G-7 Typical Thermostatic Expansion Valve (TXV) between pressure in the bulb and pressure at the evaporator inlet. A spring makes sure that the bulb pressure is higher in proportion to the desired superheat: the more spring force, the smaller the valve opening for the same pressure difference, and therefore the greater the resulting superheat.

The fluid in the bulb and the side of the diaphragm are separated from the refrigerant, and need not be the same fluid. However, they commonly are chosen to be the same substance (R134a in this sample problem), so only that case will be considered here. Still, having made that choice, two strategies remain: *gas charge* and *liquid charge*.

In a gas charge design, very little working fluid is added to the bulb such that liquid should not form anywhere. Gas charge systems have a slow response (and therefore have more danger of hunting), but they offer a maximum operating pressure limit: they will open up if the loop pressure is too high. Unfortunately, they can also lose control if condensation occurs within the valve body or capillary tube (and are therefore more likely to use an independently chosen working fluid).

In a liquid charge design, enough refrigerant is added to assure that some liquid is always present within the bulb itself, even if the valve body or capillary tube are cold and become filled with liquid. This means that the pressure in the bulb, in the capillary tube, on the control side of the diaphragm will all correspond to the saturation pressure in the bulb. Liquid charge systems offer no protection against maximum pressure, but have quick response times and little danger of loss of control in adverse environments.

G.6 Part 2 Problem Description: TXV Response

The orifice from the previous model will be replaced with a liquid charge TXV to actively control the flow rate. The purpose of the analysis is to investigate the dynamic stability of the TXV-controlled system: its ability to hold a set point after perturbations and to provide the necessary superheat. The data on the TXV is as follows:

TXV:	
Loss characteristics	table of FR vs. ΔPL (see inputs) for each pin position, *Xpin*, where *Xpin* is zero in the seated (closed) position
Pin stops	0” (closed) and 0.5” (fully open)
Throat area	π·D·*Xpin*, where D = 1/2 in.
Volume of outlet	20 cc
Spring constant	10 lbf/in
Zero force position (relative to *Xpin*)	-0.555 in (5.55 lbf when closed)
Pin/spring/diaphragm effective mass	0.2 lbm
Diaphragm diameter	0.75 in.
Pin sliding (dynamic) friction factor	1000 lbf-s/ft
Control strategy	liquid charge
Bulb effective mass	0.05 lbm (aluminum)
Bulb thermal attachment to suction line	10 BTU/hr-˚F
Suction line (between evaporator and surge tank):	
Length	1 ft
Diameter	3/8” Alum alloy pipe, Sch. A

Boundary condition in Cabin (air inlet):
Temperature. . . . . 80˚F
Relative humidity 80%

The TXV, capillary tube, bulb, suction line, and surge tank can be assumed to be insulated for simplicity: environmental heating will be neglected.

A complete system response is not necessary: the condenser and transport lines will be neglected and the compressor will be replaced with a simple constant flowrate imposed at junction 5000: the inlet to the throttling device. At a low RPM, this boundary condition becomes:

Boundary conditions, low RPM:
Temperature at TXV inlet. 125˚F
Pressure at TXV inlet. . . . . 290 psia (subcooled liq.)
Flowrate in compressor . . . . 40 lbm/hr

This data was taken from the full system model (see Part 1). In case a perturbation in flowrate is needed to test stability of the TXV, an alternate point at a higher speed is also available:

Alternate boundary conditions, higher RPM:
Temperature at TXV inlet. 160˚F
Pressure at TXV inlet. . . . . 380 psia (subcooled liq.)
Flowrate in compressor . . . . 82 lbm/hr

Based on preliminary runs, the *estimated* pin positions needed to provide about 10˚F superheat for the above two cases are *Xpin*=0.055” (low speed) and *Xpin*=0.091” (high speed).

Thus, one way to test the stability of the TXV is to ramp up from the low speed to the high speed boundary condition. However, this ramping analysis turns out not to be necessary: simply starting a transient from these approximate initial conditions provides adequate perturbations in this case, as will be discussed in the section on results.

G.7 Part 2 SINDA/FLUINT Model: TXV Response

The evaporator and “cabin” (moist air) models from Part 1 will be “reused” but the compressor and condenser models will be eliminated: a plenum will be used to represent the TXV inlet and the compressor will be replaced with an MFRSET connector pulling from the surge tank. A new element, the suction tube, will be added between the evaporator and the surge tank. This line was irrelevant in the prior model due to its low pressure drop and low fluidic mass, but it is needed as an attachment point for the TXV bulb.

Although the geometry of this model is trivial, FloCAD® will be used for demonstration purposes. Figure G-8 depicts a postprocessed FloCAD diagram of the model. The model uses two fluid submodels (“loop” and “cabin,” as in Part 1) and one thermal submodel (“AirE”, as in Part 1 plus the suction line and bulb thermal network). The evaporator and moist air are built using FloCAD *pipes,* as is the suction line. *Pipes* with nodes are turned into SINDA/FLUINT nodes, conductors, and HX macros by FloCAD. The full model is available for inspection as a Thermal Desktop drawing, therefore the following description will be brief. However, the question of “Why FloCAD and not Sinaps*Plus*®?” will be addressed.

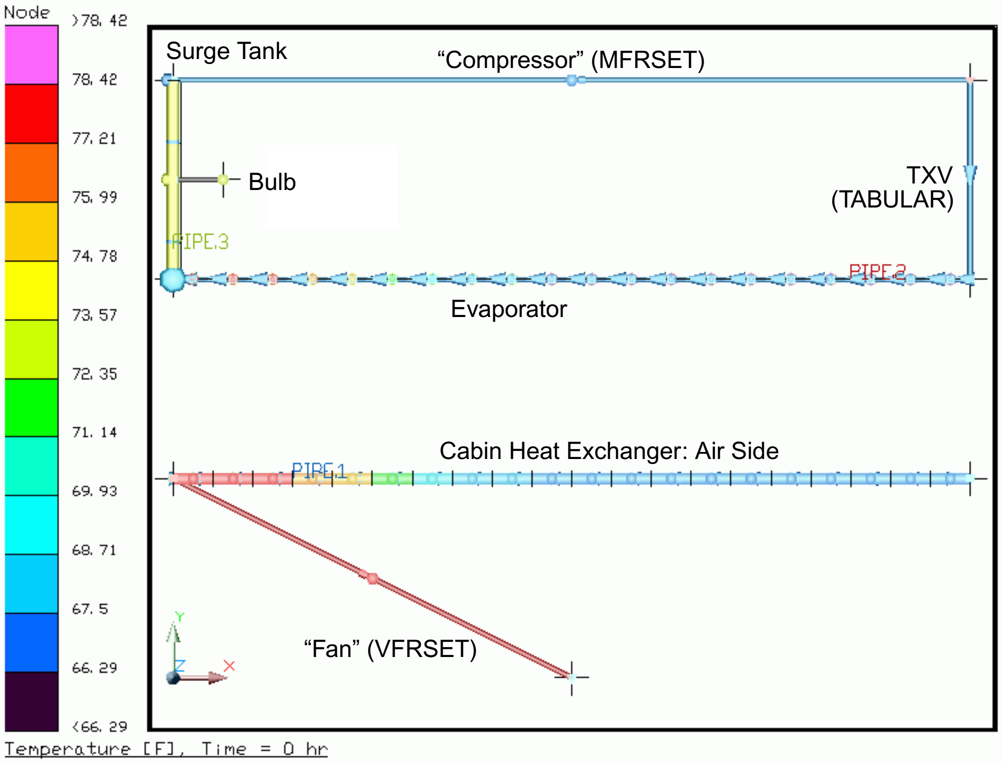

Figure G-8 Postprocessed FloCAD Depiction of the Part 2 SINDA/FLUINT Model

FloCAD is generally more useful than Sinaps*Plus* when the model geometry is detailed and specific. Sinaps*Plus*, like SINDA/FLUINT, is not “aware” of geometry and therefore cannot help building networks based on dimensions. For example, changing the resolution of the evaporator is trivially easy using FloCAD since it “knows” about lengths and can recalculate the network parameters based on the current data. On the other hand, when building free-form networks in which depicted dimensions are irrelevant (and are perhaps intentionally different from the actual dimensions), Sinaps*Plus* is preferred since it is based on arbitrarily depicted schematics. In this sample problem, either code could be used, but FloCAD would be preferable if the evaporator and air flow cross sections had been specified and needed to be modeled in detail (2D or 3D wall models instead of the current 1D model).

With respect to modeling decisions, the element choices in the evaporator must be “upgraded” from junctions and STUBE connectors used in Part 1, to tanks and tubes for Part 2. Otherwise, the flow rate and transient time lags within the evaporator would be assumed to be negligibly small, and this would give a distorted TXV response. After all, lags in the evaporator response are normally considered the major cause of TXV hunting.

The symmetry of the evaporator heat exchanger (24 parallel and identical sections) will be preserved. However, while this assumption is justified for system-level analyses, it is much more questionable for a detailed dynamic model of the evaporator, even if all air passages receive the same air flow. In evaporators, there are two superimposed causes of pressure drop: friction and acceleration. If friction is not completely dominant (e.g., long, thin evaporator lines with roughly even heating) then parallel lines can oscillate or “chug” perpetually, and can exhibit uneven flow and temperature distribution even if manifolding is perfect. While FLUINT can be used to model these events, they are assumed to be extraneous to the central problem of TXV control stability. Therefore, the duplication factors used in Part 1 will be retained in Part 2: each leg will be assumed to behave identically, representing a reasonable average response of all evaporator legs. This assumption of symmetry results in tremendous speed enhancements, but it should ideally be verified with a separate model.[*]

The suction pipe will be modeled as a single (centered) lump, since all that is needed is an attachment point for the bulb. The wall node of this pipe will be connected to a diffusion node representing the bulb. This connection uses the specified conductance of 10 BTU/hr-°F, which is presumed to represent a clamped mount.

The losses in the capillary tube and the volume of the control side of the diaphragm will be neglected (as if they were full of liquid, although this is not a necessary condition). This assumption means that the fluidic response of the bulb charge is irrelevant: all that is needed is the current saturation pressure corresponding to the bulb temperature. This pressure will then be assumed to exist on the control side of the TXV diaphragm. In other words, the bulb fluid, capillary tube, and diaphragm do not exist in the model explicitly. Rather, they exist in the user logic that calculates the forces on the TXV valve pin.[†]

These forces include not only the pressure difference across the diaphragm, but also the spring force (of the form $F_s = k*\Delta X$), the frictional force (of the form $F_f = -f*[dX/dt]$). Inertia of the pin (which includes attached masses) is also important. In other words, an “equation of motion” needs to be co-solved along with the thermohydraulic model using the ODE solvers in SINDA/FLUINT. A second order solution is needed, but single precision should be adequate: DIFFEQ2 will be invoked in FLOGIC 2 along with logic to initialize it and enforce the limits on pin motion (pin stops).

Once the pin position is known (register *Xpin*), the corresponding resistance of the TXV can be interpolated from the provided table of mass flow rate versus delta pressure. A TABULAR connector is useful for such models, with various values of *Xpin* (corresponding to the TABULAR parameter OFAC) yielding different curves of pressure drop vs. mass flow rate.

The bivariate array below, in SINDA/FLUINT input format, contains the TXV pressure drop (psid) data[‡] as a function of flow rate and valve position. The left-most column contains values of OFAC (*Xpin*, the pin position in inches). The top row contains values of flow rate (lb_m/hr).

```
               0.,      20.,      40.,      60.,      80.,     100.,      120.
      0.,      0.,    1000.,    4000.,    9000.,   16000.,   25000.,    36000.
```

---

[*] In particular, if one line discharges liquid while the other lines superheat, this liquid can affect bulb and surge tank response disproportionately. Therefore, a “perfectly identical” assumption is expedient as a first cut, but it is *not* conservative. It is also to be avoided if gravity heads are significantly different between legs.

[†] This shortcut is not possible for the modeling of a gas charge system. In such a system, the gas would need to be modeled explicitly due to temperature gradients, perhaps even in a separate fluid submodel. If it were in the same submodel, and if friction were negligible, then a SPRING iface (with nonzero EMA for the pin/diaphragm inertia) could be used instead of the co-solved differential equation approach.

[‡] Fictitious but representative, as is true of most data in the sample problems.

```
     0.02,        0.,      310.,     1260.,     2850.,      5060.,     7900.,     11400.
    0.036,        0.,      100.,      400.,      900.,      1600.,     2500.,      3600.
    0.064,        0.,       31.,      126.,      285.,       506.,      790.,      1140.
    0.112,        0.,       10.,       40.,       90.,       160.,      250.,       360.
      0.2,        0.,       3.1,      12.6,      28.5,       50.6,       79.,       114.
     0.36,        0.,        1.,        4.,        9.,        16.,       25.,        36.
     0.64,        0.,      0.31,      1.26,      2.85,       5.06,       7.9,       11.4
     1.12,        0.,       0.1,       0.4,       0.9,        1.6,       2.5,        3.6
```

G.8 Part 2 Inputs: TXV Response

[Because of the complexities of the model involved, full documentation is not provided here. The Thermal Desktop/FloCAD drawing is available as part of the install set. Temporary licenses are available to run Thermal Desktop as needed.]

The input file is listed immediately following the last section.

REGISTER DATA—Various dimensions, efficiencies, etc. are defined up-front in register data so that registers can be used as a central control panel for model changes. They are also used in various logic blocks, including those parts relevant to the equation of motion for the TXV pin. All of these registers originated as Thermal Desktop “symbols,” a subset of which are sent to the SINDA/FLUINT run as “registers.”

Important registers include:

Xpin	current pin position (inches from closed)
Xzero	point of zero spring force (in.)
Kspring	spring constant (lbf/in)
Pspring	current spring “pressure” (in -X direction, in psi)
Atxv	TXV diaphragm area (in^2)
PinM	pin mass (in slugs)
PinFrict	pin dynamic friction factor (lbf-s/ft)
CompEM	current compressor mass flow rate (lbm/hr)
Phi	current TXV inlet pressure (psia)
Thi	current TXV inlet temperature (˚F)

OPERATIONS DATA—A steady state run is made using the initial pin position as fixed, and this is used as an initial condition to initiate a transient. It turns out, no perturbation is needed, because no true time-independent state exists for this model, as will be discussed in the results section.

NODES AND CONDUCTORS—The evaporator model is largely the same as in Part 1, except that axial conductance have been included since FloCAD calculates them. New nodes (part of FloCAD pipes) are added for the suction line, which is thermally attached to AirE.1500, the diffusion node representing the TXV bulb.

FLOW DATA—Again, the evaporator model is largely the same as in Part 1, except it has been changed to tanks and tubes, and has been output by FloCAD instead of Sinaps*Plus*. A suction tube line model has been added with coarse resolution. More importantly, a TXV loss model has been added (replacing the ORIFICE) using a TABULAR connector whose OFAC corresponds to the valve pin position, *Xpin*.

FLOGIC 2 (VALVE DYNAMICS)—The first part of the valve logic consists of initialization following a steady state (when NSOL=0 or NSOL=1) using DIFFEQ2i. The valve pin's initial position is set to *Xpin*, its velocity is set to zero, and its acceleration is set to the current value (based on the current imbalance in forces since the initial value of *Xpin* is not exact). This initial acceleration and the imperfectly balanced forces associated with it turn out to be critical since they provide sufficient perturbation to evaluate control stability.

In transients (NSOL=2 or NSOL=3), the equation of motion simulation continues via a call to DIFFEQ2. The equation expected by that routine is of the form $A*d^2Xpin/dt^2 = B*dXpin/dt + C*Xpin + D$. The A term corresponds to the mass, the B term is the dynamic friction, and the C term contains the variable half of the spring force equation ($F1 = Kspring*Xpin$). The D term contains the constant half of the spring force equation ($F2 = -Kspring*Xzero$) plus the current net fluidic pressure force on the diaphragm. The saturation pressure is calculated using VPS, which expects absolute (degrees Rankine) temperature inputs and returns a double precision answer. The unit of the equation is lbf, while *Xpin* is in inches and time is in the default UID=ENG units of hours (not seconds, which is the default for UID=SI!). Therefore, various unit conversions are required, and strict attention must be paid to sign conventions for position motion (+X).

Additional logic following the DIFFEQ2 call enforces the limits in the range of motion for the pin. If those are exceeded, the pin is mathematically fixed and the differential equations are reinitialized to zero motion. Any motion *away* from those stops is tolerated in subsequent time steps.

The DEQNTAB routine is used in output calls to check the status of the ODE (including time step limits), and the current net force on the pin is printed using an extra line of user logic.

G.9 Part 2 Outputs: TXV Response

Figure G-9 shows the valve mechanical response in terms of the pin position. An initial overshoot opens the valve to about twice its normal throat area, permitting significantly more flow to enter the evaporator. Figure G-10 shows the corresponding flow rates in the evaporator, with a slight lag and damping between the inlet flow rate and the outlet.

Nonetheless, there is not enough damping within the evaporator itself: the flowrate at the outlet oscillates by about 20%. Because most of the energy into the evaporator is in the form of vaporization (vs. sensible heat), and because it is constructed using light-weight aluminum, this fluctuation results in liquid "floodback" into the surge tank. This transient flooding can be seen in Figure G-11: the occasional liquid being injected into the initially dry surge tank. Over time, the surge tank fills but does not overfill: it does its job and liquid never reaches the compressor. While there is little energy associated with superheating, most of the time the evaporator *does* produce superheated vapor, and therefore the surge tank eventually oscillates at an average quality around 20% (corresponding to a void fraction of over 90%: the surge tank actually contains very little liquid by volume). Nonetheless,

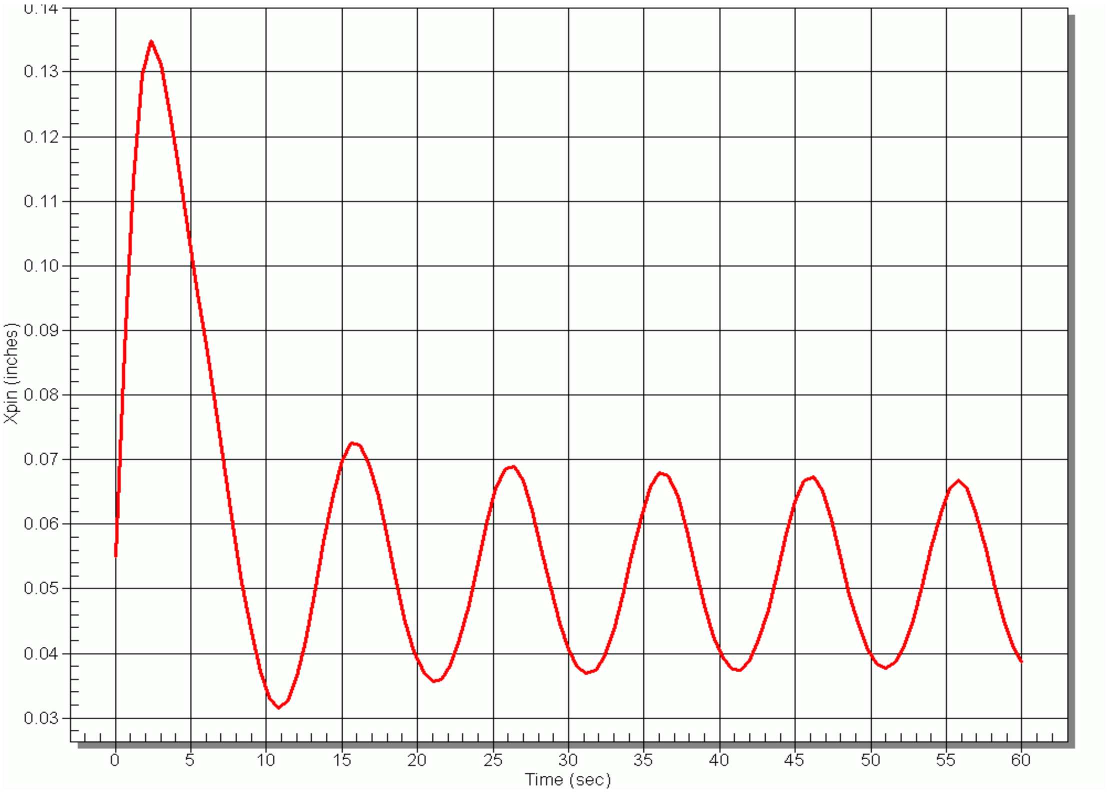

Figure G-9 TXV Response: Valve Pin Position

the system is unable to dry out the liquid produced by the initial surge, and continues in a perpetual oscillation about the set point.

This oscillation in set point is easily visible in Figure G-12. The time-averaged evaporator outlet temperature is indeed about 5˚F above saturation, but a little floodback of liquid repeats every 10 seconds or so. Therefore, the bulb is cooled about 5˚F below what a stable, superheated outlet would dictate (judging by the steady-state predictions, which do not permit such oscillations).

Based on these results alone, the TXV system looks inadequate as designed. Its set point should be raised, or other characteristics changed. For example, perhaps the TXV bulb should be placed at the outlet of the surge tank, rather than at its inlet.

However, recall that the environment on the surge tank had been neglected. That was a good assumption when the tank contained only warm (near-environment) gas, but is faulty when it contains a cold, volatile liquid. In other words, environmental heating could help break this cycle. Control stability in the face of sudden compressor shaft speed changes would still need to be demonstrated. Also, the elimination of the assumption of identical parallel legs is expected to be nonconservative and could reinstate the oscillation.

Finally, a word of caution: the details of this TXV are representative but fictitious: this model should be taken as a demonstration of analytic capabilities, but not as an indictment of any TXV design.

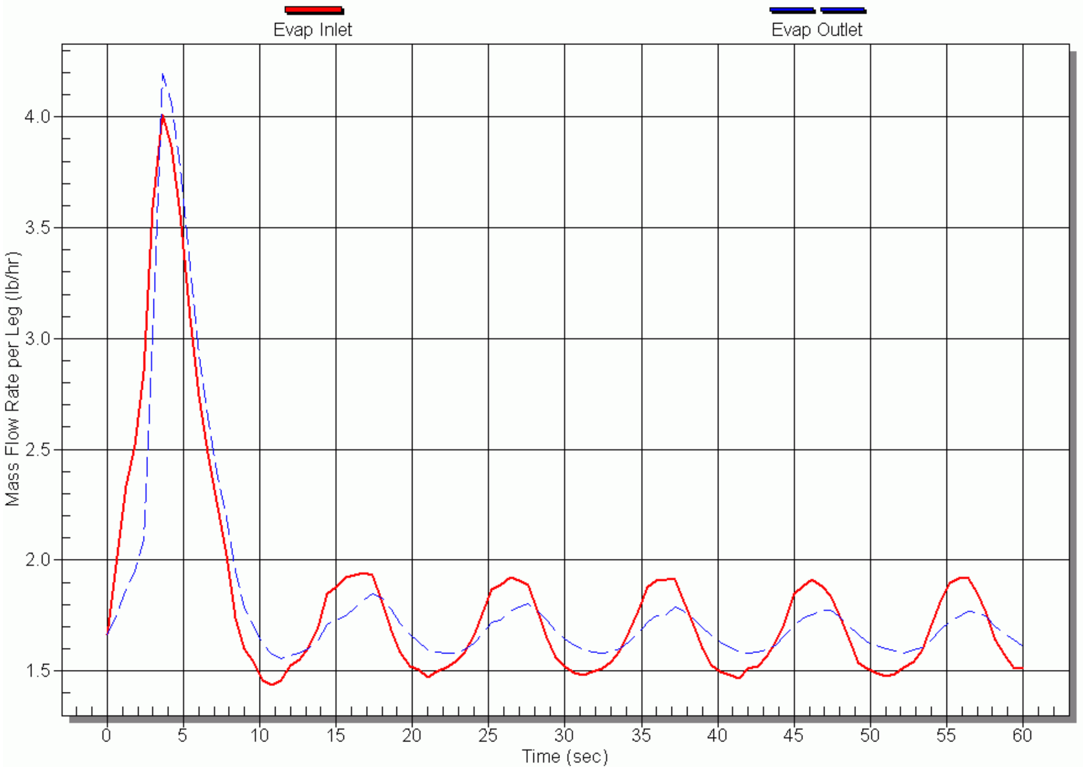

Figure G-10 TXV Response: Evaporator Flow Rates

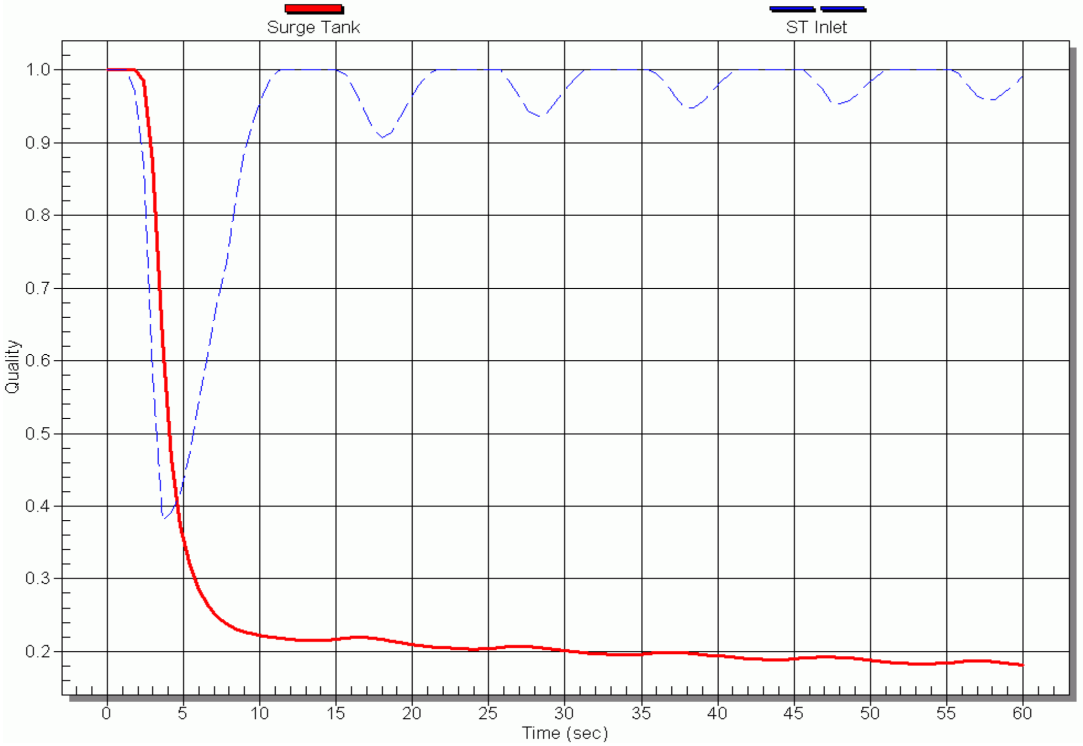

Figure G-11 TXV Response: Key Qualities

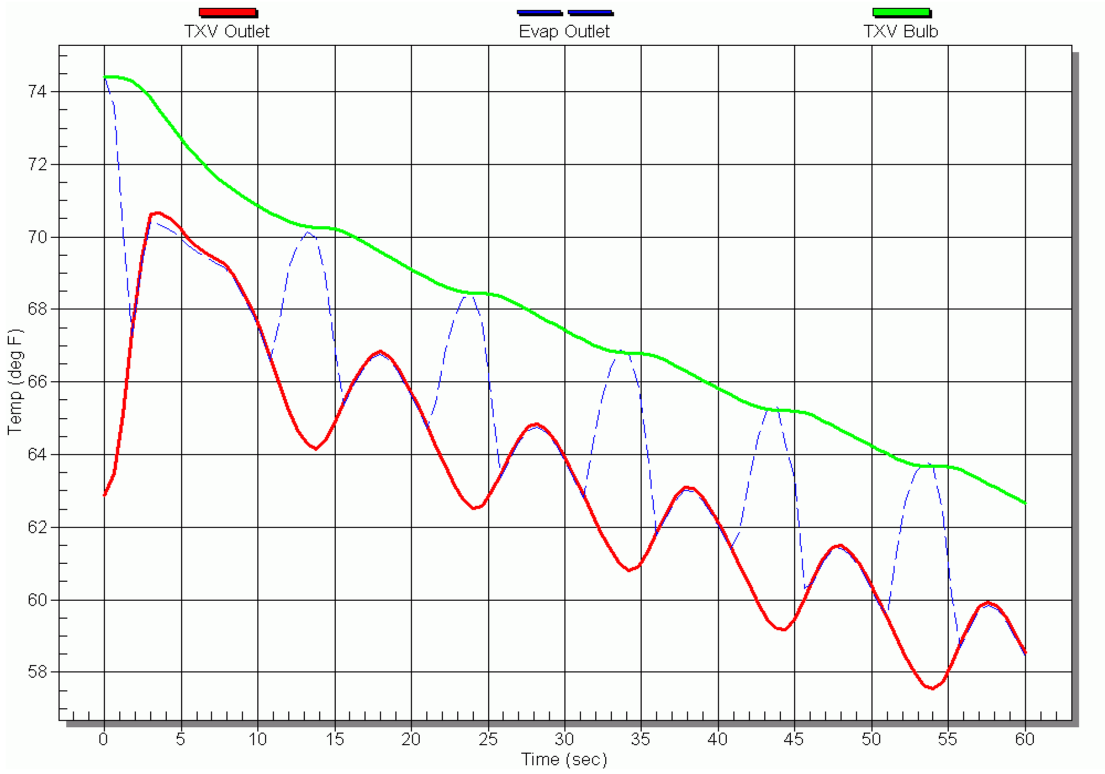

Figure G-12 TXV Response: Key Temperatures

In particular, one parameter that may not be representative is the dynamic friction factor, for which no data was immediately available. This friction factor was chosen to be high (1000 pounds per ft/s) since it represents a sliding dynamic seal: an o-ring or equivalent seal that is loaded with a pressure differential of at least 200 psid. A high value was therefore chosen for the friction factor given this dual function of both a pressure seal and a pin guide. Lower values analytically eliminated the floodback, but generated a high frequency chatter that would not likely be tolerated in a realistic design.

Two-phase Heat Transfer Notes: Perusal of the output file shows mark-ups in the ‘2P” column of the TIETAB outputs. In the air side of the evaporator an occasional “S” indicates superheated condensation: superheated water vapor but subsaturated wall. The “T” in the evaporator means transition boiling: the fluxes are high enough in that element to exceed the critical heat flux (CHF). Hysteresis in the local wall heat transfer causes some locations to “stick” in a transition boiling regime. The prediction of both the CHF and the post-CHF regimes (film and transition boiling) have large uncertainties as noted in the main volume. Sensitivity studies using the CHFF tie factors are recommended.

Input File - System Model

CAUTION: This is the input file generated by C&R Sinaps*Plus*®. It is for reference only, since it contains methods inaccessible to the ASCII text user (such as pre-expanded LINE and HX macros). Sections have been deleted as noted. The Sinaps*Plus* binary archive file “sampleG46.bin” is available as part of the install set, and should be used instead.

```
C  This file was produced by SinapsPlus
C  If you would like more information on SinapsPlus or Sinda/Fluint please contact:
C  C&R Technologies
C  9 Red Fox Ln
C  Littleton, CO 80127-5710, USA
C  (303) 971-0292 (voice)
C  (303) 971-0035 (fax)
C  info@crtech.com
C
HEADER OPTIONS DATA
TITLE      Vapor Compression Cycle Prebuilt
           MODEL      = ROOT
           RSO        = vcAir.rso
           SAVE       = vcAir.sav
           REDB       = vcAir.savdb
           OUTPUT     = vcAir.out
           USER1      = vcAir.usr
           USER2      = vcAirNC.usr
           PPOUT      = NOLIST
           DOUBLEPRECISION
HEADER OPERATIONS
buildf con,loop,cabin
build con,aire,airc
defmod loop
c
c set cabin relative humidity. make sure PL, TL are OK
c
           call chglmp(’cabin’,1000,’xl’,1.0,’xl’)
           call chglmp(’cabin’,1000,’tl’,TairE,’xl’)
           call chglmp(’cabin’,1000,’pl’,14.7,’xl’)
           call humr2x(‘cabin’,1000,RelHum,xtest)
           call chglmp(‘cabin’,1000,’xgw’,xtest,’pl’)
c
c set compressor outlet to be a heater lump
c (HL given, QDOT calculated)
c
           call htrlmp(‘loop’,2000)$ hold enthalpy of #2000
c
c for steady states, hold #9000 as a reference pressure
c
           call hldlmp(‘loop’,9000)$ hold everything of #9000
c sizing mode
           if(isolve .eq. 1)then
                      nloopo =100
                      nervus = 2                        $ ignore any points that don’t con-
verge
                      call dscanlh
                      nloopo=200
                      nervus = 3                        $ don’t abort if doesn’t converge
                      call solver
                      call lmptab(‘all’)
                      call pthtab(‘all’)
                      call tietab(‘all’)
                      call regtab
                      return
```

```
           elseif(isolve .eq. 2)then
c
c various parametric sweeps, including testing all upper lower limits (DSCANFF
c could have similarly been used
C
                      call psweep(‘rpm’,1000.,4000.,3,’proc’)
                      rpm = 3000.
c                     call psweep(‘ohole’,0.01/12.,0.022/12.,13,’proc’)
                      call psweep(‘ohole’,0.98*0.018/12.,1.03*0.018/12.,2,’proc’)
                      oHole = 0.018/12.
c                     call psweep(‘phi’,200.,425.,19,’proc’)
                      call psweep(‘phi’,200.,400.,3,’proc’)
                      phi = 350.
                      call psweep(‘TairC’,80.,110.,2,’proc’)
                      TairC = 100.
                      call psweep(‘TairE’,65.,80.,2,’proc’)
                      TairE = 80.
c add humr2x/chglmp to PROC for this to work:
c                     call psweep(’RelHum’,0.0,1.0,2,’proc’)
c                     RelHum = 0.8
                      return
           elseif(isolve .eq. 3)then
                write(nuser1,93)
93      format(’  Charge (lb)’,T16,’Pct Chg Err’,T31,’RPM’,T39,’Ohole (in)’,
     .  T52,’Tair Cond’,T64,’Tair Evap’,T76,’Rel Hum’,T88,’SupHeat’,T99,’Loopct’/)
c
c main solution for the sample problem: find the chances that the superheat
c limit won’t be achieved.
c
                      call rantab
                      nloopr = 100
                      call dsample
                      call rcsttab
                      return
           endif
c
c Do a parametric versus Phi (compressor outlet pressure).
c Calculate ChargeC (current charge) at each point, and
c store the results in array 100. This will then be used
c to find Phi given ChargeD (desired charge) in order to
c start a transient run later (currently commented out)
c
c see also alternate method using solver inside relprocedure
c and binary search method too.
c
           ktest      = 1
           do 10 mtest = 200, 500, 50
                      Phi         = float(mtest)
                      if(ktest .gt. 14) goto 10
                      call proc                          $ reuse Solver procedure
                      call resave(‘all’)     $ save to VCair.rso
c
                      a(100 + ktest) = ChargeC$ Store ChargeC(Phi)
                      a(100 + ktest + 1) = Phi
                      ktest      = ktest + 2
10         continue

c
           ChargeD = max(A(100+1),min(A(100+20-1),ChargeD))
           Call d1deg1(ChargeD,a100,Phi)$ find Phi(ChargeD)
           call chglmp(‘loop’,9000,’PL’,Phi,’XL’)
           call steady                                   $ get initial conditions
c if no transient output here
                      call lmptab(‘all’)
                      call pthtab(‘all’)
```

```
                      call tietab(‘all’)
           call lmxtab(‘all’)                $ print volumes, masses
           call chglmp(‘loop’,1000,’xl’,1.0,’pl’)
           call sumdflo(‘loop’,2000,’mass’,ChargeC)
                      call regtab
c
c if transient .... (commented here)
c
c          call rellmp(‘loop’,9000)$ return #9000 to a junction (dead end)
c          timend = 1.0
c          call transient                    $ run a transient
HEADER CONTROL DATA,GLOBAL
           TIMEO      = 0.0
           TIMEND     = 0.0
           NLOOPS     = 100
           ABSZRO     = -459.67
           PATMOS     = 0.0
           SIGMA      = 1.0
           UID        = ENG
<snip>
           EXTLIM  = 5*0
<snip>
           OUTPUT     = 0.01*timend
           OUTPTF     = 0.01*timend
<snip>
           RERRF      = 0.003
           REBALF     = -0.01
<snip>
HEADER REGISTER DATA
       AIRAF = AIRMAF*0.25*PI*AIRDIA^2 $ Air side evaporator Flow Area
       AIRDIA = 0.25/12. $ Air side evaporator Hydraulic Diameter
       AIRFINE = 0.8 $ Air side fin efficiency
       AIRMAF = 8 $ Air side evaporator Flow Area multiplier
       CFMAIR = 300 $ Evaporator air volumetric flow rate
       CHARGEC = 0.2 $ Current Charge (lb)
       CHARGED = 0.2 $ Desired Charge (lb)
       CI0 = 1.623371 $ Coefficients in Isentropic Efficiency Curve Fit
       CI1 = -0.93049
       CI2 = -0.67806
       CI3 = 0.333806
       CI4 = 0.400297
       CI5 = 0.052482
       COMPDISP = 20.0e-6*MTOFT^3  *1 $ Compressor Displacement
       COMPEM = EVOL*(COMPDISP*RPM*60)*LOOP.DG1000 $ Compressor mass flow rate
       CONDAF = CONDMAF*0.25*PI*CONDDIA^2 $ Condenser Flow Area (per passage)
       CONDCP = 0.21 $ Condenser Cp, Assume alum
       CONDDIA = 0.06/12.0 $ condenser hydraulic diameter
       CONDLEN = 4.0 $ condenser length
       CONDMAF = 2 $ Condenser AF/circular multiplier
       CONDMASS = 5.0 $ Condenser thermal mass
       CONDNUM = 30 $ No. of parallel Condenser passages
       CONDRES = 20 $ Condenser resolution (no. of lumps)
    COP = LOOP.FR1000*(LOOP.HL1000-LOOP.HL6000)/MAX(1.0,LOOP.QDOT2000) $ Coef of performance
       CV0 = -0.08469 $ Coefficients in Volumetric Efficiency Curve Fit
       CV1 = -0.31711
       CV2 = 0.085057
       CV3 = 0.153835
       CV4 = 0.014169
     EISEN = 1.0 - MAX(0,MIN(0.99,(CI0/(PRAT*RPMF) + CI1/PRAT + CI2/RPMF + CI3*RPMF/PRAT +
CI4 + CI5*PRAT/RPMF))) $ Isentropic efficiency of compressor
       EVAPAF = EVAPMAF*0.25*PI*EVAPDIA^2 $ Evaporator Flow Area (per passage)
       EVAPCP = 0.21 $ Evaporator Cp, Assume alum
       EVAPDIA = 0.06/12.0 $ Evaporator Hydraulic Diameter
       EVAPLEN = 2.0 $ evaporator length
       EVAPMAF = 2 $ Evaporator AF/circular multiplier
```

```
       EVAPMASS = 5.0 $ Evaporator thermal mass
       EVAPNUM = 24 $ No. of parallel Evap passages
       EVAPRES = 20 $ Evaporator resolution
       EVOL = 1.0 -MAX(0,MIN(0.99, (CV0/RPMF + CV1 + CV2*PRAT/RPMF + CV3*RPMF + CV4*PRAT)))
$ Volumetric efficiency of compressor
       INT:ISOLVE = 3 $ 0 = PHI sweep then Steady, 1= optimize (size), 2 = psweep, 3 = reliability
       INT:NCLEVELS = 6 $ number of levels of binary search: accuracy 300/2**NClevels
       OHOLE = 0.018/12. $ orifice hole diameter (fixed)
       PHI = 350 $ initial guess, hi pressure
       PLO = 35 $ initial guess, low pressure
       PRAT = (LOOP.PL9000-PATMOS)/(LOOP.PL1000-PATMOS) $ compressor pressure ratio
       RELHUM = 0.8 $ Evaporator inlet (cabin) relative humidty
       RPM = 2000 $ Compressor speed
       RPMF = MAX(RPM,1)/1000 $ reduced RPM for curve fits
       STVOL = 300.E-6 *MTOFT^3 $ Suction trap (surge drum) volume.
       TAIRC = 100 $ Condenser air sink temperature
       TAIRE = 80 $ Evaporator air source temperature
       TRANLDIA = 0.10/12.0 $ Transport dia, liq
       TRANLEN = 10.0 $ Transport length
       TRANLRES = 2 $ Transport resolution, liquid side
       TRANRES = 1 $ Transport resolution, vapor side
       TRANVDIA = 0.15/12.0 $ Transport dia, vap
       UAAIRC = 90 $ Overall coeff to TairC
HEADER USER DATA,GLOBAL
 pmax=0.
 pmin=0.
insert air8c.inc
INSERT f6049_r134a.inc
HEADER SOLVER DATA
           NLOOPO = (isolve==1)? 200 : 15
           OBJECT = (isolve==1)? cop : chargeC
           GOAL = (isolve==1)? 1.0e30 : ChargeD
           METHO = (isolve==1)? 1 : 1
           RERRO = (isolve==1)? 0.01 : 0.1
           AERRO = (isolve==1)? 0.0001 : 0.1
           RDERO = 0.04
           ADERO = 0.0001
           MDERO = 0
           RCHGO = 0.9
           ACHGO = 0.1
           RCACTO = 0.03
           RCERRO = 0.003
           RCVIO = 0.2
           PUSHO = 1.0
           NERVUS = 3
           NEWPRO = 0
           NCONVO = 2
           NLOOPR = 100
           RERRR = 0.0001
           AERRR = 0.00001
           ADERR = 0.01
HEADER PROCEDURE
defmod loop
           call chglmp(’cabin’,1000,’xl’,1.0,’xl’)
           call chglmp(’cabin’,1000,’tl’,TairE,’xl’)
           call chglmp(’cabin’,1000,’pl’,14.7,’xl’)
           call humr2x(’cabin’,1000,RelHum,xtest)
           call chglmp(’cabin’,1000,’xgw’,xtest,’pl’)
c
           call chglmp(‘loop’,9000,’PL’,Phi,’XL’)       $ reset pressure
           call steady
           call chglmp(‘loop’,1000,’xl’,1.0,’pl’)       $ ignore surge tank liquid
           call sumdflo(‘loop’,2000,’mass’,ChargeC)     $ find current mass
           if(isolve .eq. 1)call regtab
HEADER SOLOUTPUT
```

```
           if(isolve .eq. 1)then
                      call destab
                      call csttab
           endif
HEADER DESIGN DATA
           200 <= phi <= 500
HEADER RELPROCEDURE
c
c reset cabin relative humidity if RelHum or TairE changes
c
           call chglmp('cabin',1000,'xl',1.0,'xl')
           call chglmp('cabin',1000,'tl',TairE,'xl')
           call chglmp('cabin',1000,'pl',14.7,'xl')
           call humr2x(‘cabin',1000,RelHum,xtest)
           call chglmp(‘cabin',1000,'xgw',xtest,'pl')
c
c find the value of Phi that gets the right charge (ChargeC=ChargeD)
c using Solver:
c
c          phi = 350.
c          call solver
c          call destab
c
c find the value of Phi that gets the right charge (ChargeC=ChargeD)
c using Binary search:
c
           pmax = 500.
           pmin = 200.
           phi = 0.5*(pmax+pmin)
           do 10 itest=1,NClevels
                call proc
                if(chargeC .gt. ChargeD)then
                        pmax    = phi
                else
                        pmin    = phi
                endif
                phi = 0.5*(pmax+pmin)
10         continue
c
           call chglmp(‘loop',9000,'PL',Phi,'XL')
           call steady
           call sumdflo(‘loop',2000,'mass',ChargeC)
c
c set named relconstraints:
c
           sheat10 = loop.tl1000-loop.tl6000
           sheat20 = sheat10
HEADER RELOUTPUT CALLS
           call savedb(‘all',mtest)$ write to redb file
c summary file:
        write(nuser1,99) ChargeD, 100.*abs(ChargeC/ChargeD-1.0),
     .   RPM, Ohole*12., TairC, TairE, 100.*RelHum, sheat10, loopct
99      format(F10.5,2X,F10.2,2X,F10.1,2X,F10.5,4(2X,F10.2),4X,I5)
HEADER RANDOM DATA
           RPM,ARRAY,loop.a1001
           Ohole,NORMAL,mean=0.018/12., cv=0.03
           ChargeD,NORMAL,mean=0.2, cv = 0.1
           TairC,ARRAY,loop.a1002
           TairE,ARRAY,loop.a1003
           RelHum,UNIFORM,0.0,1.0
HEADER RELCONSTRAINT DATA
           chargec*1 $ check charge: same as input?
           32 <= AirE.T1 $  no freeze on evap wall
           cop*1 $ how does COP fare?
           10 <= sheat10 $ crux: superheat
```

```
           20 <= sheat20 $ same thing, diff level (20 vs 10)
HEADER NODE DATA,AIRC
           1,TairC,CondMass*CondCp/CondRes
           2,TairC,CondMass*CondCp/CondRes
           3,TairC,CondMass*CondCp/CondRes
<snip>
           18,TairC,CondMass*CondCp/CondRes
           19,TairC,CondMass*CondCp/CondRes
           20,TairC,CondMass*CondCp/CondRes
           -1000,TairC,0.0
HEADER CONDUCTOR DATA,AIRC
           1,1,1000,UAairC/CondRes
           2,2,1000,UAairC/CondRes
<snip>
           19,1000,19,UAairC/CondRes
           20,1000,20,UAairC/CondRes
HEADER NODE DATA,AIRE
           1,TairE,EvapMass*EvapCp/EvapRes/EvapNum
           2,TairE,EvapMass*EvapCp/EvapRes/EvapNum
           3,TairE,EvapMass*EvapCp/EvapRes/EvapNum
<snip>
           19,TairE,EvapMass*EvapCp/EvapRes/EvapNum
           20,TairE,EvapMass*EvapCp/EvapRes/EvapNum
HEADER CONDUCTOR DATA,AIRE
           1,1,2,1.0e-10
<snip>
           19,19,20,1.0e-10
           111,10,11,1.0e-10
HEADER ARRAY DATA,LOOP
c workspace for parametric sweep: chargeC vs PHI
 100       = space,14

c transient compressor and environmental profiles
 200       = 0.,      1000.
             0.6, 3000.
             1.0,     1000.
 300       = 0.,  80.0
             0.4, 120.0
             1.0, 80.0
c prob dist functions
 1001 =    800.0, 0.0 $ RPM
                      1000.0, 0.3
                      2000.0, 0.1
                      3000.0, 0.6
                      4000.0, 0.0
 1002 =    80.0, 0.0  $ Tair Cond
                      90.0, 1.0
                      110.0, 0.0
 1003 =    65.0, 0.0  $ Tair Evap
                      70.0, 1.0
                      80.0, 0.0
HEADER FLOGIC0,LOOP
c
c          look up current compressor speed, evap temperature
c
           if(nsol .gt. 1)then
                      call d1deg1(timen,a200,rpm)
                      call d1deg1(timen,a300,TairE)
           elseif(xl1000 .lt. 1.0)then
                      call chglmp(‘loop’,1000,’xl’,1.0,’pl’)
           endif
c
c calculate T (and therefore H) of compressor outlet.
c
           if(fr1000*CompEm*rpm .le. 0.0 .or. pl2000 .le. pl1000
```

```
     .      .or. xl1000 .le. 0.0)then
                      ttest      = tl1000
           else
                      stest      = vs(tl1000-abszro,1.0/dg1000,loop.fi)
                      call vtav1(ttest,vtest,pl2000-patmos,stest,loop.fi)
                      htest      = vh(pl2000-patmos,ttest,vtest,loop.fi)
                      if(Eisen .le. 0.0)then
                                 htest      = hl1000
                      else
                                 htest      = hl1000 + (htest-hl1000)/Eisen
                      endif
                      call vtav2(ttest,vtest,pl2000-patmos,htest,loop.fi)
                      ttest      = min(0.999*vtgmax(loop.fi),ttest) + abszro
           endif
           call chglmp(‘loop’,2000,’tl’,ttest,’pl’)

HEADER FLOGIC1,LOOP
f          double precision newpl,savedpl
C
C Compressor logic
c set new flowrate, calculate derivative by finite
c difference perturbation of upstream pressure
c
           if(nsol .le. 1 .and. xl1000 .lt. 1.0)
     .          call chglmp(‘loop’,1000,’XL’,1.0,’PL’)
c
SPELLoff
           hk1000 = CompEM - fr1000          $ offset term
           atest      = CompEM
c
c temporary change to Prat to get slope (GK), suction density, then changes to
c PL will reset it automatically later
c
           savedpl= PL1000
           newpl      = 0.99D0*savedpl
           call chglmp(‘loop’,1000,’PL’,sngl(newpl),’XL’)
           call upreg            $ update CompEM, eVol, etc. with perturbed pressure
c
c calculate slope (derivative) for more implicit (stable) solution
c
           gk1000 = (atest-CompEM)/(0.01*sngl(pl1000-patmos))
           gk1000 = max(1.0e-10,gk1000)
c
c reset pressure to current. Just to be sure: reset to saved DP value too.
c hide from SINDA preprocessor since setting PL is not normally permitted
c
           call chglmp(‘loop’,1000,’PL’,sngl(savedpl),’XL’)
           global.PL(intlmp(‘loop’,1000))= savedpl
SPELLon
HEADER OUTPUT CALLS,LOOP
           if(nsol .gt. 1 .or. (isolve .eq. 2 .and. loopct .ne. 0))then
                      call lmptab(‘all’)
                      call pthtab(‘all’)
                      call tietab(‘all’)
                      call save(‘all’,0)     $ transient profiles
           elseif(loopct .eq. nloops)then
                      write(nuser2,99)Phi,RPM,TairC,TairE,relhum,ohole,xl1000
99                    format(1p,’Phi=’,g12.5,’       RPM=’,g12.5,’       TairC=’,g12.5,’
TairE=’,g12.5,’  RelHum=’,g12.5,’  Ohole=’,g12.5,’ XL1000=’,g12.5)
                      call regtab
                      call lmptab(‘all’)
                      call pthtab(‘all’)
                      call tietab(‘all’)
                      call resave(‘all’)     $ debugging: didn’t converge
C                                often useful to save last 5-10 points: loopct>nloops-10
```

```
           endif
HEADER FLOW DATA,LOOP, FID = 6049
LU TANK,1000
           , TL=TairE
           , XL=1.0
           , PL! =Plo
           , LSTAT=STAG
           , VDOT=0.0
           , COMP=0.0
           , QL=0.0
           , VOL=CompDisp + STvol + 0.5*EvapAF*EvapLen*EvapNum
LU JUNC,2000
           , TL=TairC+100
           , XL=1.0
           , PL! =Phi
           , LSTAT=NORM
           , QL=0.0
LU JUNC,3000
           , TL=TairC+100
           , XL=1.0
           , PL=Phi
           , LSTAT=NORM
           , QL=0.0
LU JUNC,4000
           , TL=TairC
           , XL=0.0
           , PL! =Phi
           , LSTAT=NORM
           , QL=0.0
LU JUNC,5000
           , TL=TairC
           , XL=0.0
           , PL! =Phi
           , LSTAT=NORM
           , QL=0.0
LU TANK,6000
           , TL=TairC
           , XL=1.0
           , PL! =Plo
           , LSTAT=NORM
           , VDOT=0.0
           , COMP=0.0
           , QL=0.0
           , VOL=0.5*EvapAF*EvapLen*EvapNum
LU JUNC,9000
           , TL=TairC+100
           , XL=1.0
           , PL! =phi
           , LSTAT=NORM
           , QL=0.0
PA CONN,1000,1000,2000
           , FR=compEm
           , STAT=VS
           , DUPI=1.0
           , DUPJ=1.0
           , EI=0.0
           , EJ=0.0
           , DK=0.0
           , GK=1.0
           , HK=0.0
            DEV=NULL
PA CONN,5000,5000,6000
           , FR=CompEm
           , STAT=NORM
           , DUPI=1.0
```

```
           , DUPJ=1.0
<snip>
           DEV=ORIFICE , AF=0.25*pi*TranLDia^2
           , AORI=0.25*pi*Ohole^2
                      , MODO=     -1
PA CONN,9000,2000,9000
           , FR=CompEm
           , STAT=NORM
           , DUPI=1.0
           , DUPJ=1.0
<snip>
           DEV=STUBE  , TLEN=1.0
           , DH=Ohole
<snip>
LU TANK,2001
           , TL=0.0
           , XL=1.0
           , PL=Phi
           , LSTAT=NORM
           , VDOT=0.0
           , COMP=0.0
           , QL=0.0
           , VOL=((pi*0.25*(TranVdia)^2)) * (Tranlen)  / TranRes
            MACRO =2000,6,1
PA CONN,2000,2000,2001
           , FR=CompEm
           , STAT=NORM
<snip>
            MACRO =2000,6,1
           DEV=STUBE  , TLEN=((Tranlen / TranRes) / 2.0)
           , DH=TranVdia
           , WRF=0.0
           , UPF=1.0
<snip>
PA CONN,2001,2001,3000
           , FR=CompEm
           , STAT=NORM
<snip>
            MACRO =2000,6,2
           DEV=STUBE  , TLEN=((Tranlen / TranRes) / 2.0)
           , DH=TranVdia
           , UPF=1.0
<snip>
LU TANK,3001
           , TL=TairC
           , XL=0.0
           , PL! =PHI
           , LSTAT=NORM
           , VDOT=0.0
           , COMP=0.0
           , QL=0.0
           , VOL=(COndAF) * (CondLen)  / CondRes
            MACRO =3000,9,1
<snip>
LU TANK,3020
           , TL=TairC
           , XL=0.0
           , PL! =PHI
           , LSTAT=NORM
           , VDOT=0.0
           , COMP=0.0
           , QL=0.0
           , VOL=(COndAF) * (CondLen)  / CondRes
            MACRO =3000,9,20
PA CONN,3000,3000,3001
```

```
           , FR=CompEm/Condnum
           , STAT=NORM
           , DUPI=CondNum
           , DUPJ=1.0
<snip>
            MACRO =3000,9,1
           DEV=STUBE  , TLEN=((CondLen / CondRes) / 2.0)
           , DH=CondDia
           , AF=COndAF
           , WRF=0.0
<snip>
PA CONN,3001,3001,3002
           , FR=CompEm/Condnum
           , STAT=NORM
<snip>
            MACRO =3000,9,2
           DEV=STUBE  , TLEN=(CondLen / CondRes)
           , DH=CondDia
           , AF=COndAF
           , WRF=0.0
<snip>
PA CONN,3020,3020,4000
           , FR=CompEm/Condnum
           , STAT=NORM
           , DUPI=1.0
<snip>
            MACRO =3000,9,21
           DEV=STUBE  , TLEN=((CondLen / CondRes) / 2.0)
           , DH=CondDia
           , AF=COndAF
           , WRF=0.0
<snip>
T HTNC,3001,3001,AIRC.1,3000,1.0,3001,0.5, DUPN=30.0, DUPL=1.0
            MACRO =3000,9,1
<snip>
T HTNC,3020,3020,AIRC.20,3019,0.5,3020,1.0, DUPN=30.0, DUPL=1.0
            MACRO =3000,9,20
LU TANK,4001
           , TL=0.0
           , XL=0.0
           , PL=Phi
           , LSTAT=NORM
           , VOL=((pi*0.25*(TranLdia)^2)) * (TranLen)  / TranLRes
            MACRO =4000,6,1
LU TANK,4002
           , TL=0.0
           , XL=0.0
           , PL=Phi
           , LSTAT=NORM
           , VOL=((pi*0.25*(TranLdia)^2)) * (TranLen)  / TranLRes
            MACRO =4000,6,2
PA TUBE,4000,4000,4001
           , FR=CompEm
           , TLEN=((TranLen / TranLRes) / 2.0)
           , DH=TranLdia
           , WRF=0.0
<snip>
            MACRO =4000,6,1
<snip>
PA TUBE,4002,4002,5000
           , FR=CompEm
           , TLEN=((TranLen / TranLRes) / 2.0)
           , DH=TranLdia
<snip
            MACRO =4000,6,3
```

```
LU JUNC,6001
           , TL=TairE
           , XL=0.0
           , PL! =PLO
           , LSTAT=NORM
           , QL=0.0
           , VOL=EvapAF*EvapLen/EvapRes
            MACRO =6000,9,1
<snip>
LU JUNC,6020
           , TL=TairE
           , XL=0.0
           , PL! =PLO
           , LSTAT=NORM
           , QL=0.0
           , VOL=EvapAF*EvapLen/EvapRes
            MACRO =6000,9,20
PA CONN,6000,6000,6001
           , FR=CompEm/EvapNum
           , STAT=NORM
           , DUPI=EvapNum
           , DUPJ=1.0
<snip>
            MACRO =6000,9,1
           DEV=STUBE  , TLEN=((EvapLen / EvapRes) / 2.0)
           , DH=EvapDia
           , AF=EvapAF
<snip>
PA CONN,6020,6020,1000
           , FR=CompEm/EvapNum
           , STAT=NORM
           , DUPI=1.0
           , DUPJ=EvapNum
<snip>
            MACRO =6000,9,21
           DEV=STUBE  , TLEN=((EvapLen / EvapRes) / 2.0)
           , DH=EvapDia
           , AF=EvapAF
<snip>
T HTNC,6001,6001,AIRE.1,6000,1.0,6001,0.5, DUPN=1.0, DUPL=1.0
            MACRO =6000,9,1
<snip>
T HTNC,6020,6020,AIRE.20,6019,0.5,6020,1.0, DUPN=1.0, DUPL=1.0

            MACRO =6000,9,20
HEADER FLOW DATA,CABIN
           , FIDA = 8729
           , FIDW = 718
LU PLEN,1000
           , TL=TairE
           , XL=1.0
           , PL! =14.7
           , LSTAT=STAG
           , XGA = 0.9999
           , XGW = 0.0001
LU JUNC,1001
           , TL=TairE
           , XL=1.0
           , PL=14.7
           , LSTAT=NORM
           , XGA = 1.0
           , XGW = 0.0
           , QL=0.0
PA CONN,1000,1000,1001
           , FR=0.0
```

```
           , STAT=NORM
           , DUPI=1.0
           , DUPJ=1.0
<snip>
           DEV=VFRSET , SVFR=CFMair*60.0
LU JUNC,1
           , TL=TairE
           , XL=1.0
           , PL=14.7
           , LSTAT=NORM
           , QL=0.0
            MACRO =1,9,1
<snip>
LU JUNC,20
           , TL=TairE
           , XL=1.0
           , PL=14.7
           , LSTAT=NORM
           , QL=0.0
            MACRO =1,9,20
PA CONN,1,1001,1
           , FR=0.001
           , STAT=NORM
           , DUPI=EvapNum
           , DUPJ=1.0
<snip>
            MACRO =1,9,1
           DEV=STUBE  , TLEN=((EvapLen / EvapRes) / 2.0)
           , DH=AirDia
           , AF=AirAF
<snip>
PA CONN,21,20,1000
           , FR=0.001
           , STAT=NORM
           , DUPI=1.0
           , DUPJ=EvapNum
<snip>
            MACRO =1,9,21
           DEV=STUBE  , TLEN=((EvapLen / EvapRes) / 2.0)
           , DH=AirDia
           , AF=AirAF
           , WRF=0.0
<snip>
T HTNC,1,1,AIRE.20,1,1.0,2,0.5, DUPN=1.0, DUPL=1.0
           , UAM=AirFinE
            MACRO =1,9,1
<snip>
T HTNC,20,20,AIRE.1,20,0.5,21,1.0, DUPN=1.0, DUPL=1.0
            MACRO =1,9,20
           , UAM=AirFinE
END OF DATA
```

Input File - TXV Hunting Model

```
C ======================================================================
C BEGIN INPUT FILE FOR SECOND HALF: TXV RESPONSE. Written by Thermal Desktop/FloCAD
```

CAUTION: This is the input file generated by C&R Thermal Desktop®. It is for reference only, since it contains methods inaccessible to the ASCII text user (such as pre-expanded LINE and HX macros). Sections have been deleted as noted. The binary drawing file “TXVhunting.dwg” is available as part of the install set and should be used instead.

```
HEADER OPTIONS
    OUTPUT = Strans1.out
    SAVE = Strans1.sav
    USER1 = Strans1.us1
    USER2 = Strans1.us2
    DOUBLEPRECISION
    MLINE = 100000 $ Limits headers output
    MIXARRAY
HEADER OPERATION DATA
BUILD ALL
BUILDF ALL
      CALL DPCS
defmod loop
           call prpmap(400.0d0,400.0,loop.fi)
c          call psweep(‘xpin’,0.27,0.28,11,’steady’)
           call steady
           timend = 60.0/3600.0
           outptf = 0.05/3600.0
           call transient
HEADER OUTPUT CALLS, AIRE
      CALL HNQCAL(‘ALL’)
      IF(NSOL .GT. 1 .OR. LOOPCT .GT. 0 ) CALL SAVE(‘ALL’,0)
HEADER CONTROL DATA, GLOBAL
    abszro = -459.67
    sigma  = 1.712182e-009
    arlxca = 0.001
    drlxca = 0.001
    extlim = 5.
    matmet = 2
    iterxt = 3
    ebalsa = 0.001
    UID =    ENG
<snip>
HEADER FLOGIC2, LOOP
           ptest = vps(aire.t1500-abszro,loop.fi)
           if(nsol .le. 1)then
                      call regtab
                      write(nuser1,*)’ Pin position: ‘,Xpin
                      write(nuser1,*)’ Bulb Sat: ‘,ptest
                      write(nuser1,*)’ Delta Press: ‘,ptest-sngl(pl6000)
                      write(nuser1,*)’ Superheat: ‘,aire.t1500-tl6000
                      write(nuser1,*)’  ‘
c
c initialize pin motion
c
                      ztest = ptest-sngl(pl6000) - Pspring
                      ztest = (ztest*Atxv/pinM)*12.*3600.**2   $ accel in/hr2
                      call diffeq2i(1,Xpin,0.0,ztest)
           else
                      atest      = pinM/(12.*3600.**2)
                      btest      = - PinFrict$ lbf pr in/hr already (!!)
```

```
                      ctest      = - Kspring*Atxv
                      dtest      = (ptest - sngl(pl6000) + Kspring*Xzero)*Atxv
                      call diffeq2(1,Xpin,atest,btest,ctest,dtest)
c
c check limits
c
                      if(Xpin .le. 0.0)then
                                 Xpin        = 0.0
                                 call diffeq2i(1,Xpin,0.0,0.0)
                      elseif(Xpin .ge. 0.5)then
                                 Xpin        = 0.5
                                 call diffeq2i(1,Xpin,0.0,0.0)
                      endif
           endif
HEADER OUTPUT CALLS, LOOP
           if(nsol .gt. 1)then
                      call save('all',0)
                      call lmptab('all')
                      call pthtab('all')
                      call tietab('all')
                      call nodtab('all')
                      call deqntab
                      write(nout,*)' Net force in +X direction: ',(sngl(vps(aire.t1500-
abszro,loop.fi)-pl6000)-Pspring)*Atxv
           elseif(loopct .gt. 0)then
                      call lmptab('all')
                      call pthtab('all')
                      call tietab('all')
                      call nodtab('all')
           endif

INSERT Strans1.cc

C Select Contents of Strans1.cc ===================================
HEADER OPTIONS
C    SINDA Data generated with Thermal Desktop 4.6
C    Generated on Sun Oct 26 06:33:44 2003
C    TDUNITS,   Energy   =    BTU
C    TDUNITS,   Time     =    hr
C    TDUNITS,   Temp     =    F
C    TDUNITS,   Mass     =    lbm
C    TDUNITS,   Length   =    ft
C    TDUNITS,   Orbit    =    nm
C    TDUNITS,   Pressure =    psi
C    Symbol names, values
C    AirAF, AirMAF*0.25*pi*AirDia^2
C    AirDia, 0.25/12.
C    AirFinE, 0.8
C    AirMAF, 8
C    AirXS, EvapMass/EvapLen/DenAlum/EvapNum
C    Atxv, 0.25*pi*(0.75)^2
C    BulbG, 10
C    BulbM, 0.05
C    CFMair, 300.
C    chgrate, 10/3600
C    CompEM, (hilo==1)? CompEM1 : CompEM2
C    CompEM1, 82
C    CompEM2, 40
C    denAlum, 2.7*62.4
C    EvapAF, EvapMAF*0.25*pi*EvapDia^2
C    EvapDia, 0.06/12.
C    EvapLen, 2
C    EvapMAF, 2
C    EvapMass, 5.0
C    EvapNum, 24
```

```
C    hilo, 0
C    Kspring, 10
C    phi, (hilo==1)? Phi1 : Phi2
C    Phi1, 380
C    phi2, 290
C    PinFrict, 1000/(12.*3600.)
C    PinM, 0.2/32.174
C    Plo, 65
C    Pspring, Kspring*(Xpin-Xzero)/Atxv
C    RelHum, 0.8
C    STvol, 300.0e-6/0.3048^3
C    SuctLen, 1.0
C    TairE, 80
C    thi, (hilo==1)? Thi1 : Thi2
C    Thi1, 160
C    thi2, 125
C    timen, 0.
C    Tlo, 80
C    VolTXV, 20.0e-6*mtoft^3
C    Xpin, (hilo==1)? Xpin1 : Xpin2
C    Xpin1, 0.091
C    Xpin2, 0.055
C    Xzero, -0.555
C
HEADER REGISTER DATA
      AIRFINE = 0.8
      ATXV = 0.441786
      CFMAIR = 300.
      CHGRATE = 0.00277778
      COMPEM = 40.
      COMPEM1 = 82.
      COMPEM2 = 40.
      EVAPAF = 3.926991e-005
      EVAPDIA = 0.005
      EVAPMAF = 2.
      EVAPNUM = 24.
      HILO = 0.
      KSPRING = 10.
      PHI = 290.
      PHI1 = 380.
      PHI2 = 290.
      PINFRICT = 0.0231481
      PINM = 0.0062162
      PLO = 65.
      PSPRING = Kspring*(Xpin-Xzero)/Atxv
      THI = 125.
      THI1 = 160.
      THI2 = 125.
      XPIN = 0.055
      XPIN1 = 0.091
      XPIN2 = 0.055
      XZERO = -0.555
INSERT f6049_r134a.inc
HEADER NODE DATA, AIRE
            1,    68.,    0.0021875
<snip>
            20,    68.,    0.0021875
            21,    68.,    -1.
            100,    68.,    0.00459274
            1000,    68.,    -1.
            1500,    80.,    0.0105
HEADER CONDUCTOR DATA, AIRE
            1,    AIRE.1,    AIRE.2,    0.58736
            2,    AIRE.1,    AIRE.100,    0.0986549
            3,    AIRE.1,    AIRE.1000,    1.17472
```

```
            4,    AIRE.2,    AIRE.3,    0.58736
 <snip>
            20,    AIRE.18,    AIRE.19,    0.58736
            21,    AIRE.19,    AIRE.20,    0.58736
            22,    AIRE.20,    AIRE.21,    1.17472
            23,    AIRE.21,    AIRE.100,    0.0986549
C Bulb braze or other attachment
            24,    AIRE.100,    AIRE.1500,    10.
HEADER FLOW DATA, CABIN, FIDA = 8729, FIDW = 718
LU JUNC, 1
       PL = 14.6957, TL = 68.
       CX = 0., CY = 0.5, CZ = 0.
       XGA = 1.
C Cabin Air
LU PLEN, 1000
       LSTAT=STAG
       PL = 14.6957, TL = 80.
       CX = 1., CY = 0., CZ = 0.
       XL = 1.
       XFW = 1.
       XGA = 0.982095
       XGW = 0.0179051

LU PLEN, 1001
       LSTAT=STAG
       PL = 14.6957, TL = 80.
       CX = 2., CY = 0.5, CZ = 0.
       XL = 1.
       XFW = 1.
       XGA = 0.982095
       XGW = 0.0179051

LU JUNC, 2
       PL = 14.6957, TL = 68.
       CX = 0.05, CY = 0.5, CZ = 0.
       MACRO = 1,4,1
       XGA = 1.
       XGA = 1.
<snip>
LU JUNC, 20
       PL = 14.6957, TL = 68.
       CX = 1.85, CY = 0.5, CZ = 0.
       MACRO = 1,4,19
       XGA = 1.
LU JUNC, 21
       PL = 14.6957, TL = 68.
       CX = 1.95, CY = 0.5, CZ = 0.
       MACRO = 1,4,20
       XGA = 1.
PA CONN,1000,    1000,    1
       DEV=VFRSET, SVFR=(CFMair)*60.
  DUPJ=1.0/EvapNum
PA CONN,1,    1,    2,   FR= 0.
       MACRO = 1,4,1
       DEV=STUBE, TLEN=0.05
       AF=0.00272708
       DH=0.0208333
       DH=0.0208333
<snip>
PA CONN,20,    20,    21,   FR= 0.
       MACRO = 1,4,20
       DEV=STUBE, TLEN=0.1
       AF=0.00272708
       DH=0.0208333
PA CONN,21,    21,    1001,   FR= 0.
```

```
       MACRO = 1,4,21
       DEV=STUBE, TLEN=0.05
       AF=0.00272708
       DH=0.0208333
  dupj=evapnum
T HTNC, 1,    2,    AIRE.20,    1,   1.,    2,   0.5
  uam=AirFinE
<snip>
T HTNC, 20,    21,    AIRE.1,    20,   0.5,    21,   1.
  uam=AirFinE
HEADER FLOW DATA, LOOP, FIDA = 6049
LU JUNC, 25
       PL = 65., TL = 80.
       CX = 0., CY = 1., CZ = 0.
       XL = 1.

C Surge Tank
LU TANK, 1000, VOL = 0.0105944
       PL = 65., TL = 80.
       CX = 0., CY = 1.5, CZ = 0.
       XL = 1.

LU PLEN, 5000
       LSTAT=STAG
       PL = (Phi), TL = (Thi)
       CX = 2., CY = 1.5, CZ = 0.
       XL = 0.

LU TANK, 6000, VOL = 0.000706293
       PL = 65., TL = 65.
       CX = 2., CY = 1., CZ = 0.
       XL = 0.3

LU TANK, 2, VOL = 3.926991e-006
       PL = 65., TL = 68.
       CX = 1.95, CY = 1., CZ = 0.
       MACRO = 2,4,1

<snip>
LU TANK, 20, VOL = 3.926991e-006
       PL = 65., TL = 68.
       CX = 0.15, CY = 1., CZ = 0.
       MACRO = 2,4,19

LU TANK, 21, VOL = 3.926991e-006
       PL = 65., TL = 68.
       CX = 0.05, CY = 1., CZ = 0.
       MACRO = 2,4,20

LU TANK, 26, VOL = 0.000253686
       PL = 65., TL = 80.
       CX = 0., CY = 1.25, CZ = 0.
       MACRO = 3,4,1
       XL = 1.

C TXV
PA CONN,23,    5000,    6000,   FR= 0.
       DEV=Tabular
       AF=(EvapAF*EvapNum)
       AFTH=(min(1.0e-3,xpin*pi*0.5/144))
       HGTABLE=1
       OMULT=1.
       HU=105,   GU=112
       OFAC=(Xpin)
  DUPJ = 1.0/EvapNum
```

```
C Compressor
PA CONN,1000,    1000,    5000
       DEV=MFRSET, SMFR=(CompEM)
  STAT = VS
PA TUBE,1,    6000,    2,   FR= 0.
       TLEN=0.05
       DH=0.005
       AF=3.926991e-005
       MACRO = 2,4,1
<snip>
PA TUBE,21,    21,    25,   FR= 0.
       TLEN=0.05
       DH=0.005
       AF=3.926991e-005
       MACRO = 2,4,21
PA CONN,24,    25,    26,   FR= 0.
       MACRO = 3,4,1
       DEV=STUBE, TLEN=0.5
       AF=0.000507373
       DH=0.0254167
  dupi=1.0/evapnum
PA CONN,25,    26,    1000,   FR= 0.
       MACRO = 3,4,2
       DEV=STUBE, TLEN=0.5
       AF=0.000507373
       DH=0.0254167

T HTNC, 1,    2,    AIRE.1,    1,   1.,    2,   0.5
T HTNC, 2,    3,    AIRE.2,    2,   0.5,    3,   0.5
<snip>
T HTNC, 19,    20,    AIRE.19,    19,   0.5,    20,   0.5
T HTNC, 20,    21,    AIRE.20,    20,   0.5,    21,   1.
T HTNC, 21,    26,    AIRE.100,    24,   1.,    25,   1.
HEADER ARRAY DATA, LOOP
C Bivariate    TabularHeadVsFlowBivariate.LOOP.23:
            1 =
             7,            0.,           20.,           40.,           60.
                          80.,          100.,          120.,
            0.,            0.,         1000.,         4000.,         9000.
                       16000.,        25000.,        36000.,
          0.02,            0.,          310.,         1260.,         2850.
                        5060.,         7900.,        11400.,
         0.036,            0.,          100.,          400.,          900.
                        1600.,         2500.,         3600.,
         0.064,            0.,           31.,          126.,          285.
                         506.,          790.,         1140.,
         0.112,            0.,           10.,           40.,           90.
                         160.,          250.,          360.,
           0.2,            0.,           3.1,          12.6,          28.5
                         50.6,           79.,          114.,
          0.36,            0.,            1.,            4.,            9.
                          16.,           25.,           36.,
          0.64,            0.,          0.31,          1.26,          2.85
                         5.06,           7.9,          11.4,
          1.12,            0.,           0.1,           0.4,           0.9
                          1.6,           2.5,           3.6,
```

Processor Outputs - Both Models

STATISTICAL RESPONSE: SYSTEM-LEVEL MODEL

```
MODEL = ROOT                           Vapor Compression Cycle Prebuilt

        NUMBER OF RANDOM VARIABLES =         6               NUMBER OF REL. CONSTRAINTS =         5
        RELPROCEDURE CALLS (LOOPCR) =        0               VS. MAXIMUM (NLOOPR) =             100
        OVERALL RELIABILITY TALLY =   -1.00000 (UNAVAIL.)    TOTAL CUMULATIVE CALLS =             0
        NSEED =   122859703, AERRR = 1.000000E-05, RERRR =  1.000000E-04, LAST ROUTINE: NONE

                                   RANDOM VARIABLE TABULATION

NAME      TYPE        MEAN          STD DEV       COEF VAR      LOWER LIM       1%           50%           99%          UPPER LIM

RPM      ARRAY       2531.8        809.72        0.31982        800.00       908.32        2738.1        3828.7        4000.0
OHOLE    NORMAL     1.50000E-03   4.50000E-05   3.00000E-02  -1.00000E+30   1.39531E-03   1.50000E-03   1.60469E-03   1.00000E+30
CHARGED  NORMAL     0.20000       2.00000E-02   0.10000      -1.00000E+30   0.15347       0.20000       0.24653       1.00000E+30
TAIRC    ARRAY       93.333        6.2361       6.68155E-02    80.000        81.732        92.679        107.55        110.00
TAIRE    ARRAY       71.667        3.1190       4.35215E-02    65.000        65.866        71.340        78.775        80.000
RELHUM   UNIFORM    0.50000       0.28868       0.57735        0.0000       1.00000E-02   0.50000       0.99000        1.0000




MODEL = ROOT                           Vapor Compression Cycle Prebuilt


        NUMBER OF RANDOM VARIABLES =         6               NUMBER OF REL. CONSTRAINTS =         5
        RELPROCEDURE CALLS (LOOPCR) =      100               VS. MAXIMUM (NLOOPR) =             100
        OVERALL RELIABILITY TALLY =    1.00000 ( 100.000%)   TOTAL CUMULATIVE CALLS =           100
        NSEED =   104015765, AERRR = 1.000000E-05, RERRR =  1.000000E-04, LAST ROUTINE: DSAMPLE

                                   RELIABILITY CONSTRAINT TABULATION

  NO.  NAME       MEAN         STD DEV      COEF VAR     LOWER LIM    REL: TALLY    REL: NORM     UPPER LIM    REL: TALLY    REL: NORM

    1 UNNAMED   0.20069      1.98764E-02  9.90379E-02
    2 UNNAMED    45.521       3.5478      7.79369E-02   32.000       1.0000       0.99993
    3 UNNAMED    2.0549      0.58974      0.28699
    4 SHEAT10    46.777       9.5303      0.20374       10.000       1.0000       0.99994
    5 SHEAT20    46.777       9.5303      0.20374       20.000       1.0000       0.99752
```

```
 Charge (lb)  Pct Chg Err   RPM     Ohole (in)   Tair Cond   Tair Evap   Rel Hum     SupHeat     Loopct

  0.19037        0.73      2885.9    0.01683       81.22       73.24       22.50       65.12         8
  0.16080        2.64      3224.5    0.01822      100.05       70.71       16.50       53.00         7
  0.18489        0.54      2747.4    0.01839       90.95       70.79       29.50       51.66         9
  0.19975        0.53      1295.8    0.01862       96.47       68.92       88.50       30.09         7
  0.20481        0.86      3205.9    0.01820       84.42       68.62       49.50       51.74         9
  0.21648        0.22      1125.2    0.01882      101.34       73.46       60.50       24.91         7
  0.17256        0.01      3394.5    0.01661       87.65       71.92       27.50       65.91         8
  0.20963        0.38      2436.2    0.01855       86.82       77.40        4.50       52.32         8
  0.17970        1.37      1190.8    0.01780       89.87       69.86       31.50       37.84         7
  0.17379        0.57      2538.6    0.01837       88.40       69.62       21.50       52.44         8
  0.18052        0.98      3598.3    0.01868       84.06       67.81       45.50       52.57         9
  0.18980        0.14      2917.9    0.01829      106.13       66.62       89.50       42.19         8
  0.20690        0.57      2313.8    0.01714       92.42       70.16        0.50       50.67         8
  0.18555        1.28       932.7    0.01732       96.92       65.61       61.50       25.95         7
  0.22116        0.30      1371.3    0.01825       90.79       66.84       93.50       30.56         8
  0.20378        0.27      1586.8    0.01803       90.48       75.85       99.50       46.31         9
  0.18804        1.15      3023.6    0.01844       94.03       72.91       57.50       51.94         9
  0.22030        0.38      1062.6    0.01735       82.12       73.13       90.50       38.86         8
  0.19202        2.87      3347.8    0.01694       95.61       70.09       53.50       55.65         8
  0.20798        0.49      3500.7    0.01738       83.67       71.74       26.50       58.09         9
  0.22507        0.24      2562.1    0.01794       97.63       74.88       36.50       45.46        10
  0.20852        0.18      3069.8    0.01798       97.15       69.37       23.50       46.64         9
  0.20744        0.61      2801.6    0.01878      101.00       69.94       38.50       41.21        10
  0.20025        0.61      2151.0    0.01906       94.80       75.34       65.50       44.84         8
  0.16609        0.59      3243.7    0.01846       92.94       74.59       74.50       58.09         7
  0.18619        1.25      2689.9    0.01812       84.74       69.29       13.50       53.55        11
  0.22621        0.37      2347.0    0.01791       96.70       79.13       42.50       48.22         9
  0.20125        0.70      2096.6    0.01817       86.36       68.41       75.50       46.12         9
  0.17493        0.75      1688.8    0.01769       93.66       68.72        8.50       44.90         7
  0.19415        0.58      3531.0    0.01917       91.92       71.83        9.50       47.98         9
  0.19571        0.92      3636.7    0.01802       87.04       71.21       72.50       55.77         8
  0.24340        0.61      1636.3    0.01781       92.59       69.78       46.50       32.44        10
  0.19092        3.25      2765.8    0.01832       90.64       72.02       70.50       51.08        10
  0.16972        0.37      1745.0    0.01784       98.13       66.37       63.50       41.33         7
  0.20277        0.11      3472.1    0.01814       92.77       76.65       76.50       55.74        23
  0.20637        0.47      1872.3    0.01702       98.91       68.52       35.50       43.61         7
  0.22206        0.25      2669.9    0.01831       83.24       76.03       59.50       52.35         9
  0.22744        0.28      1002.7    0.01848       93.30       67.52       67.50       20.24         7
  0.22401        0.23      3263.3    0.01793       89.72       70.32       25.50       46.88         9
  0.21578        0.26      2240.0    0.01764       91.75       78.06       28.50       53.41         8
  0.23920        0.26      2584.9    0.01763       93.12       76.23       84.50       45.10        12
  0.23624        0.29      2514.4    0.01708      101.69       69.46       80.50       40.17        12
  0.14848        0.38      3370.7    0.01726       88.57       75.67        3.50       68.51         8
  0.19256        3.13      2649.5    0.01761       93.84       73.35       39.50       53.82         9
 ...
```

INITIAL CONDITIONS: TXV TRANSIENT

```
                           SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE    16

MODEL = SINDA
  FASTIC


 FLUID SUBMODEL NAME = CABIN   ; FLUID NO. = 8729,  718


        LOOPCT =     19
        CONVERGENCE STATUS = SUBMODEL CONVERGED AS OF      11 ITERATIONS


                                    LUMP PARAMETER TABULATION FOR SUBMODEL CABIN

  LUMP  TYPE     TEMP       PRESSURE     QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

     1  JUNC    79.53        14.83        1.000        1.000       7.3533E-02    146.4        0.000        0.000      -1.9486E-04
     2  JUNC    79.46        14.83        1.000        1.000       7.3526E-02    146.4      -0.9845        0.000      -3.7438E-04
     3  JUNC    79.39        14.82        1.000        1.000       7.3502E-02    146.4      -0.9240        0.000       3.7014E-05
     4  JUNC    79.31        14.82        1.000        1.000       7.3479E-02    146.4       -1.092        0.000      -2.7883E-04
     5  JUNC    79.20        14.81        1.000        1.000       7.3459E-02    146.3       -1.379        0.000      -6.7115E-05
     6  JUNC    79.07        14.80        1.000        1.000       7.3443E-02    146.3       -1.773        0.000       4.9353E-05
     7  JUNC    78.89        14.79        1.000        1.000       7.3432E-02    146.3       -2.306        0.000       2.2650E-05
     8  JUNC    78.67        14.79        1.000        1.000       7.3429E-02    146.2       -3.001        0.000       4.6253E-05
     9  JUNC    78.38        14.78        1.000        1.000       7.3434E-02    146.1       -3.848        0.000       1.3947E-04
    10  JUNC    78.02        14.77        1.000        1.000       7.3449E-02    146.0       -4.754        0.000      -4.6253E-04
    11  JUNC    77.59        14.77        1.000        1.000       7.3474E-02    145.9       -5.763        0.000      -5.1165E-04
    12  JUNC    77.08        14.76        1.000        1.000       7.3510E-02    145.8       -6.738        0.000      -3.2187E-04
    13  JUNC    76.51        14.75        1.000        1.000       7.3554E-02    145.7       -7.588        0.000       1.8835E-04
    14  JUNC    75.90        14.75        1.000        1.000       7.3605E-02    145.5       -8.204        0.000      -3.5000E-04
    15  JUNC    75.27        14.74        1.000        1.000       7.3657E-02    145.4       -8.330        0.000       2.5749E-04
    16  JUNC    74.69        14.73        1.000        1.000       7.3703E-02    145.2       -7.774        0.000       2.1648E-04
    17  JUNC    74.37        14.73        1.000        1.000       7.3714E-02    145.1       -7.398        0.000       -3.131
    18  JUNC    74.35        14.72        1.000        1.000       7.3681E-02    145.1       -7.243        0.000       -7.064
    19  JUNC    74.34        14.71        1.000        1.000       7.3649E-02    145.1       -7.097        0.000       -6.918
    20  JUNC    74.33        14.71        1.000        1.000       7.3616E-02    145.1       -6.947        0.000       -6.768
    21  JUNC    74.31        14.70        1.000        1.000       7.3584E-02    145.1       -6.696        0.000       -6.517
  1000  PLEN    80.00        14.70        1.000        1.000       7.2791E-02    146.5        0.000       -1310.      -1.9198E+05
  1001  PLEN    80.00        14.70        1.000        1.000       7.2791E-02    146.5        0.000        1310.       1.9031E+05
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                                    PATH PARAMETER TABULATION FOR SUBMODEL CABIN
   PATH  TYPE    LMP 1   LMP 2   DUP I      DUP J    STAT   XL UPSTRM    FLOWRATE     DELTA PRES    REYNOLDS    MACH    REGIME
  1000   VFRSET   1000       1    1.0       4.17E-02 NORM     1.000        1310.      -0.1369
     1   STUBE       1       2    1.0         1.0    NORM     1.000        54.59       3.4371E-03    9466.      0.069   1 PHASE
     2   STUBE       2       3    1.0         1.0    NORM     1.000        54.59       6.8887E-03    9467.      0.069   1 PHASE
     3   STUBE       3       4    1.0         1.0    NORM     1.000        54.59       6.8886E-03    9468.      0.069   1 PHASE
     4   STUBE       4       5    1.0         1.0    NORM     1.000        54.59       6.8867E-03    9469.      0.069   1 PHASE
     5   STUBE       5       6    1.0         1.0    NORM     1.000        54.59       6.8831E-03    9471.      0.069   1 PHASE
     6   STUBE       6       7    1.0         1.0    NORM     1.000        54.59       6.8771E-03    9472.      0.069   1 PHASE
     7   STUBE       7       8    1.0         1.0    NORM     1.000        54.59       6.8683E-03    9475.      0.069   1 PHASE
     8   STUBE       8       9    1.0         1.0    NORM     1.000        54.59       6.8567E-03    9478.      0.069   1 PHASE
     9   STUBE       9      10    1.0         1.0    NORM     1.000        54.59       6.8432E-03    9482.      0.069   1 PHASE
    10   STUBE      10      11    1.0         1.0    NORM     1.000        54.59       6.8273E-03    9487.      0.069   1 PHASE
    11   STUBE      11      12    1.0         1.0    NORM     1.000        54.59       6.8106E-03    9494.      0.069   1 PHASE
    12   STUBE      12      13    1.0         1.0    NORM     1.000        54.59       6.7944E-03    9501.      0.069   1 PHASE
    13   STUBE      13      14    1.0         1.0    NORM     1.000        54.59       6.7803E-03    9509.      0.069   1 PHASE
    14   STUBE      14      15    1.0         1.0    NORM     1.000        54.59       6.7720E-03    9518.      0.069   1 PHASE
    15   STUBE      15      16    1.0         1.0    NORM     1.000        54.59       6.7727E-03    9527.      0.069   1 PHASE
    16   STUBE      16      17    1.0         1.0    NORM     1.000        54.59       6.8136E-03    9536.      0.069   1 PHASE
    17   STUBE      17      18    1.0         1.0    NORM     1.000        54.59       6.8665E-03    9541.      0.069   1 PHASE
    18   STUBE      18      19    1.0         1.0    NORM     1.000        54.59       6.8695E-03    9541.      0.069   1 PHASE
    19   STUBE      19      20    1.0         1.0    NORM     1.000        54.59       6.8725E-03    9541.      0.069   1 PHASE
    20   STUBE      20      21    1.0         1.0    NORM     1.000        54.59       6.8756E-03    9541.      0.069   1 PHASE
    21   STUBE      21    1001    1.0        24.     NORM     1.000        54.59       3.4413E-03    9541.      0.069   1 PHASE

                                    TIE PARAMETER TABULATION FOR SUBMODEL CABIN
  TIE   TYPE      UA         QTIE         LUMP     TEF           NODE              TEMP.    2P  PATH 1    FRACT   PATH 2    FRACT
     1  HTNC    1.167       -6.696          21    74.73      AIRE.1                67.56     S      20    0.5000      21    1.0000
     2  HTNC    1.164       -6.738          12    77.50      AIRE.10               70.27     S      11    0.5000      12    0.5000
     3  HTNC    1.164       -5.763          11    78.01      AIRE.11               71.82     S      10    0.5000      11    0.5000
     4  HTNC    1.164       -4.754          10    78.44      AIRE.12               73.34     S       9    0.5000      10    0.5000
     5  HTNC    1.185       -3.848           9    78.80      AIRE.13               74.74             8    0.5000       9    0.5000
     6  HTNC    1.186       -3.001           8    79.09      AIRE.14               75.93             7    0.5000       8    0.5000
     7  HTNC    1.186       -2.306           7    79.32      AIRE.15               76.88             6    0.5000       7    0.5000
     8  HTNC    1.186       -1.773           6    79.49      AIRE.16               77.62             5    0.5000       6    0.5000
     9  HTNC    1.186       -1.379           5    79.62      AIRE.17               78.17             4    0.5000       5    0.5000
    10  HTNC    1.187       -1.092           4    79.73      AIRE.18               78.58             3    0.5000       4    0.5000
    11  HTNC    1.187      -0.9240           3    79.81      AIRE.19               78.83             2    0.5000       3    0.5000
    12  HTNC    1.167       -6.947          20    74.75      AIRE.2                67.31     S      19    0.5000      20    0.5000
    13  HTNC    1.187      -0.9845           2    79.88      AIRE.20               78.84             1    1.0000       2    0.5000
    14  HTNC    1.168       -7.097          19    74.76      AIRE.3                67.16     S      18    0.5000      19    0.5000
    15  HTNC    1.168       -7.243          18    74.77      AIRE.4                67.02     S      17    0.5000      18    0.5000
    16  HTNC    1.168       -7.398          17    74.79      AIRE.5                66.87     S      16    0.5000      17    0.5000
    17  HTNC    1.164       -7.774          16    75.11      AIRE.6                66.76     S      15    0.5000      16    0.5000
    18  HTNC    1.164       -8.330          15    75.69      AIRE.7                66.75     S      14    0.5000      15    0.5000
    19  HTNC    1.164       -8.204          14    76.32      AIRE.8                67.51     S      13    0.5000      14    0.5000
    20  HTNC    1.164       -7.588          13    76.93      AIRE.9                68.79     S      12    0.5000      13    0.5000
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                          LUMP PARAMETER TABULATION FOR SUBMODEL LOOP

 LUMP  TYPE     TEMP         PRESSURE     QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

 1000  TANK    74.47         75.78         1.000         1.000         1.530        178.2         0.000         0.000        1.6384E-05
 6000  TANK    62.87         75.93        0.2778        0.9492         5.429        118.1         0.000         0.000        1.1932E-05
    2  TANK    62.87         75.93        0.3324        0.9603         4.590        122.5         7.223         0.000       -1.0967E-05
    3  TANK    62.87         75.92        0.3853        0.9682         3.992        126.7         7.011         0.000         0.000
    4  TANK    62.86         75.92        0.4390        0.9744         3.526        130.9         7.099         0.000       -1.1444E-05
    5  TANK    62.86         75.91        0.4937        0.9793         3.151        135.3         7.238         0.000        1.4782E-05
    6  TANK    62.85         75.90        0.5497        0.9834         2.841        139.7         7.421         0.000       -5.7220E-06
    7  TANK    62.85         75.90        0.6089        0.9869         2.574        144.4         7.831         0.000        1.3351E-05
    8  TANK    62.84         75.89        0.6753        0.9902         2.329        149.7         8.785         0.000       -1.0490E-05
    9  TANK    62.84         75.88        0.7396        0.9928         2.132        154.8         8.508         0.000       -6.6757E-06
   10  TANK    62.83         75.87        0.7978        0.9948         1.980        159.4         7.707         0.000        1.9073E-05
   11  TANK    62.83         75.87        0.8490        0.9964         1.863        163.5         6.780         0.000        1.0490E-05
   12  TANK    62.82         75.86        0.8924        0.9975         1.775        166.9         5.740         0.000        4.2915E-06
   13  TANK    62.82         75.85        0.9278        0.9984         1.708        169.8         4.689         0.000        7.6294E-06
   14  TANK    62.81         75.85        0.9559        0.9991         1.659        172.0         3.718         0.000        6.4373E-06
   15  TANK    62.81         75.84        0.9776        0.9995         1.623        173.7         2.870         0.000        1.8835E-05
   16  TANK    62.80         75.83        0.9940        0.9999         1.596        175.0         2.175         0.000       -1.1444E-05
   17  TANK    65.07         75.83         1.000         1.000         1.576        176.0         1.664         0.000        3.4571E-06
   18  TANK    68.40         75.83         1.000         1.000         1.560        176.8         1.294         0.000       -4.6492E-06
   19  TANK    70.99         75.82         1.000         1.000         1.547        177.4         1.006         0.000       -8.5831E-06
   20  TANK    73.00         75.82         1.000         1.000         1.538        177.9        0.7751         0.000        8.9407E-07
   21  TANK    74.50         75.81         1.000         1.000         1.531        178.2        0.5771         0.000        1.7166E-05
   26  TANK    74.45         75.80         1.000         1.000         1.531        178.2       -0.2716         0.000        3.3677E-04
   25  JUNC    74.48         75.81         1.000         1.000         1.531        178.2         0.000         0.000        2.7148E-05
 5000  PLEN    125.0         290.0         0.000         0.000         68.31        118.1         0.000         0.000         2402.
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                          PATH PARAMETER TABULATION FOR SUBMODEL LOOP
  PATH  TYPE     LMP 1    LMP 2    DUP I        DUP J     STAT    XL UPSTRM     FLOWRATE        DELTA PRES      REYNOLDS      MACH      REGIME
     1  TUBE      6000        2     1.0          1.0      NORM     0.2778         1.667          2.7480E-03    1.0154E+04   0.009     ANNULAR
     2  TUBE         2        3     1.0          1.0      NORM     0.3324         1.667          4.9260E-03    1.1814E+04   0.010     ANNULAR
     3  TUBE         3        4     1.0          1.0      NORM     0.3853         1.667          5.3763E-03    1.3426E+04   0.010     ANNULAR
     4  TUBE         4        5     1.0          1.0      NORM     0.4390         1.667          5.8135E-03    1.5058E+04   0.011     ANNULAR
     5  TUBE         5        6     1.0          1.0      NORM     0.4937         1.667          6.2345E-03    1.6723E+04   0.012     ANNULAR
     6  TUBE         6        7     1.0          1.0      NORM     0.5497         1.667          6.6643E-03    1.8429E+04   0.012     ANNULAR
     7  TUBE         7        8     1.0          1.0      NORM     0.6089         1.667          7.1495E-03    2.0230E+04   0.013     ANNULAR
     8  TUBE         8        9     1.0          1.0      NORM     0.6753         1.667          7.4076E-03    2.2250E+04   0.013     ANNULAR
     9  TUBE         9       10     1.0          1.0      NORM     0.7396         1.667          7.4904E-03    2.4206E+04   0.014     ANNULAR
    10  TUBE        10       11     1.0          1.0      NORM     0.7978         1.667          7.4409E-03    2.5978E+04   0.014     ANNULAR
    11  TUBE        11       12     1.0          1.0      NORM     0.8490         1.667          7.2633E-03    2.7537E+04   0.015     ANNULAR
    12  TUBE        12       13     1.0          1.0      NORM     0.8924         1.667          6.9801E-03    2.8857E+04   0.015     ANNULAR
    13  TUBE        13       14     1.0          1.0      NORM     0.9278         1.667          6.6147E-03    2.9936E+04   0.015     ANNULAR
    14  TUBE        14       15     1.0          1.0      NORM     0.9559         1.667          6.1751E-03    3.0791E+04   0.015     ANNULAR
    15  TUBE        15       16     1.0          1.0      NORM     0.9776         1.667          5.6208E-03    3.1451E+04   0.016     ANNULAR
    16  TUBE        16       17     1.0          1.0      NORM     0.9940         1.667          4.9490E-03    3.1951E+04   0.016     ANNULAR
    17  TUBE        17       18     1.0          1.0      NORM      1.000         1.667          4.6123E-03    3.1979E+04   0.016     1 PHASE
    18  TUBE        18       19     1.0          1.0      NORM      1.000         1.667          4.6146E-03    3.1756E+04   0.016     1 PHASE
    19  TUBE        19       20     1.0          1.0      NORM      1.000         1.667          4.6152E-03    3.1585E+04   0.016     1 PHASE
    20  TUBE        20       21     1.0          1.0      NORM      1.000         1.667          4.6123E-03    3.1455E+04   0.016     1 PHASE
    21  TUBE        21       25     1.0          1.0      NORM      1.000         1.667          2.2677E-03    3.1358E+04   0.016     1 PHASE
    23  TABULR    5000     6000     1.0      4.17E-02 NORM      0.000         40.00           214.1                      0.001
  1000  MFRSET    1000     5000     1.0          1.0      VS        1.000         40.00          -214.2
    24  STUBE       25       26  4.17E-02        1.0      NORM      1.000         40.00          1.2791E-02    7.1067E+04   0.029     1 PHASE
    25  STUBE       26     1000     1.0          1.0      NORM      1.000         40.00          1.2786E-02    7.1072E+04   0.029     1 PHASE

                          TIE PARAMETER TABULATION FOR SUBMODEL LOOP
 TIE   TYPE      UA          QTIE          LUMP      TEF        NODE                  TEMP.    2P   PATH 1     FRACT    PATH 2     FRACT
    1  HTNC     1.540         7.223            2     62.87      AIRE.1                67.56              1     1.0000        2     0.5000
    2  HTNC    0.9107         6.780           11     62.83      AIRE.10               70.27     T       10     0.5000       11     0.5000
    3  HTNC    0.6375         5.740           12     62.82      AIRE.11               71.82     T       11     0.5000       12     0.5000
    4  HTNC    0.4455         4.689           13     62.82      AIRE.12               73.34     T       12     0.5000       13     0.5000
    5  HTNC    0.3116         3.718           14     62.81      AIRE.13               74.74     T       13     0.5000       14     0.5000
    6  HTNC    0.2188         2.870           15     62.81      AIRE.14               75.93     T       14     0.5000       15     0.5000
    7  HTNC    0.1545         2.175           16     62.80      AIRE.15               76.88     T       15     0.5000       16     0.5000
    8  HTNC    0.1326         1.664           17     65.07      AIRE.16               77.62             16     0.5000       17     0.5000
    9  HTNC    0.1324         1.294           18     68.40      AIRE.17               78.17             17     0.5000       18     0.5000
   10  HTNC    0.1326         1.006           19     70.99      AIRE.18               78.58             18     0.5000       19     0.5000
   11  HTNC    0.1328        0.7751           20     73.00      AIRE.19               78.83             19     0.5000       20     0.5000
   12  HTNC     1.579         7.011            3     62.87      AIRE.2                67.31              2     0.5000        3     0.5000
   13  HTNC    0.1329        0.5771           21     74.50      AIRE.20               78.84             20     0.5000       21     1.0000
   14  HTNC     1.651         7.099            4     62.86      AIRE.3                67.16              3     0.5000        4     0.5000
   15  HTNC     1.739         7.238            5     62.86      AIRE.4                67.02              4     0.5000        5     0.5000
   16  HTNC     1.847         7.421            6     62.85      AIRE.5                66.87              5     0.5000        6     0.5000
   17  HTNC     2.001         7.831            7     62.85      AIRE.6                66.76              6     0.5000        7     0.5000
   18  HTNC     2.249         8.785            8     62.84      AIRE.7                66.75              7     0.5000        8     0.5000
   19  HTNC     1.821         8.508            9     62.84      AIRE.8                67.51     T        8     0.5000        9     0.5000
   20  HTNC     1.294         7.707           10     62.83      AIRE.9                68.79     T        9     0.5000       10     0.5000
   21  HTNC     4.070       -0.2716           26     74.47      AIRE.100              74.40             24     1.0000       25     1.0000
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                                  NODE PARAMETER TABULATION FOR SUBMODEL AIRE

NODE  TYPE    TEMPERATURE   CAPACITANCE      CSG            Q          NET ENERGY      LINEAR      RADIATIVE        TIES
              (DEG.)      (ENERGY/DEG)    (TIME)     (ENERGY/TIME) (ENERGY/TIME) (ENERGY/TIME) (ENERGY/TIME) (ENERGY/TIME)

   1   DIFF    67.5600      2.187500E-03  5.046896E-04 -0.526559      1.466274E-05  0.526574        0.00000     -0.526559
   2   DIFF    67.3075      2.187500E-03  5.932619E-04 -6.332970E-02  3.352761E-06  6.333305E-02   0.00000     -6.332970E-02
   3   DIFF    67.1627      2.187500E-03  5.818309E-04 -1.644611E-03  9.387732E-07  1.645550E-03   0.00000     -1.644611E-03
   4   DIFF    67.0207      2.187500E-03  5.684907E-04  4.618645E-03  6.109476E-07 -4.618034E-03   0.00000      4.618645E-03
   5   DIFF    66.8709      2.187500E-03  5.528797E-04 -2.379942E-02  5.140901E-07  2.379993E-02   0.00000     -2.379942E-02
   6   DIFF    66.7616      2.187500E-03  5.325930E-04 -5.665112E-02  1.598150E-06  5.665271E-02   0.00000     -5.665112E-02
   7   DIFF    66.7487      2.187500E-03  5.022389E-04 -0.454710      2.294779E-06  0.454712        0.00000     -0.454710
   8   DIFF    67.5100      2.187500E-03  5.570253E-04 -0.303905      6.705523E-06  0.303911        0.00000     -0.303905
   9   DIFF    68.7887      2.187500E-03  6.433629E-04 -0.119600      1.347065E-05  0.119614        0.00000     -0.119600
  10   DIFF    70.2711      2.187500E-03  7.250717E-04 -4.182529E-02 -1.221895E-05  4.181308E-02   0.00000     -4.182529E-02
  11   DIFF    71.8246      2.187500E-03  7.972473E-04  2.238894E-02 -1.007318E-05 -2.239901E-02   0.00000      2.238894E-02
  12   DIFF    73.3401      2.187500E-03  8.572433E-04  6.569624E-02 -9.298325E-06 -6.570554E-02   0.00000      6.569624E-02
  13   DIFF    74.7436      2.187500E-03  8.984859E-04  0.129896     -1.710653E-05 -0.129914        0.00000      0.129896
  14   DIFF    75.9260      2.187500E-03  9.339733E-04  0.131161     -6.359816E-05 -0.131225        0.00000      0.131161
  15   DIFF    76.8849      2.187500E-03  9.602482E-04  0.131162     -2.083182E-05 -0.131183        0.00000      0.131162
  16   DIFF    77.6205      2.187500E-03  9.694870E-04  0.109456      1.141429E-05 -0.109445        0.00000      0.109456
  17   DIFF    78.1698      2.187500E-03  9.694938E-04  8.432031E-02  1.601875E-05 -8.430429E-02   0.00000      8.432031E-02
  18   DIFF    78.5756      2.187500E-03  9.693624E-04  8.607924E-02  1.691282E-05 -8.606233E-02   0.00000      8.607924E-02
  19   DIFF    78.8348      2.187500E-03  9.692680E-04  0.148927      1.931190E-05 -0.148907        0.00000      0.148927
  20   DIFF    78.8405      2.187500E-03  7.690723E-04  0.407375      2.163649E-05 -0.407353        0.00000      0.407375
 100   DIFF    74.4015      4.592740E-03  3.219046E-04  0.271619      6.799698E-04 -0.270940        0.00000      0.271619
1500   DIFF    74.4015      1.050000E-02  1.050000E-03   0.00000        0.00000        0.00000        0.00000       0.00000
  21   ARITH   78.4966       0.00000       0.00000       0.00000     -2.980232E-08 -2.980232E-08   0.00000       0.00000
1000   ARITH   67.5600       0.00000       0.00000       0.00000        0.00000        0.00000        0.00000       0.00000
```

```
                                   DIFFERENTIAL EQUATION TABULATION

EQN ID   ORDER       X          DXDT       D2XDT2      DT CHG       ERR        DT ERR

     1   SECOND   5.50000E-02  0.0000     3.05638E+10 1.00000E+30  0.0000     1.00000E+30

Net force in +X direction:    1.221648
```

PROBLEM H: COMPARISONS WITH CLOSED FORM SOLUTION

This problem analyzes a thermal/fluid transient event for which a closed form solution exists. In addition to validating the code, this problem was chosen to demonstrate the following FLUINT features:

1. lumped parameter (finite difference) ties versus segment-oriented ties
2. axial resolution requirements for adequate accuracy
3. use of registers
4. user logic for specialized initial and boundary conditions

H.1 Problem Description

A one inch diameter pipe carries liquid water flowing at 1000 lb_m/hr over a distance of ten feet (see Figure H-1). The pipe wall temperature is constant at 200°F. Dr. R. K. McMordie demonstrated that if both the initial axial temperature profile and the inlet temperature profile obeyed certain exponential relationships in space and time, respectively, and if most properties and coefficients could be assumed constant, then the energy equation was separable and a closed form 1D solution for the fluid temperature as a function of location and time, T(x,τ), could be found.

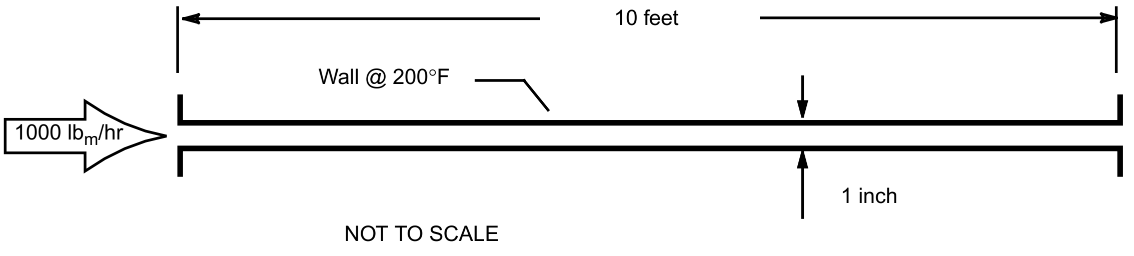

Figure H-1 Water Line

The inlet temperature is determined by the following relationship in time:

$$T_i(\tau) = T_w \cdot e^{\left(-\frac{\tau}{\alpha}\right)} \qquad \text{(H-1)}$$

$$\alpha = \frac{D \cdot \rho \cdot C_p}{4 \cdot U}$$

where T_w is the wall temperature, α is the time constant, ρ is the density, D the diameter, C_p is the specific heat, and U is the heat transfer coefficient.

The initial temperature profile is a function of distance from the inlet:

$$T_o(x) = T_w \cdot \left(2 - e^{\left(-\frac{x}{\beta}\right)}\right) \tag{H-2}$$

$$\beta = \frac{\dot{m} \cdot C_p}{\pi \cdot D \cdot U}$$

where β is the characteristic length, and $\dot{m}$ is the mass flowrate.

Under these circumstances, the 1D analytic solution is:

$$T(x, \tau) = T_w \cdot \left(1 - e^{\left(-\frac{x}{\beta}\right)} + e^{\left(-\frac{\tau}{\alpha}\right)}\right) \tag{H-3}$$

In summary, the relevant characteristics of the problem are:

Line:	
Diameter	1 inch
Length	10 feet
Fluid:	
Density	62.4 lb_m/ft^3
Specific Heat	1.0 BTU/lb_m-°F
Flowrate	1000 lb_m/hr
Boundary condition:	
Wall temperature	200°F
Heat transfer coefficient	242 BTU/hr-ft^2-°F
Inlet temperature profile	equation H-1
Initial condition:	
Axial temperature profile	equation H-2

Assuming a 1D velocity profile, the time it takes for the fluid to move through the entire length of the line is about 12.3 seconds. Therefore, the transient event duration will be longer than this time, say 15 seconds, in order to provide a good basis of comparison.

All of the above values have been input using registers such that they can be easily varied.

H.2 A FLUINT Model

At least one modeling choice is clear: the line itself must be modeled with tanks to capture the transient movement of liquid. Any path may be used, since flowrate and density are both constant and pressure drop is irrelevant.

The thermal boundary condition will be represented by a boundary node, and the flowrate boundary condition will be represented by an MFRSET connector.

Also, it seems straight forward to use a plenum for the inlet state. The temperature of the inlet will be set to a register named Tinit, whose value will be specified as a function of time (TIMEN). This will impose a step-wise variation which is acceptable as long as the time step is constrained (using DTMAXF) such that this is a reasonable approximation. For the purist, a tank could similarly have been used, with the QL calculated such that the correct time derivative, dT/dt, was also imposed.

Other choices are less clear, and are mainly driven by the need to compare with a closed form solution that relies on simplifying assumptions: FLUINT must be prevented from including higher order effects, which it would by default. For example, using the default library description of water (or even one generated by RAPPR) would not only result in slight differences in density and C_p, it would include the variation of both of those parameters with temperature. As the liquid in the pipe cools due to the influx of colder liquid, it would shrink and therefore cause the outlet flowrate to differ from the prescribed 1000 lb_m/hr by as much as 3%. Therefore, a very simple 9000 series fluid description must be used in which both the density and specific heat are constants.

Similarly, using convection ties (HTN, HTNC, HTNS) would violate the comparison because the calculated values of the heat transfer coefficients would be slightly different from 242 BTU/hr^2-°F, and would also vary with temperature. Therefore, user-defined ties (HTU and HTUS) must be used to hold the heat transfer coefficient constant.

Two decisions remain:

1. How many lumps are required to provide adequate accuracy?
2. Should the heat transfer be modeled using lumped parameter/finite difference methods (HTU ties) or as a collection of heat transfer segments (HTUS ties)?

These questions, which turn out to be interrelated, are the focus of the rest of this subsection.

The question of how many lumps are needed to adequately capture the transient event can be addressed to some extent by rules-of-thumb, the reliance on which is always somewhat dangerous. The first rule of thumb is that of length to diameter ratio: a good breakdown will have a L/D ratio for each element on the order of 10 (which is liberally construed to mean from 3 to 30). In this model, this advice would result in the use of about 10 lumps. The second rule of thumb for single-phase flow and conductive thermal systems in general is that temperature differences between nodes should not be greater than about 10°F. In this example problem, the range of temperatures in the problem are expected to be on the order of 100°F, so this rule-of-thumb concurs with the guess of 10 sections.

To envelope this guess and test its sensitivity, at least three models will be built using 5, 10, and 20 sections. While a real analyst would probably have rerun the same problem three times with slightly different inputs, for illustration purposes all models will be run simultaneously using different submodels for each discretization. These three submodels will use the standard HTU or lumped parameter style user-defined tie, which assumes that the lump and node each represent the average state of the fluid and wall, respectively, for each section. With these methods, there are no “hidden” temperature gradients within each section, and the user must use enough sections to capture any anticipated gradients in temperature or other properties. Too few sections will result in a slight underprediction of the heat transfer rates.

The lumped parameter HTU tie can be contrasted with the segment-oriented HTUS tie, which assumes that the endpoint lumps on each path represent distinct inlet and outlet fluid states, and that the node represents the average wall temperature over that entire length. Temperature gradients internal to the segment are presumed to follow an exponential relationship (e.g., LMTD methods are employed), enabling the use of far fewer lumps without sacrificing accuracy in single-phase flows. To compare this approach with the above submodels, a fourth submodel is added that uses HTUS ties instead of HTU ties, and breaks the line into only five sections.

All models use downstream discretized LINE macros. Part of the reason for using downstream lumps (as opposed to upstream or centered) is to better enable comparisons between HTU and HTUS ties, which are otherwise intrinsically difficult to substitute for each other.

The other reason for using downstream methods is more subtle, and demands an answer to the question: What axial coordinate, x, should be attributed to each lump? In other words, if Tank #1 models the first foot of the line, should it be assigned x=0.0 ft, x=0.5 ft, or x=1.0 ft? For the segment-oriented model, the lumps have defined locations corresponding to the inlet and outlets of each path length. For the lumped parameter models, the answer is less definitive.

Normally, the user need not be concerned with the following distinctions; where exactly a lump resides is largely immaterial. In fact, the user normally should not attempt to define locations to a tighter degree than the resolution of the model itself, which becomes the limiting uncertainty. However, to be able to compare with a continuous, analytic solution, and to calculate the correct initial conditions, the better understanding is necessary.

From the perspective of hydrodynamics (e.g., pressure profiles, etc.), the lump location is defined by the lengths of the paths adjacent to it. In other words, the first lump in the 10 tank model is located at x=0.0 ft for upstream discretization, x=0.5 ft for centered, and x=1.0 ft for downstream. On the other hand, from a thermal and heat transfer perspective, the lump always ‘resides’ at the current downstream end of the section it represents. Thus, while these two locations are coincident for downstream discretization, they are different for the other methods.

In this model, where hydrodynamics are irrelevant and temperature profiles are paramount, the axial coordinates of the lumps will be taken to be at the downstream end of each section—coincident with the segment-oriented approach. Initial conditions and analytic comparisons will be performed consistent with this convention.

H.3 The Input File

The input file is listed immediately following the last section.

OPTIONS DATA—Two user files are named, one to contain a summary of the temperature responses for all submodels and one to contain the temperature difference between the closed form solution and the FLUINT predictions. The spell checker feature is turned off globally.

REGISTER DATA—Values that will be used in the definition of the model are either initialized (lengths, diameters, properties, etc.) or calculated (α and β). By using registers, variations of the basic model can be easily explored, and the sensitivity to the input values can be measured.

NODE DATA—The wall temperature is set. Notice the reference to the register “twall.”

OPERATIONS—All submodels are built, and headers are written to the user files. FASTIC is called to initialize the pressure profile (although it is largely irrelevant), and the initial spatial temperature profile is established using calls to CHGLMP. Next, the transient integration is performed using FORWRD, and the summary user files are written.

CONTROL DATA—English units are chosen, with units of °F and psia. The values of OUTPUT and OUTPTF are required, but are set larger than the solution time, resulting in OUTPUT CALLS only before and after the transient. The transient duration (TIMEND) is set to 15 seconds.

FLOW DATA—Four fluid submodels are built. Three are built using lumped parameter heat transfer methods and varying spatial discretization: LINE20, LINE10, and LINE5. A variation of LINE5 is written using segment-oriented methods: LINE5S. The working fluid is the same for all submodels: 9718, meaning a simple incompressible water description that is provided later in the input file.

The names and types of the elements are as follows:

PLENUM 100	.inlet condition, temperature set to variable *Tinlet*
TANKs 1-N.	.tanks in the line, numbered from the inlet
STUBEs 1-N	.paths in the line
MFRSET 100.	.flowrate boundary condition at the end of the line
HTU(S) 1-N	.heat transfer ties to node WALL.1

The lines are generated using downstream-discretized LINE macros, and the ties are generated with the GENT macro. The values of pressure are arbitrary.

OUTPUT CALLS—Lump and tie tabulation routines are called for all submodels.

FPROP DATA—A very simple liquid water description is input, the purpose of which is to assure that density and specific heat stay constant. The use of registers in FPROP blocks is highly unusually although legal. Normally, the contents of an FPROP block are independent of the rest of the model such that the block can be reused in other models. Furthermore, changes to values of these registers during execution will be ignored.

H.4 Output Description

The user summary files and selected printings from the OUTPUT file are listed following the input file.

Warnings are produced which can be ignored for this model. Normally, plena represent stagnation states (LSTAT=STAG), but in this model static pressures (LSTAT=NORM) are desired instead (actually, the choice is largely irrelevant in this particular case). Another warning concerns the absence of compressibility data for the working fluid, which has been neglected. This lack causes choked flow calculations to be suspended, which again is of no relevance in this particular case, but which deserves a caution message since this conclusion will not be true in many other models.

The initial temperature profile for all models along with the final temperature profiles for each model are all plotted in Figure H-2. The match is very good for all models, even the relatively coarse 5 tank submodel LINE5. For the rest of the models, the differences are nearly indistinguishable at this scale. As will be shown later, the maximum error in any submodel at any location was 3%, which is well within the noise range of engineering uncertainties. For the 20 tank lumped-parameter model (LINE20) and the 5 tank segment-oriented model (LINE5S), the match is excellent.

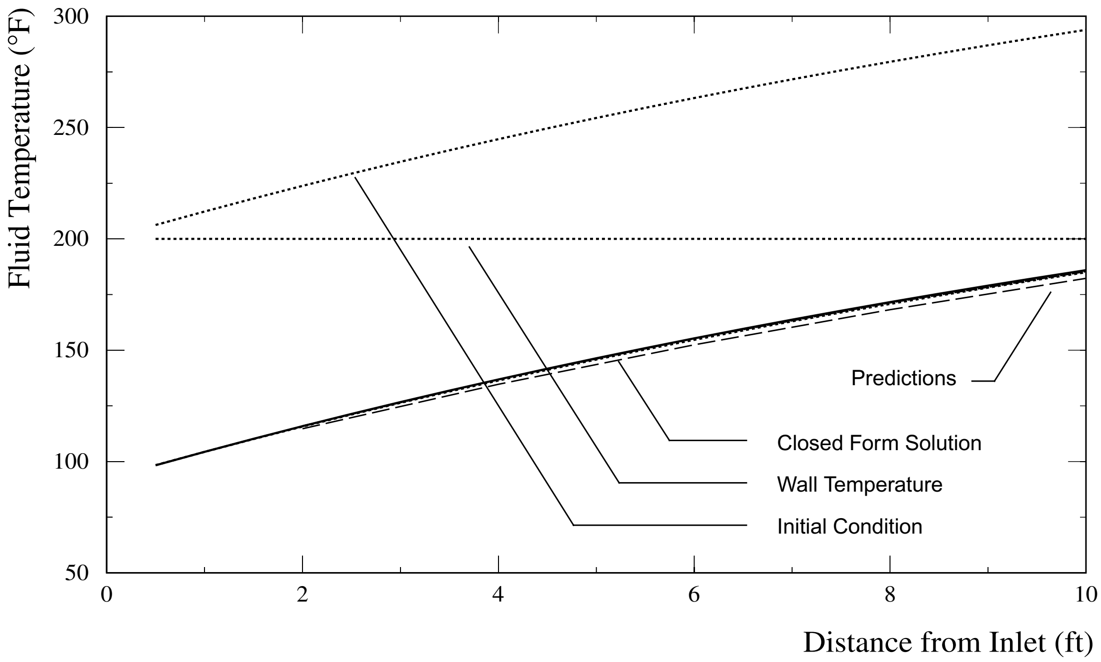

Figure H-2 Temperature Profiles for All Models

To better visualize the comparison between the closed form solution and the predictions, the difference in temperature between the closed form solution and the FLUINT predictions for each model are plotted in Figure H-3 For all cases, the temperature difference grows gradually along the length of the line, which is to be expected due to the flow-wise accumulation of error. The maximum error at the end of the 5 section lumped parameter model called LINE5 is 3.7 degrees. Since the temperature in that lump changed by about 110 degrees (in a mere 15 seconds), this represents a maximum error of 3.4% for a model that was acknowledged to exceed good modeling practices. Each time the spatial resolution was increased by a factor of two (in the submodels LINE10 and LINE20), the error diminished by the same factor. With lumped parameter methods, the aforementioned rules-of-thumb that led to a breakdown into 10 sections yielded very acceptable accuracies.

Even the 20 tank lumped parameter model (LINE20) was outperformed by the 5 tank segment-oriented model (LINE5S), which achieved the best accuracy of all. Curiously, the accumulation of error in the lumped parameter models seems to have an asymptotic limit, whereas the error in the segment-oriented model, while very small, appears to grow without bound.

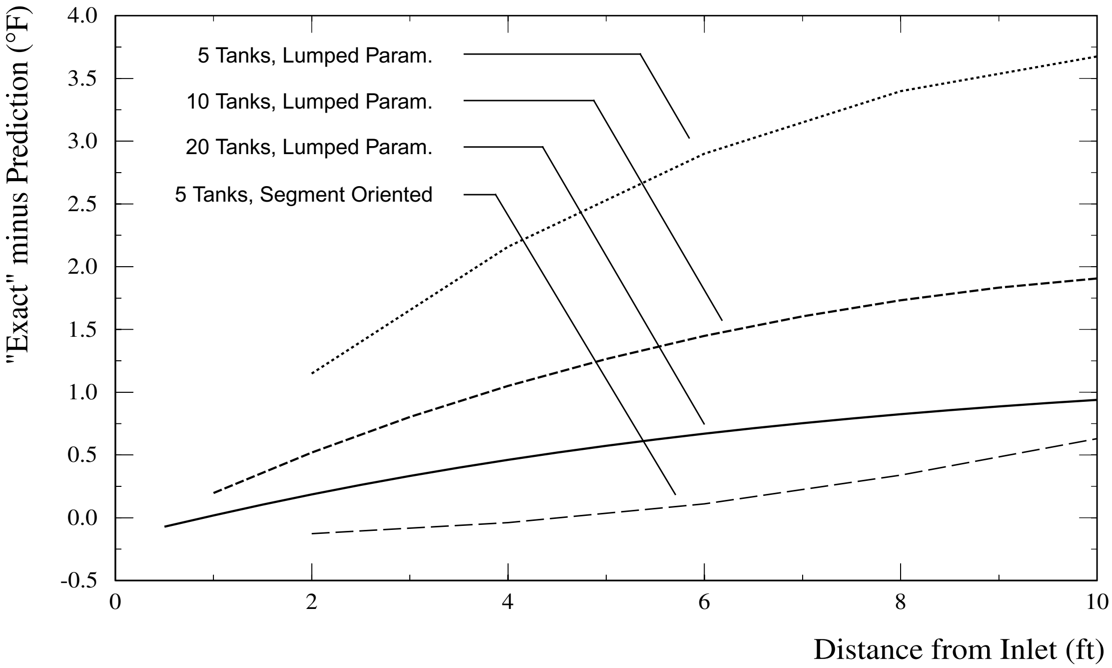

Figure H-3 Temperature Errors for All Models

The success of the segment-oriented ties in this example should be viewed with some caution. Their forte is single-phase incompressible flows with spatially-invariant wall temperatures and relatively constant fluid properties, all of which exist in by this example. In fact, for two-phase flows, the methods revert to those of lumped parameter ties. In most other cases, other important gradients will likely be present in fluid properties, wall temperatures, or even heat transfer coefficients. Capturing such gradients requires adequate resolution. Still, for preliminary design of single-phase heat exchangers, segment-oriented ties represent a significant tool for model reduction.

Input File

```
HEADER OPTIONS DATA
TITLE WATER LINE, COMPARISON WITH ANALYTIC RESULT
         MODEL            = WLINE
         OUTPUT           = waterline.out
         USER1            = waterline.comp
         USER2            = waterline.terr
         SPELLOFF
C
HEADER REGISTER DATA
C
C Fluid Cp
         cp       = 1.0
C Fluid Density
         den      = 62.4
C Mass Flowrate
         frate    = 1000.0
C Total Length

         length   = 10.0
C Pipe ID
         diam     = 1.0/12.0
C Heat transfer coef.
         htc      = 242.0
C Eigenvalues
         ALPHA    = 0.25*diam*cp*den/htc
         BETA     = frate*cp/(htc*pi*diam)
C Wall Temperature
         Twall    = 200.0
C Time point to use for comparison
         duration = 15.0/3600.0
C
C Inlet condition, a function of time (TIMEN)
         Tinlet    = Twall*EXP(-TIMEN/ALPHA)
C
HEADER NODE DATA,WALL
         -1,Twall,0.0      $ WALL BOUNDARY
C
```

```
HEADER OPERATIONS
BUILDF ALL
BUILD ALL
C
C PRINT OUT CP AND DENSITY, AND TIME/SPACE CONSTANTS
C
DEFMOD LINE20
         WRITE(NUSER1,100)CP,DEN,CP*DEN,ALPHA,BETA
100      FORMAT(1P,
     .  ’ Cp      : ’,G13.6,’ BTU/LBm-F’/
     .  ’ DEN     : ’,G13.6,’ LBm/FT3’/
     .  ’ Cp*DEN  : ’,G13.6,’ BTU/FT3-F’/
     .  ’ ALPHA   : ’,G13.6,’ HR’/
     .  ’ BETA    : ’,G13.6,’ FT’/)
         WRITE(NUSER1,101)
         WRITE(NUSER2,102)
101      FORMAT(//’ SEG NO.    DIST(FT)’,9X,’TINIT’,10X,’T EQN’
     .   ,10X,’T 20 ’,10X,’T 10 ’,10X,’T 5LP’,10X,’T 5SG’/)
102      FORMAT(//’ SEG NO.    DIST(FT)’,9X,’E 20’,10X,’E 10 ’
     .   ,10X,’E 5LP’,10X,’E 5SG’/)
C
         CALL FASTIC
C
C PRESSURES NOW STABLE: SET UP IC FOR TRANSIENT
DEFMOD WALL
         DO 5 I=1,5
                  DIST              = (length/5.0)*FLOAT(I)
                  TEMP              = Twall*(2.0-EXP(-DIST/BETA))
                  CALL CHGLMP(’LINE5’,I,’TL’,TEMP,’PL’)
                  CALL CHGLMP(’LINE5S’,I,’TL’,TEMP,’PL’)
5        CONTINUE
         DO 10 I=1,10
                  DIST              = (length/10.0)*FLOAT(I)
                  TEMP              = Twall*(2.0-EXP(-DIST/BETA))
                  CALL CHGLMP(’LINE10’,I,’TL’,TEMP,’PL’)
10       CONTINUE
         DO 20 I=1,20
                  DIST              = (length/20.0)*FLOAT(I)
                  TEMP              = Twall*(2.0-EXP(-DIST/BETA))
                  CALL CHGLMP(’LINE20’,I,’TL’,TEMP,’PL’)
20       CONTINUE
C
         CALL FORWRD
```

```
C
C FIND EXACT SOLUTION FOR COMPARISON
C
         DO 201 I=1,20
                  DIST  = 0.5 + 0.5*FLOAT(I-1)
                  TEMP  = T1*(1.0-EXP(-DIST/BETA) + EXP(-TIMEN/ALPHA))
                  TINIT = Twall*(2.0-EXP(-DIST/BETA))
                  TEMP1 = 0.
                  TEMP2 = 0.
                  TEMP3 = 0.
                  IF(MOD(I,2) .EQ. 0)THEN
                        II      = I/2
                        TEMP1   = GLOBAL.TL(INTLMP('LINE10',II))
                        IF(MOD(I,4) .EQ. 0) THEN
                                II      = I/4
                                TEMP2   = GLOBAL.TL(INTLMP('LINE5',II))
                                TEMP3   = GLOBAL.TL(INTLMP('LINE5S',II))
                        ENDIF
                  ENDIF
                  WRITE(NUSER1,200)I,DIST,TINIT,TEMP,
     .                GLOBAL.TL(INTLMP('LINE20',I)),TEMP1,TEMP2,TEMP3
                  IF(TEMP1 .EQ. 0.0) TEMP1 = TEMP
                  IF(TEMP2 .EQ. 0.0) TEMP2 = TEMP
                  IF(TEMP3 .EQ. 0.0) TEMP3 = TEMP
                  WRITE(NUSER2,200)I,DIST,
     .                     TEMP-GLOBAL.TL(INTLMP('LINE20',I)),
     .                     TEMP-TEMP1,TEMP-TEMP2,TEMP-TEMP3
F200              FORMAT(1X,I3,5X,1P,7G15.6)
201      CONTINUE
C
HEADER CONTROL DATA,GLOBAL
         NLOOPS             = 50
         UID                = ENG
C MAKE SURE TIME STEP COVERS CHANGING INLET PROFILE
         DTMAXF             = 1.0E-5
C 12.25 SEC IS TIME FOR FLAT-FRONT TO MOVE ALL THE WAY THROUGH
         TIMEND             = duration
         OUTPTF             = 1.0
         OUTPUT             = 1.0
C
```

```
HEADER FLOW DATA,LINE5,FID=9718
PA DEF, FR = frate
LU DEF, TL= Twall, PL= 100.,XL = 0.0
LU PLEN,100                                      $ UPSTREAM PLENUM
         TL        = Tinlet
PA CONN,100,5,100, DEV = MFRSET$ SET FLOWRATE
M LINE,1,D,1,1,100,NSEG    = 5
         TLENT     = length,         DHS       = diam
         PA        = STUBE, UPF      = 0.0
M GENT,2,HTU,1,1,WALL.1,N=5,NINC= 0
         UA        = htc*pi*diam*(length/5.0)
C
HEADER FLOW DATA,LINE10,FID=9718
PA DEF, FR = frate
LU DEF, TL= Twall, PL= 100.,XL = 0.0
LU PLEN,100                                      $ UPSTREAM PLENUM
         TL        = Tinlet
PA CONN,100,10,100, DEV = MFRSET$ SET FLOWRATE
M LINE,1,D,1,1,100,NSEG    = 10
         TLENT     = length,         DHS       = diam
         PA        = STUBE, UPF      = 0.0
M GENT,2,HTU,1,1,WALL.1,N=10,NINC= 0
         UA        = htc*pi*diam*(length/10.0)
C
HEADER FLOW DATA,LINE20,FID=9718
PA DEF, FR = frate
LU DEF, TL= Twall, PL= 100.,XL = 0.0
LU PLEN,100                                      $ UPSTREAM PLENUM
         TL        = Tinlet
PA CONN,100,20,100, DEV = MFRSET$ SET FLOWRATE
M LINE,1,D,1,1,100,NSEG    = 20
         TLENT     = length,         DHS       = diam
         PA        = STUBE, UPF      = 0.0
M GENT,2,HTU,1,1,WALL.1,N=20,NINC= 0
         UA        = htc*pi*diam*(length/20.0)
C
HEADER FLOW DATA,LINE5S,FID=9718
PA DEF, FR = frate
LU DEF, TL= Twall, PL= 100.,XL = 0.0
LU PLEN,100                                      $ UPSTREAM PLENUM
         TL        = Tinlet
PA CONN,100,5,100, DEV = MFRSET$ SET FLOWRATE
M LINE,1,D,1,1,100,NSEG    = 5
         TLENT     = length,         DHS       = diam
         PA        = STUBE, UPF      = 0.0
M GENT,2,HTUS,1,1,WALL.1,N=5,NINC= 0
         UA        = htc*pi*diam*(length/5.0)
```

```
HEADER OUTPUT CALLS, LINE10
         CALL LMPTAB('ALL')
         CALL TIETAB('ALL')
C
HEADER FPROP DATA,9718,ENG,-460.0
C SIMPLIFIED WATER
         V        = 2.32
         K        = 0.350
         CP       = cp
         D        = den
END OF DATA
```

Processor Output

```
CP      :   1.00000     BTU/LBM-F
DEN     :   62.4000     LBM/FT3
CP*DEN  :   62.4000     BTU/FT3-F
ALPHA   :  5.371901E-03 HR
BETA    :   15.7840     FT


SEG NO.    DIST(FT)         TINIT          T EQN          T 20           T 10           T 5LP          T 5SG

  1        0.500000        206.236        98.3179        98.3894        0.00000        0.00000        0.00000
  2         1.00000        212.278        104.360        104.341        104.163        0.00000        0.00000
  3         1.50000        218.131        110.213        110.109        0.00000        0.00000        0.00000
  4         2.00000        223.802        115.884        115.698        115.365        114.735        116.011
  5         2.50000        229.296        121.378        121.116        0.00000        0.00000        0.00000
  6         3.00000        234.619        126.701        126.368        125.898        0.00000        0.00000
  7         3.50000        239.776        131.858        131.458        0.00000        0.00000        0.00000
  8         4.00000        244.772        136.854        136.392        135.803        134.695        136.893
  9         4.50000        249.612        141.694        141.175        0.00000        0.00000        0.00000
 10         5.00000        254.301        146.383        145.810        145.118        0.00000        0.00000
 11         5.50000        258.844        150.926        150.303        0.00000        0.00000        0.00000
 12         6.00000        263.246        155.328        154.658        153.879        152.427        155.217
 13         6.50000        267.510        159.592        158.879        0.00000        0.00000        0.00000
 14         7.00000        271.641        163.723        162.970        162.119        0.00000        0.00000
 15         7.50000        275.644        167.725        166.935        0.00000        0.00000        0.00000
 16         8.00000        279.521        171.603        170.778        169.870        168.205        171.264
 17         8.50000        283.278        175.360        174.502        0.00000        0.00000        0.00000
 18         9.00000        286.917        178.999        178.112        177.166        0.00000        0.00000
 19         9.50000        290.443        182.525        181.611        0.00000        0.00000        0.00000
 20         10.0000        293.860        185.941        185.003        184.035        182.266        185.312
```

```
SEG NO.    DIST(FT)         E 20          E 10           E 5LP          E 5SG

  1        0.500000      -7.148743E-02    0.00000        0.00000        0.00000
  2         1.00000       1.828766E-02   0.196754        0.00000        0.00000
  3         1.50000       0.104546        0.00000        0.00000        0.00000
  4         2.00000       0.185646       0.519264        1.14878      -0.126976
  5         2.50000       0.261810        0.00000        0.00000        0.00000
  6         3.00000       0.332901       0.802811        0.00000        0.00000
  7         3.50000       0.399292        0.00000        0.00000        0.00000
  8         4.00000       0.461319        1.05031        2.15883      -3.898621E-02
  9         4.50000       0.519058        0.00000        0.00000        0.00000
 10         5.00000       0.573151        1.26474        0.00000        0.00000
 11         5.50000       0.623154        0.00000        0.00000        0.00000
 12         6.00000       0.669830        1.44864        2.90018       0.110443
 13         6.50000       0.713120        0.00000        0.00000        0.00000
 14         7.00000       0.753250        1.60432        0.00000        0.00000
 15         7.50000       0.790665        0.00000        0.00000        0.00000
 16         8.00000       0.825058        1.73253        3.39830       0.339401
 17         8.50000       0.857239        0.00000        0.00000        0.00000
 18         9.00000       0.886993        1.83322        0.00000        0.00000
 19         9.50000       0.914001        0.00000        0.00000        0.00000
 20         10.0000       0.938629        1.90622        3.67496       0.629730
```

```
 FLUID SUBMODEL NAME = LINE5   ; FLUID NO. = 9718


        MAX TIME STEP =  2.777778E+08 ; LIMITING TANK =        1     REASON  = NO LIMIT: TIME INDEPENDENT
        LAST TIME STEP =  6.028451E-06 VS. DTMAXF/DTMINF =  1.000000E-05 /   0.00000    ;   AVERAGE TIME STEP =  9.602842E-06
        PROBLEM TIME                  TIMEN  = 4.166667E-03 VS. TIMEND  = 4.166667E-03


                                    LUMP PARAMETER TABULATION FOR SUBMODEL LINE5

  LUMP  TYPE     TEMP        PRESSURE     QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

     1  TANK    114.7         100.0       0.000        0.000        62.40        574.7        1.0791E+04   0.000       -1.1863E+04
     2  TANK    134.7         99.99       0.000        0.000        62.40        594.7        8262.        0.000       -1.1698E+04
     3  TANK    152.4         99.99       0.000        0.000        62.40        612.4        6015.        0.000       -1.1718E+04
     4  TANK    168.2         99.98       0.000        0.000        62.40        628.2        4016.        0.000       -1.1762E+04
     5  TANK    182.3         99.98       0.000        0.000        62.40        642.2        2234.        0.000       -1.1828E+04
   100  PLEN    92.08         100.0       0.000        0.000        62.40        552.0        0.000        0.000        9.0185E+04




                           SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE    30

MODEL = WLINE                          WATER LINE, COMPARISON WITH ANALYTIC RESULT
  FORWRD


 FLUID SUBMODEL NAME = LINE5S  ; FLUID NO. = 9718


        MAX TIME STEP =  2.777778E+08 ; LIMITING TANK =        1     REASON  = NO LIMIT: TIME INDEPENDENT
        LAST TIME STEP =  6.028451E-06 VS. DTMAXF/DTMINF =  1.000000E-05 /   0.00000    ;   AVERAGE TIME STEP =  9.602842E-06
        PROBLEM TIME                  TIMEN  = 4.166667E-03 VS. TIMEND  = 4.166667E-03


                                    LUMP PARAMETER TABULATION FOR SUBMODEL LINE5S

  LUMP  TYPE     TEMP        PRESSURE     QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

     1  TANK    116.0         100.0       0.000        0.000        62.40        576.0        1.2082E+04   0.000       -1.1847E+04
     2  TANK    136.9         99.99       0.000        0.000        62.40        596.9        9243.        0.000       -1.1638E+04
     3  TANK    155.2         99.99       0.000        0.000        62.40        615.2        6756.        0.000       -1.1568E+04
     4  TANK    171.3         99.98       0.000        0.000        62.40        631.2        4570.        0.000       -1.1477E+04
     5  TANK    185.3         99.98       0.000        0.000        62.40        645.3        2639.        0.000       -1.1409E+04
   100  PLEN    92.08         100.0       0.000        0.000        62.40        552.0        0.000        0.000        9.3230E+04
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 FLUID SUBMODEL NAME = LINE20  ; FLUID NO. = 9718


        MAX TIME STEP =  2.777778E+08 ; LIMITING TANK =        1     REASON  = NO LIMIT: TIME INDEPENDENT
        LAST TIME STEP =  6.028451E-06 VS. DTMAXF/DTMINF =  1.000000E-05 /   0.00000    ;   AVERAGE TIME STEP =  9.602842E-06
        PROBLEM TIME                  TIMEN  = 4.166667E-03 VS. TIMEND  = 4.166667E-03


                                    LUMP PARAMETER TABULATION FOR SUBMODEL LINE20

  LUMP  TYPE     TEMP        PRESSURE     QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

     1  TANK    98.39         100.0       0.000        0.000        62.40        558.4        3215.        0.000        -3092.
     2  TANK    104.3         100.0       0.000        0.000        62.40        564.3        3027.        0.000        -2925.
     3  TANK    110.1         100.0       0.000        0.000        62.40        570.1        2844.        0.000        -2923.
     4  TANK    115.7         100.0       0.000        0.000        62.40        575.7        2667.        0.000        -2923.
     5  TANK    121.1         100.0       0.000        0.000        62.40        581.1        2496.        0.000        -2922.
     6  TANK    126.4         99.99       0.000        0.000        62.40        586.3        2329.        0.000        -2922.
     7  TANK    131.5         99.99       0.000        0.000        62.40        591.4        2168.        0.000        -2922.
     8  TANK    136.4         99.99       0.000        0.000        62.40        596.4        2012.        0.000        -2922.
     9  TANK    141.2         99.99       0.000        0.000        62.40        601.1        1860.        0.000        -2922.
    10  TANK    145.8         99.99       0.000        0.000        62.40        605.8        1713.        0.000        -2922.
    11  TANK    150.3         99.99       0.000        0.000        62.40        610.3        1571.        0.000        -2922.
    12  TANK    154.7         99.99       0.000        0.000        62.40        614.6        1433.        0.000        -2922.
    13  TANK    158.9         99.99       0.000        0.000        62.40        618.8        1299.        0.000        -2922.
    14  TANK    163.0         99.99       0.000        0.000        62.40        622.9        1170.        0.000        -2921.
    15  TANK    166.9         99.99       0.000        0.000        62.40        626.9        1044.        0.000        -2921.
    16  TANK    170.8         99.98       0.000        0.000        62.40        630.7        922.4        0.000        -2921.
    17  TANK    174.5         99.98       0.000        0.000        62.40        634.5        804.4        0.000        -2920.
    18  TANK    178.1         99.98       0.000        0.000        62.40        638.1        690.1        0.000        -2920.
    19  TANK    181.6         99.98       0.000        0.000        62.40        641.6        579.2        0.000        -2920.
    20  TANK    185.0         99.98       0.000        0.000        62.40        645.0        471.8        0.000        -2920.
   100  PLEN    92.08         100.0       0.000        0.000        62.40        552.0        0.000        0.000        9.2921E+04
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                           SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE    14

MODEL = WLINE                         WATER LINE, COMPARISON WITH ANALYTIC RESULT
  FASTIC


 FLUID SUBMODEL NAME = LINE20  ; FLUID NO. = 9718


        LOOPCT =    10
        CONVERGENCE STATUS = SUBMODEL CONVERGED AS OF      10 ITERATIONS


                                    LUMP PARAMETER TABULATION FOR SUBMODEL LINE20

  LUMP  TYPE     TEMP       PRESSURE     QUALITY      VOID FRACT.  DENSITY      ENTHALPY     HEAT RATE    MASS RATE    ENERGY RATE

     1  TANK    200.0        100.0        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
     2  TANK    200.0        100.0        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
     3  TANK    200.0        100.0        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
     4  TANK    200.0        100.0        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
     5  TANK    200.0        100.0        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
     6  TANK    200.0        99.99        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
     7  TANK    200.0        99.99        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
     8  TANK    200.0        99.99        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
     9  TANK    200.0        99.99        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
    10  TANK    200.0        99.99        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
    11  TANK    200.0        99.99        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
    12  TANK    200.0        99.99        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
    13  TANK    200.0        99.99        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
    14  TANK    200.0        99.99        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
    15  TANK    200.0        99.99        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
    16  TANK    200.0        99.98        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
    17  TANK    200.0        99.98        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
    18  TANK    200.0        99.98        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
    19  TANK    200.0        99.98        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
    20  TANK    200.0        99.98        0.000        0.000        62.40        660.0      -1.9335E-03    0.000      -1.9335E-03
   100  PLEN    200.0        100.0        0.000        0.000        62.40        660.0        0.000        0.000        0.000
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                           SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE    31

MODEL = WLINE                         WATER LINE, COMPARISON WITH ANALYTIC RESULT
  FORWRD


 FLUID SUBMODEL NAME = LINE5   ; FLUID NO. = 9718


        MAX TIME STEP =  2.777778E+08 ; LIMITING TANK =       1    REASON   = NO LIMIT: TIME INDEPENDENT
        LAST TIME STEP =  6.028451E-06 VS. DTMAXF/DTMINF =  1.000000E-05 /   0.00000    ;   AVERAGE TIME STEP =  9.602842E-06
        PROBLEM TIME                  TIMEN  = 4.166667E-03 VS. TIMEND  = 4.166667E-03


                                    TIE PARAMETER TABULATION FOR SUBMODEL LINE5

  TIE   TYPE      UA          QTIE         LUMP     TEF           NODE              TEMP.    2P  PATH 1    FRACT   PATH 2    FRACT

     1  HTU     126.7       1.0791E+04       1    114.7      WALL.1                200.0
     2  HTU     126.7        8262.           2    134.7      WALL.1                200.0
     3  HTU     126.7        6015.           3    152.4      WALL.1                200.0
     4  HTU     126.7        4016.           4    168.2      WALL.1                200.0
     5  HTU     126.7        2234.           5    182.3      WALL.1                200.0


                           SYSTEMS IMPROVED NUMERICAL DIFFERENCING ANALYZER WITH FLUID INTEGRATOR           PAGE    34

MODEL = WLINE                         WATER LINE, COMPARISON WITH ANALYTIC RESULT
  FORWRD


 FLUID SUBMODEL NAME = LINE5S  ; FLUID NO. = 9718


        MAX TIME STEP =  2.777778E+08 ; LIMITING TANK =       1    REASON   = NO LIMIT: TIME INDEPENDENT
        LAST TIME STEP =  6.028451E-06 VS. DTMAXF/DTMINF =  1.000000E-05 /   0.00000    ;   AVERAGE TIME STEP =  9.602842E-06
        PROBLEM TIME                  TIMEN  = 4.166667E-03 VS. TIMEND  = 4.166667E-03


                                    TIE PARAMETER TABULATION FOR SUBMODEL LINE5S

   TIE   TYPE      UA          QTIE         LUMP     TEF           NODE              TEMP.    2P  PATH 1    FRACT   PATH 2    FRACT

     1  HTUS    126.7       1.2082E+04       1    116.0      WALL.1                200.0
     2  HTUS    126.7        9243.           2    136.9      WALL.1                200.0
     3  HTUS    126.7        6756.           3    155.2      WALL.1                200.0
     4  HTUS    126.7        4570.           4    171.3      WALL.1                200.0
     5  HTUS    126.7        2639.           5    185.3      WALL.1                200.0
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FLUID SUBMODEL NAME = LINE20  ; FLUID NO. = 9718


       MAX TIME STEP =  2.777778E+08 ; LIMITING TANK =       1    REASON  = NO LIMIT: TIME INDEPENDENT
       LAST TIME STEP =  6.028451E-06 VS. DTMAXF/DTMINF =  1.000000E-05 /   0.00000    ;   AVERAGE TIME STEP =  9.602842E-06
       PROBLEM TIME                   TIMEN  = 4.166667E-03 VS. TIMEND  = 4.166667E-03


                                   TIE PARAMETER TABULATION FOR SUBMODEL LINE20

 TIE   TYPE      UA          QTIE         LUMP      TEF           NODE               TEMP.    2P  PATH 1    FRACT   PATH 2    FRACT

    1  HTU     31.68        3215.           1     98.39      WALL.1                200.0
    2  HTU     31.68        3027.           2     104.3      WALL.1                200.0
    3  HTU     31.68        2844.           3     110.1      WALL.1                200.0
    4  HTU     31.68        2667.           4     115.7      WALL.1                200.0
    5  HTU     31.68        2496.           5     121.1      WALL.1                200.0
    6  HTU     31.68        2329.           6     126.4      WALL.1                200.0
    7  HTU     31.68        2168.           7     131.5      WALL.1                200.0
    8  HTU     31.68        2012.           8     136.4      WALL.1                200.0
    9  HTU     31.68        1860.           9     141.2      WALL.1                200.0
   10  HTU     31.68        1713.          10     145.8      WALL.1                200.0
   11  HTU     31.68        1571.          11     150.3      WALL.1                200.0
   12  HTU     31.68        1433.          12     154.7      WALL.1                200.0
   13  HTU     31.68        1299.          13     158.9      WALL.1                200.0
   14  HTU     31.68        1170.          14     163.0      WALL.1                200.0
   15  HTU     31.68        1044.          15     166.9      WALL.1                200.0
   16  HTU     31.68        922.4          16     170.8      WALL.1                200.0
   17  HTU     31.68        804.4          17     174.5      WALL.1                200.0
   18  HTU     31.68        690.1          18     178.1      WALL.1                200.0
   19  HTU     31.68        579.2          19     181.6      WALL.1                200.0
   20  HTU     31.68        471.8          20     185.0      WALL.1                200.0
```

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