Overview of GFSSP v605

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- Additional Capabilities
- VTASC Improvement
- New Example Problems
- Summary & Future Work
- Acknowledgement

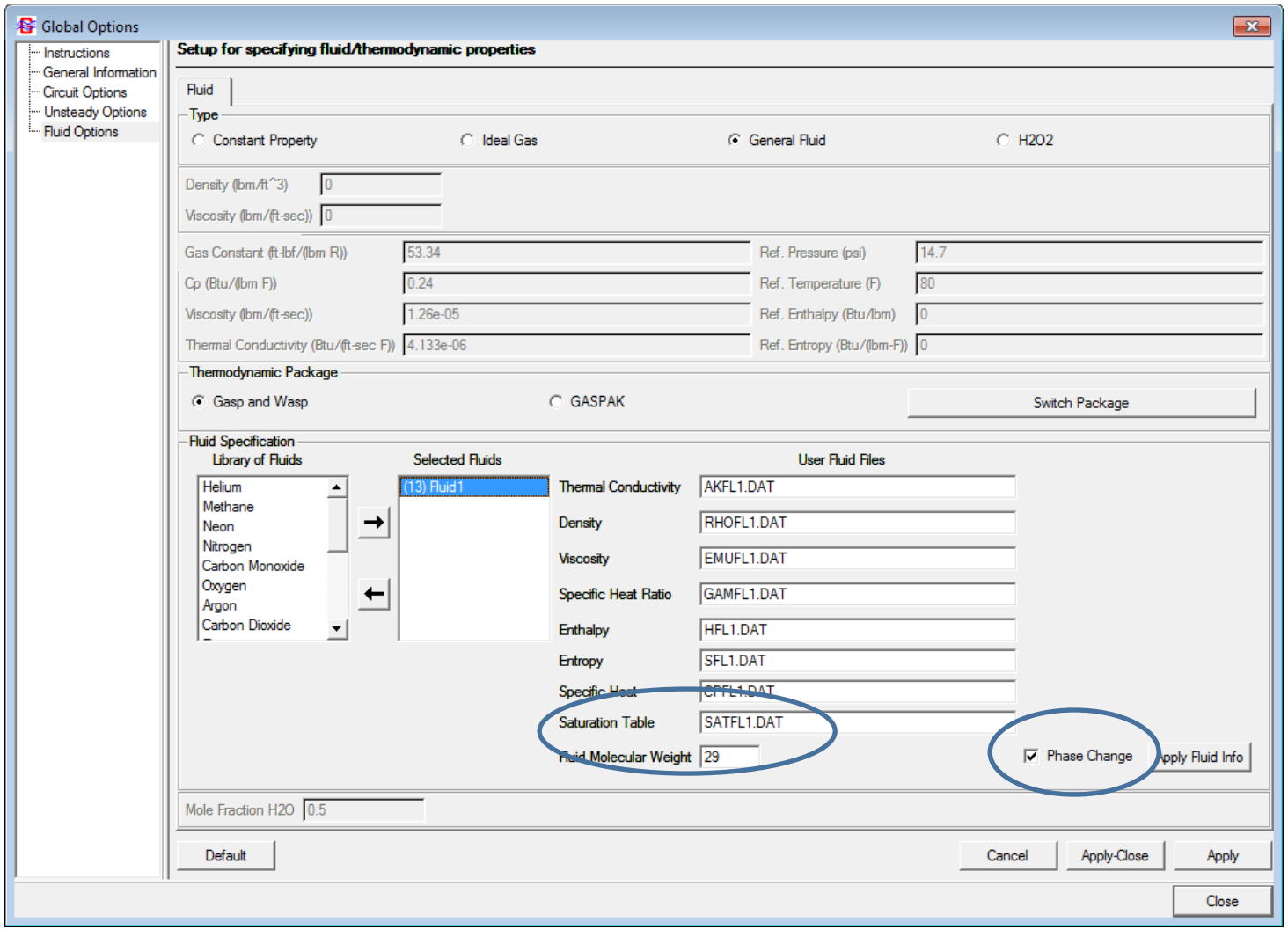
Additional Capabilities in Version 605

- GFSSP
  - Expansion of User-Defined Fluid Tables
  - Utility Subroutines for Calculating Fluid Properties
  - Efficiency Improvements in Indexing Subroutines
  - Five New Example Problems
  - Minor Bug Fixes
- VTASC
  - Expanded Tool Tips
  - Show Text Description on Canvas
  - Both Pressure Regulator and Flow Regulator in Same Model
  - Choice of Inertia Formulation

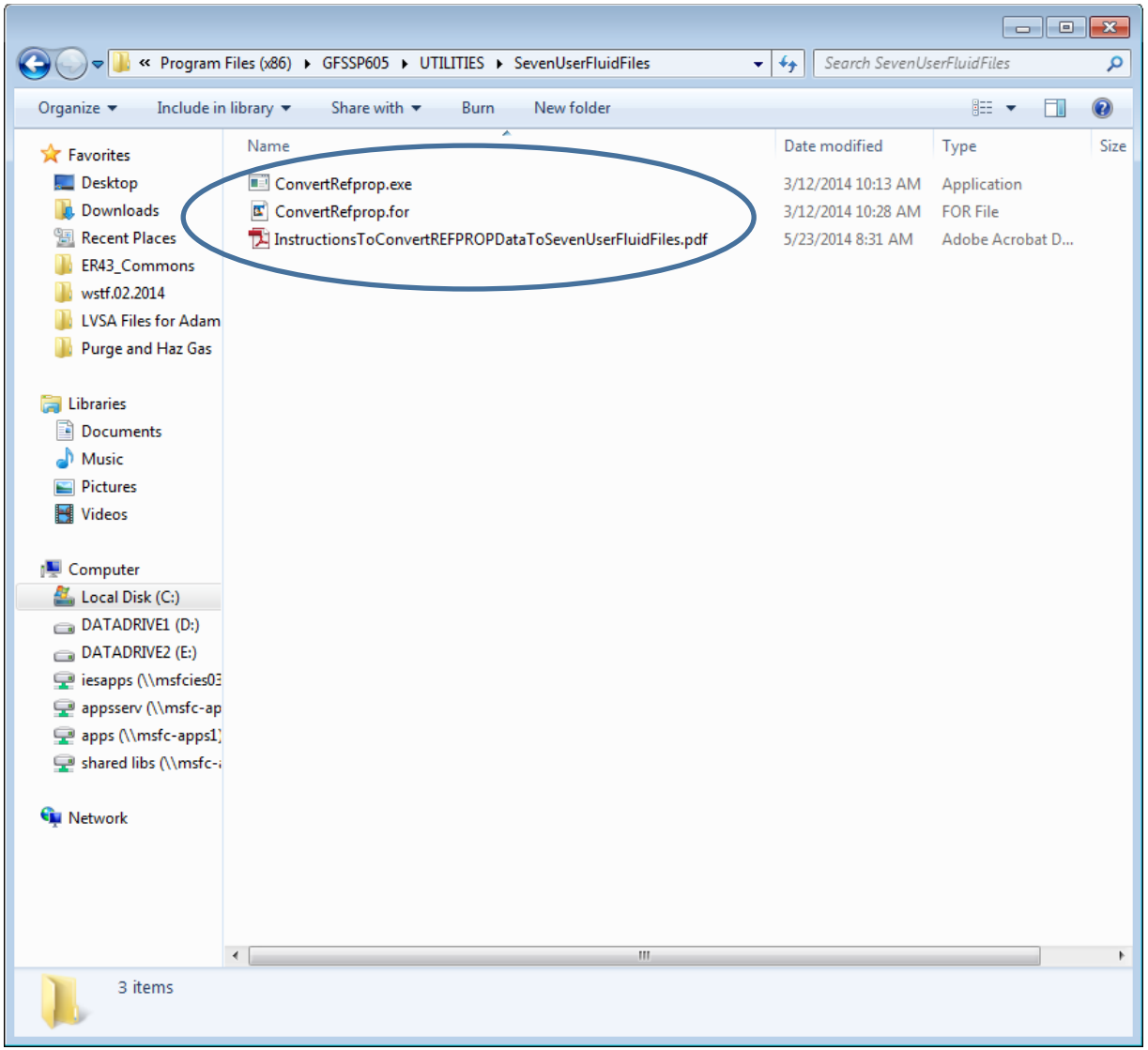
User-Defined Fluid Tables

- User-defined fluids may now be used in both steady-state and transient models.
- Saturation and phase change of user-defined fluids can be added by providing an extra table of saturation properties.
- Utility programs are provided in the GFSSP installation directory to convert REFPROP fluid output into GFSSP user-defined fluid tables.

User-Defined Fluid Tables



User-Defined Fluid Tables



Fluid Property Subroutines

- User subroutines may sometimes require fluid properties at pressures or temperatures other than the node P/T. For example, some convection correlations use properties evaluated at the film temperature.
- Four new utility subroutines return fluid properties as functions of P/T, P/H, P/S, or Psat.
- The subroutines call GASP/WASP, RP-1 tables, and User-Defined Fluid Tables. (GASPAK is not supported at this time.)

Fluid Property Subroutines

```
      CALL PROPS_PT(I_NFLUID, Z_P, Z_T, Z_RHO, Z_H,
     +              Z_CP, Z_CV, Z_S, Z_GAMMA, Z_MU
     +              Z_K, I_KR, Z_XV)
```

- Input
  - I_NFLUID: Fluid ID code (see next slide)
  - Z_P: Pressure
  - Z_T: Temperature
- Output
  - Z_RHO: Density
  - Z_H: Enthalpy
  - Z_CP, Z_CV: Specific heats
  - Z_S: Entropy
  - Z_GAMMA: Ratio of specific heats
  - Z_MU: Viscosity
  - Z_K: Thermal conductivity
  - I_KR: Fluid phase code (0 unknown; 1 saturated; 2 liquid; 3 gas)
  - Z_XV: Quality (vapor mass fraction)

Fluid Property Subroutines

Property	English Units
Pressure (P)	Psf
Temperature (T)	°R
Conductivity (k)	BTU/ft-s-R
Density (ρ)	lb/ft^3
Viscosity (μ)	lb/ft-s
Specific Heat Ratio (γ)	Dimensionless
Enthalpy (H)	BTU/lb
Entropy (S)	BTU/lb-R
Specific Heat (Cp)	BTU/lb-R
Specific Heat (Cv)	BTU/lb-R

ID Number	Fluid	Pcrit (psia)
1	GASP He	33.0
2	GASP CH4	671.1
3	GASP Ne	384.9
4	GASP N2	495.6
5	GASP CO	507.4
6	GASP O2	737.2
7	GASP Ar	705.6
8	GASP CO2	1070.9
9	GASP F2	756.4
10	GASP H2	187.5
11	WASP H2O	3204.0
12	RP-1 Tables	
37	User Fluid 1 Tables	
38	User Fluid 2 Tables	
39	User Fluid 3 Tables	

Fluid Property Subroutines

```
 CALL PROPS_PH(I_NFLUID, Z_P, Z_T, Z_RHO, Z_H, Z_CP, Z_CV,
+        Z_S, Z_GAMMA, Z_MU, Z_K, I_KR, Z_XV,
+        Z_RHOL, Z_HL, Z_CPL, Z_CVL, Z_SL, Z_GAMMAL, Z_MUL, Z_KL,
+        Z_RHOV, Z_HV, Z_CPV, Z_CVV, Z_SV, Z_GAMMAV, Z_MUV, Z_KV)

 CALL PROPS_PS(I_NFLUID, Z_P, Z_T, Z_RHO, Z_H, Z_CP, Z_CV,
+        Z_S, Z_GAMMA, Z_MU, Z_K, I_KR, Z_XV,
+        Z_RHOL, Z_HL, Z_CPL, Z_CVL, Z_SL, Z_GAMMAL, Z_MUL, Z_KL,
+        Z_RHOV, Z_HV, Z_CPV, Z_CVV, Z_SV, Z_GAMMAV, Z_MUV, Z_KV)
```

- Input
  - I_NFLUID: Fluid ID code
  - Z_P: Pressure
  - Z_H or Z_S: Enthalpy or Entropy
- Output
  - Similar to PROPS_PT
  - If the fluid is saturated (I_KR = 1), properties suffixed in “L” or “V” are the properties of the pure liquid or vapor. The other properties are quality-weighted averages of the two-phase mixture.
  - PROPS_PS is for GASP/WASP fluids only.

Fluid Property Subroutines

```
 CALL PROPS_PSATX(I_NFLUID, Z_P, Z_T, Z_RHO, Z_H, Z_CP, Z_CV,
+        Z_S, Z_GAMMA, Z_MU, Z_K, I_KR, Z_XV,
+        Z_RHOL, Z_HL, Z_CPL, Z_CVL, Z_SL, Z_GAMMAL, Z_MUL, Z_KL,
+        Z_RHOV, Z_HV, Z_CPV, Z_CVV, Z_SV, Z_GAMMAV, Z_MUV, Z_KV)
```

- Input
  - I_NFLUID: Fluid ID code
  - Z_P: Saturation pressure
  - Z_XV: Quality
- Output
  - Z_T: Saturation temperature
  - PROPS_PSATX is for GASP/WASP fluids only.
  - If the input saturation pressure is greater than P_{crit}, an error message is returned.

New Example Problems

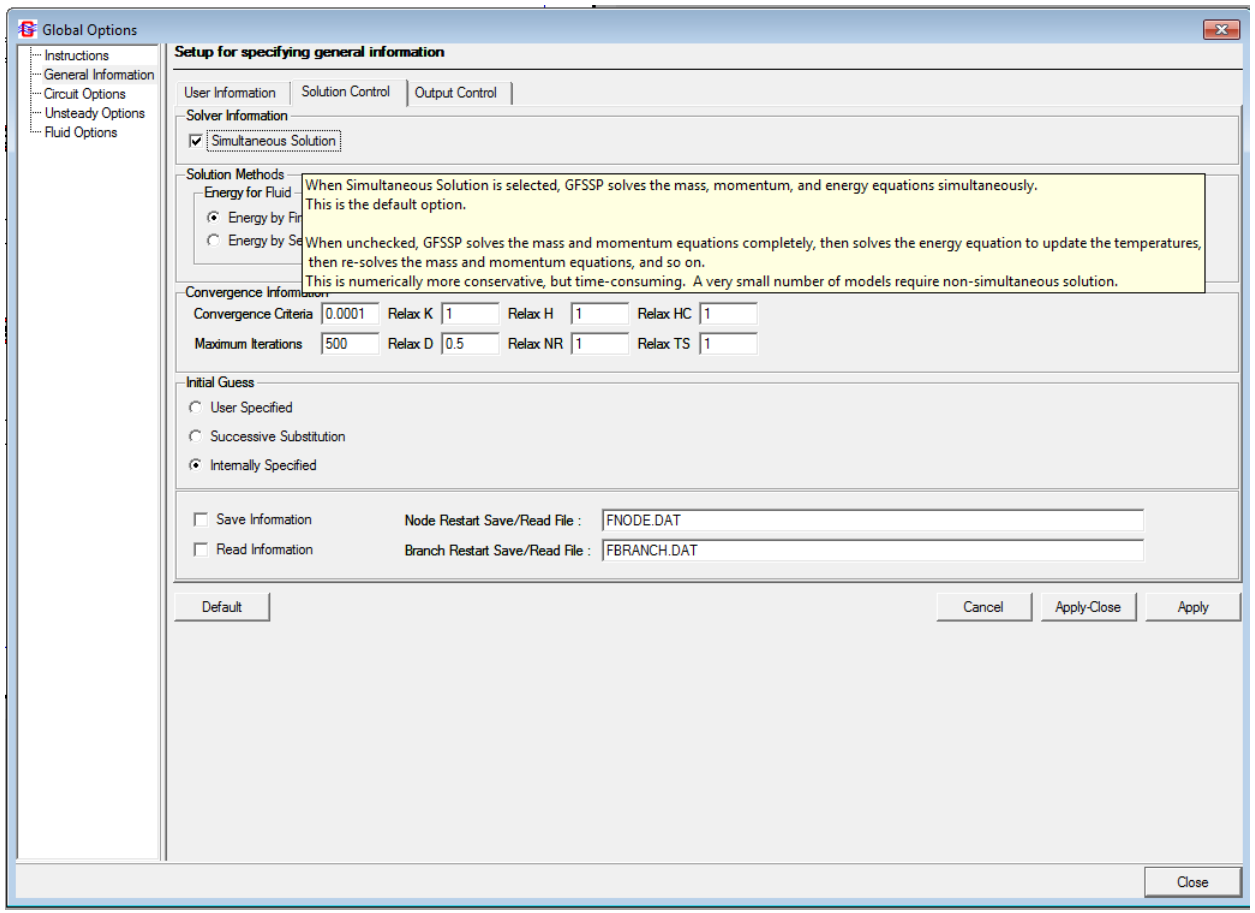
- Ex26: Fluid Transient in Pipes Due to Sudden Opening of Valve
  - Models Georgia Tech experimental study
- Ex27: Boiling Water Reactor
  - Demonstrates use of User-Defined Fluid Tables with Phase Change
- Ex28: No-Vent Tank Fill and Chill
  - Models K-Site Test Facility Data
- Ex29: Self-Pressurization of a Cryogenic Propellant Tank Due to Boil-Off
  - Includes MLI User Subroutine to Model MHTB
- Ex30: Modeling Solid Propellant Ballistic
  - Demonstrates User Subroutine to Model Mass Source

Minor Bug Fixes

- Miropolskii correlation was calculating unrealistically low values of the convection coefficient when the fluid was pure liquid. (Two-phase and pure vapor flows were correct.)
- For steady-state models with 1st Law Energy Equation, printed entropy was for initial guess P/T, not solution P/T.
- In transient models, Fixed Flow Rate branch area was not converted from in^2 to ft^2

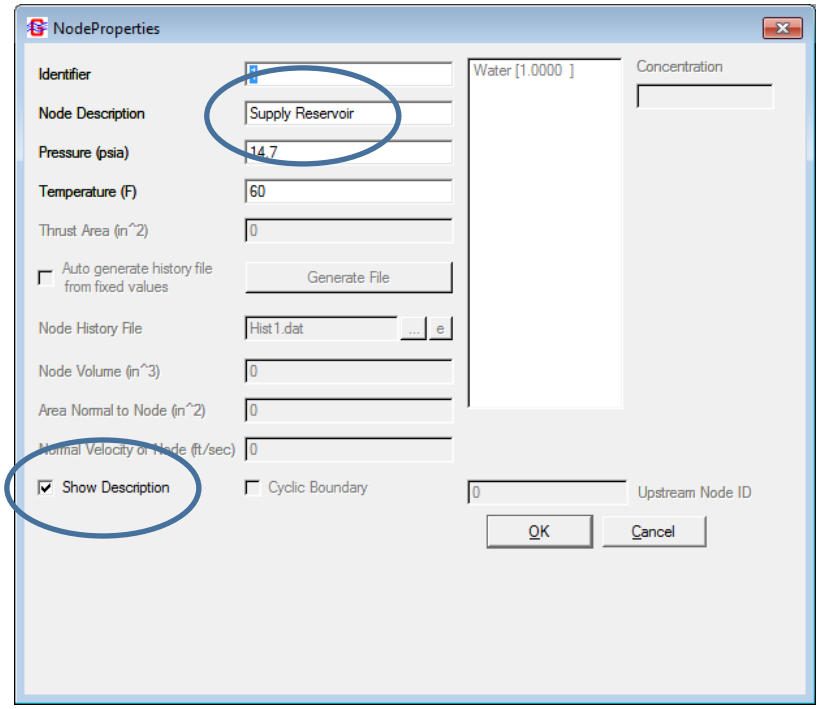
VTASC Improvements

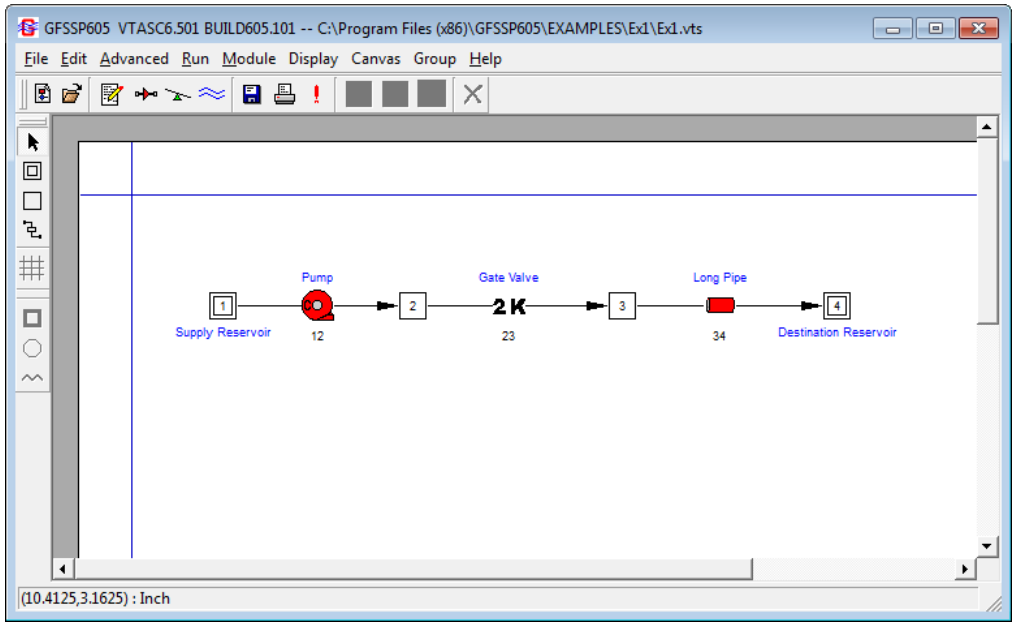
Expanded tool-tips



VTASC Improvements

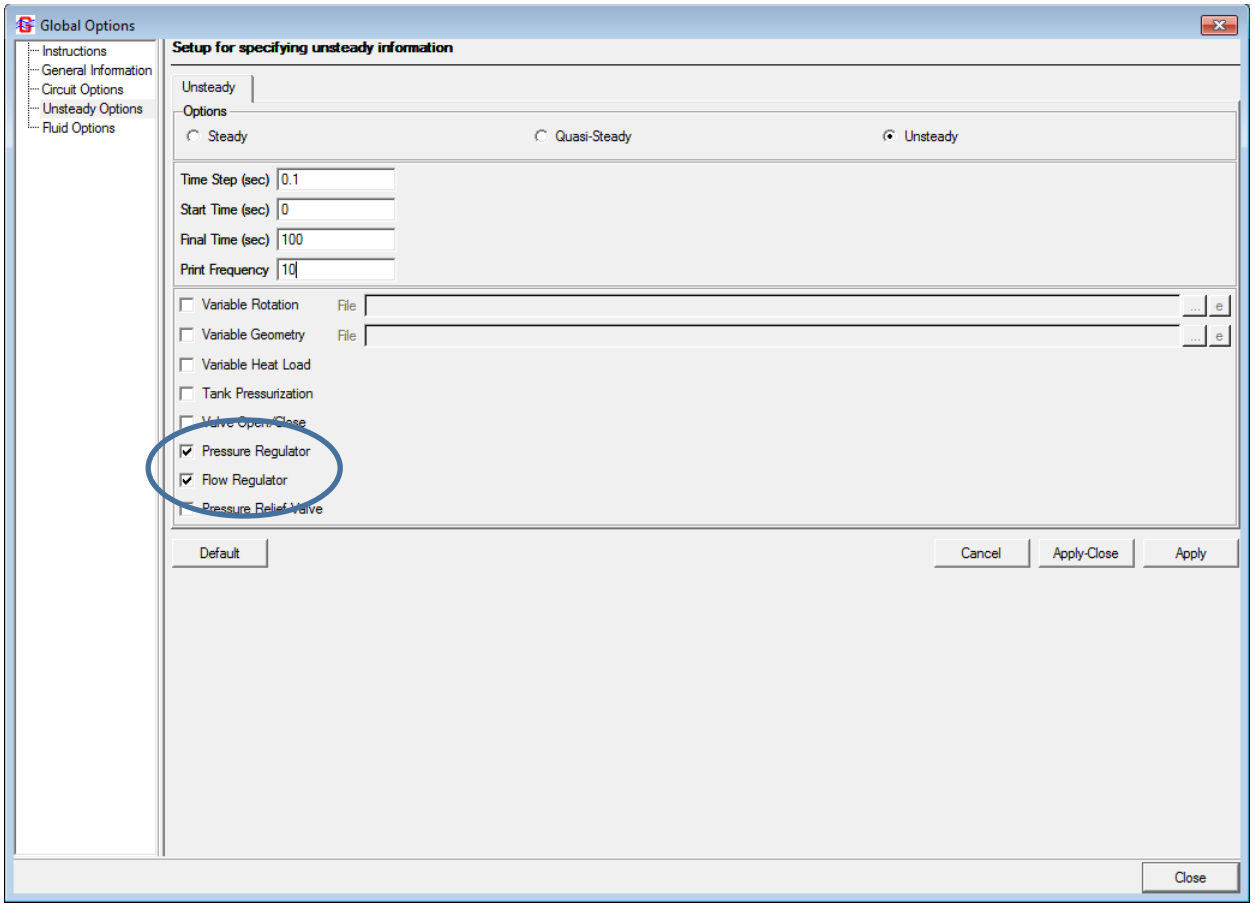
Show Text Description on Canvas





VTASC Improvements

Can Have Both Pressure and Flow Regulator in Same Model



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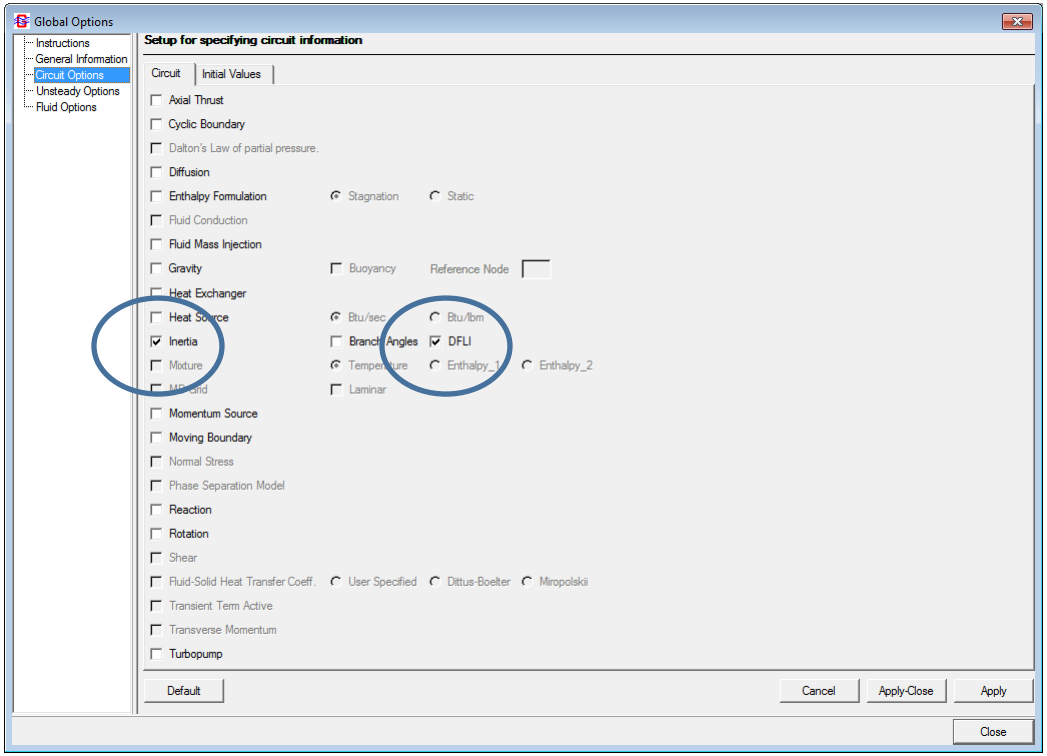
VTASC Improvements

Choice of Inertia Formulation



- DFLI (Differential Formulation for Longitudinal Inertia) writes the inertia term of the momentum equation as $m_{ij}\, d(m/\rho A)$.
- When DFLI is unchecked, GFSSP reverts to the original formulation: $m_{ij}\,(u_{upstream} - u_{ij})$
- DFLI has been GFSSP's default for many years. It could only be disabled by user subroutine.
- If a pre-v605 model with the inertia term activated gives different results when run with v605, verify that DFLI is checked.

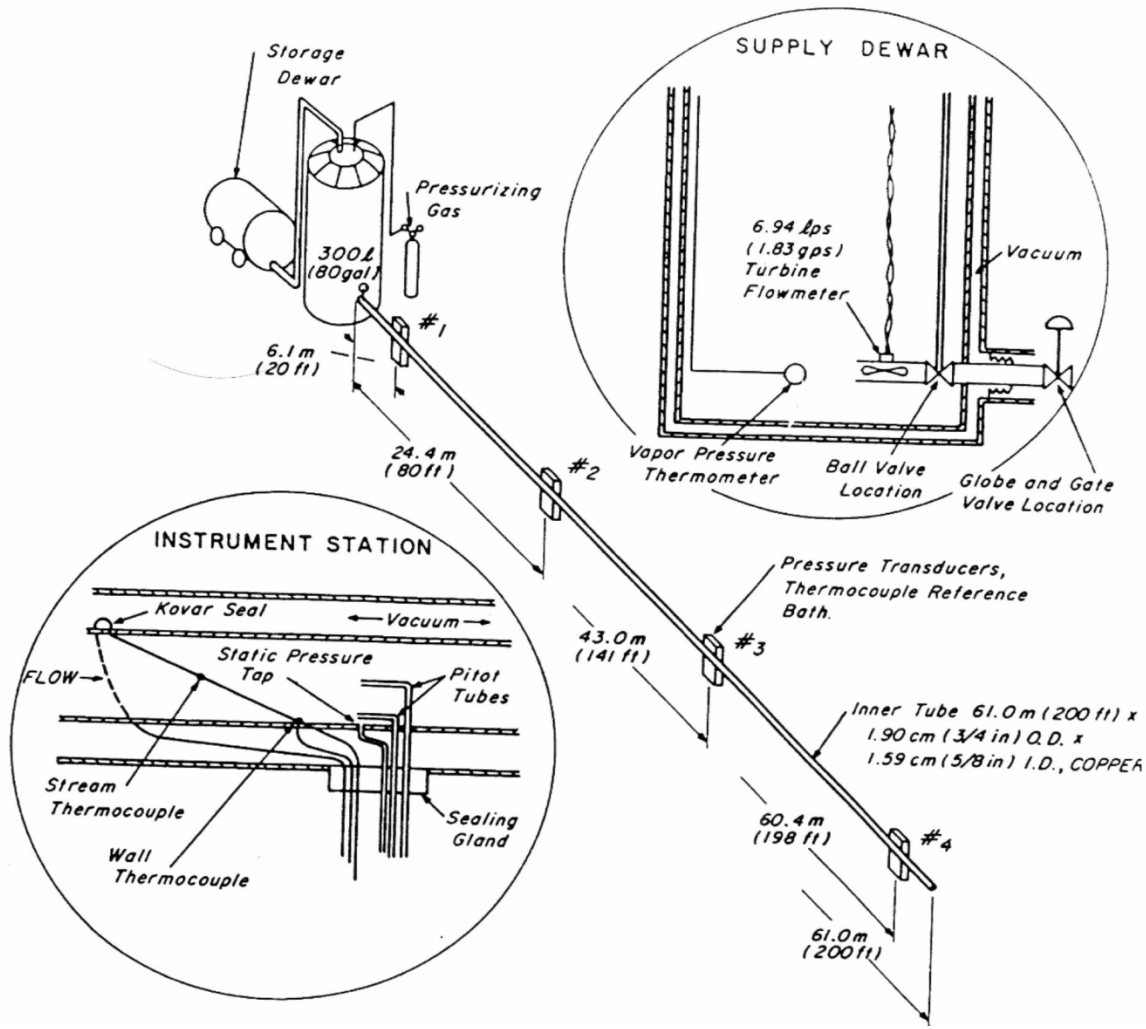
For More Information

- The file *SupplementaryDocumentationOfGFSSPVersion605.pdf* is located in the v605 installation directory. It documents:
  - User-defined fluids
  - Utility programs for creating user-defined fluid tables from REFPROP
  - New utility subroutines for getting fluid properties
  - Revised Example 14
  - New Examples 26-30

New Example Problems

- Version 605 has five new example problems (Examples 26-30) and revised Example 14
  - Chilldown of a Cryogenic Pipeline (Revised Example 14)
  - Fluid Transients in Pipes Due to Sudden Opening of Valve (EXAMPLE 26)
  - Boiling Water Reactor (Example 27)
  - No-Vent Tank Chill & Fill Model (Example 28)
  - Self-Pressurization of a Cryogenic Propellant Tank Due to Boil-off (Example 29)
  - Modeling Solid Propellant Ballistic with GFSSP (Example 30)

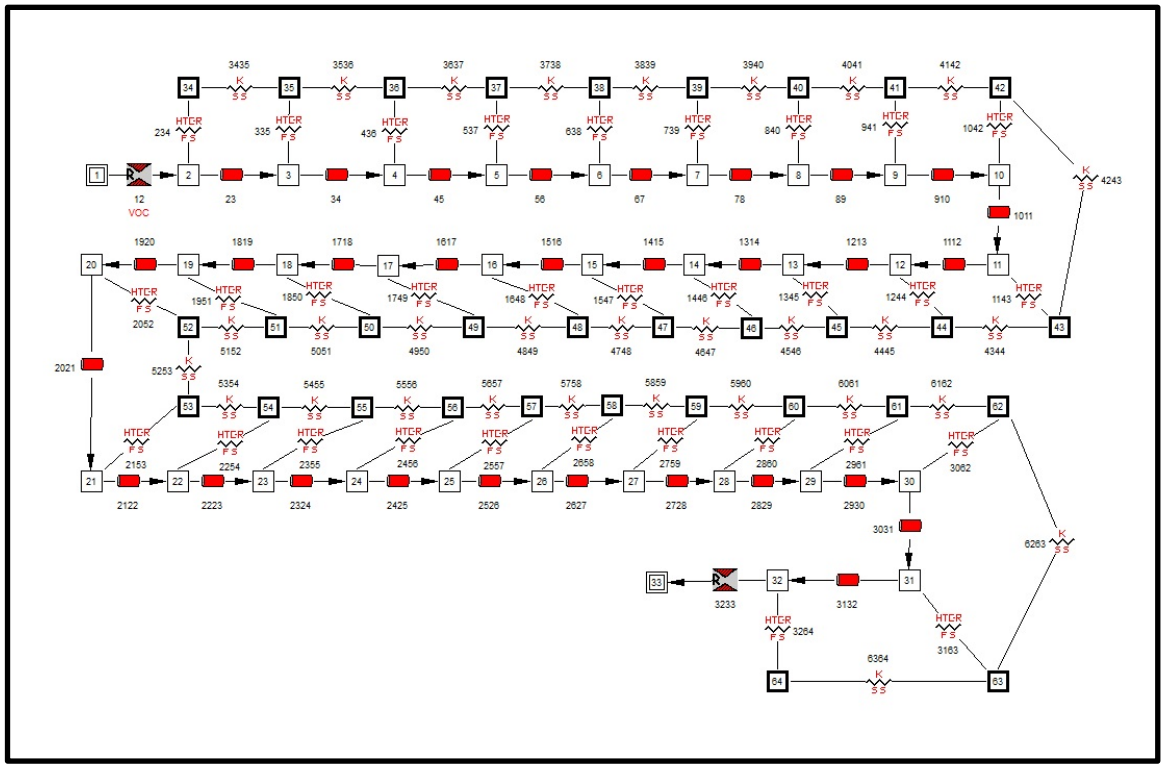
Chilldown of a Cryogenic Pipeline (Revised Example 14)



- This example models NBS Chilldown Test (Vacuum-jacketed 200 foot long copper pipe of 5/8 inch dia) with LH2
- Illustrates two-phase flows with phase change
- Calculates temperature history of fluid and solid nodes and compared with Test Data

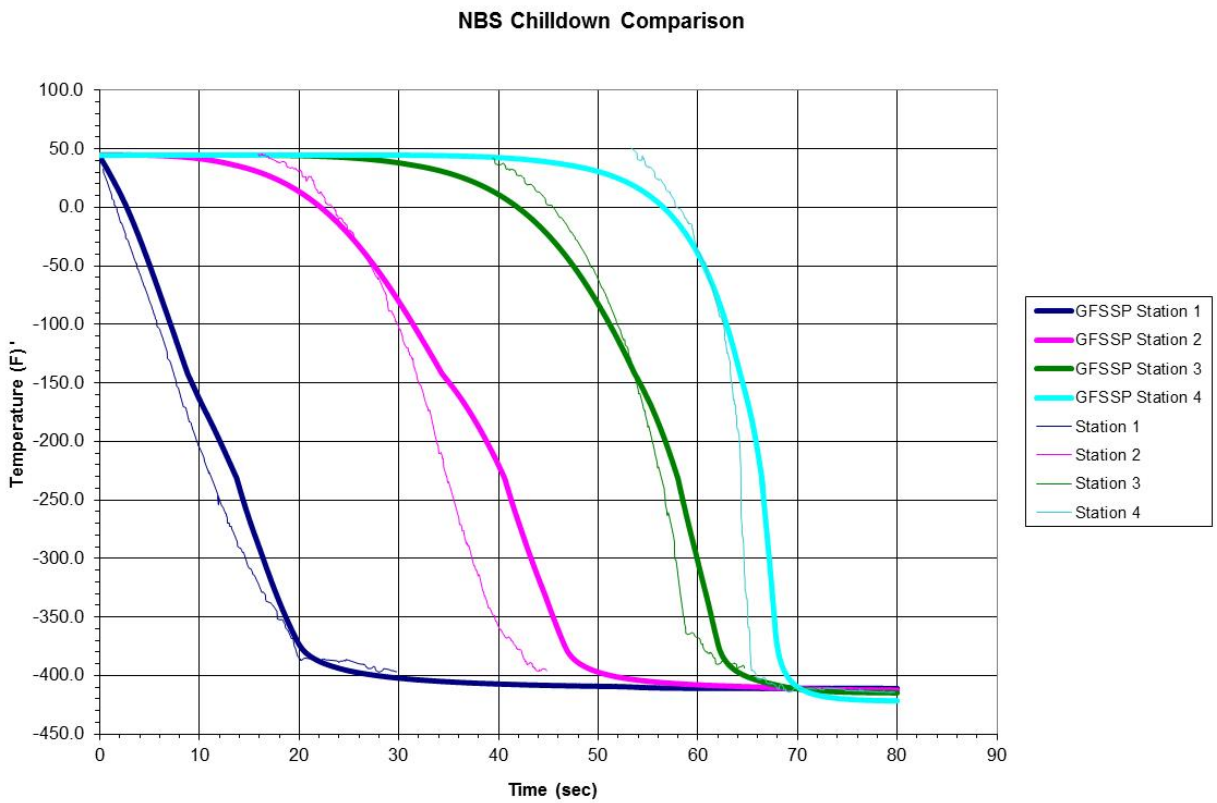
Reference: Brennan, J. A., Brentari, E. G., Smith, R. V., and Steward, W. G., "Cooldown of Cryogenic Transfer Lines, An Experimental Report," National Bureau of Standards Report 9264, November 1966.

GFSSP Model

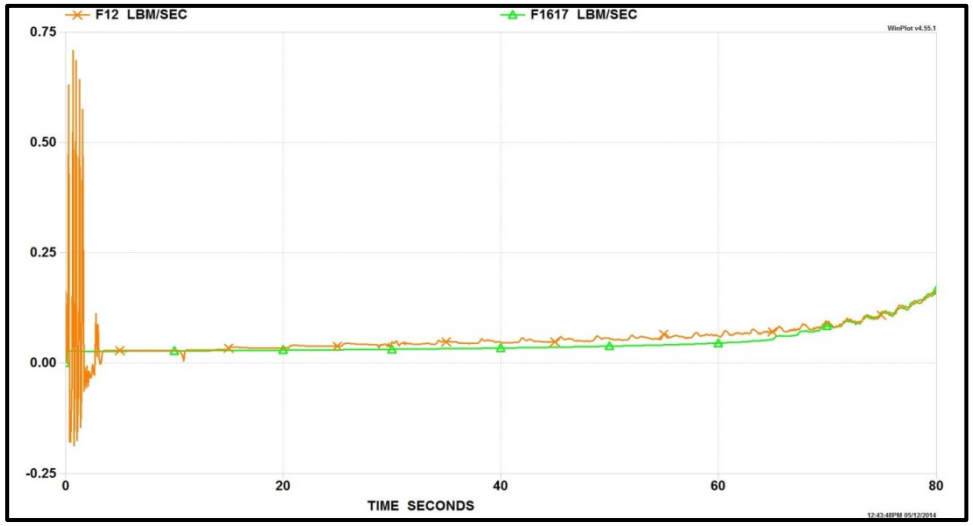


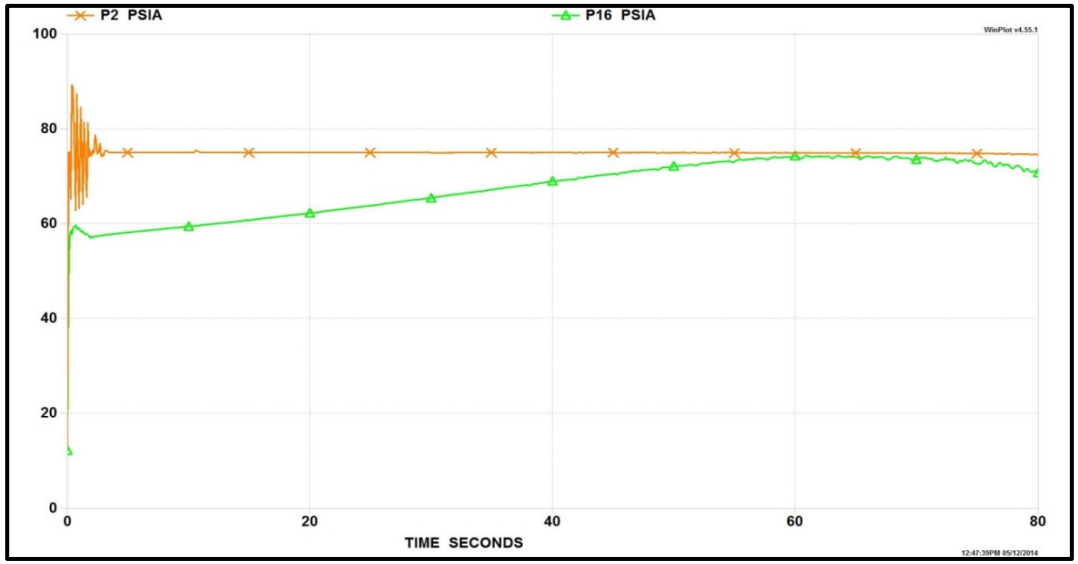
- 30 Pipe Branches each 80 inches long
- 31 Fluid and Solid Nodes
- Dewar Pressure and Temperatures are 74.97 psia and -411 °F
- Time step =
- Heat Transfer Coefficient was computed by Miropolsky Correlation

Comparison with Test Data



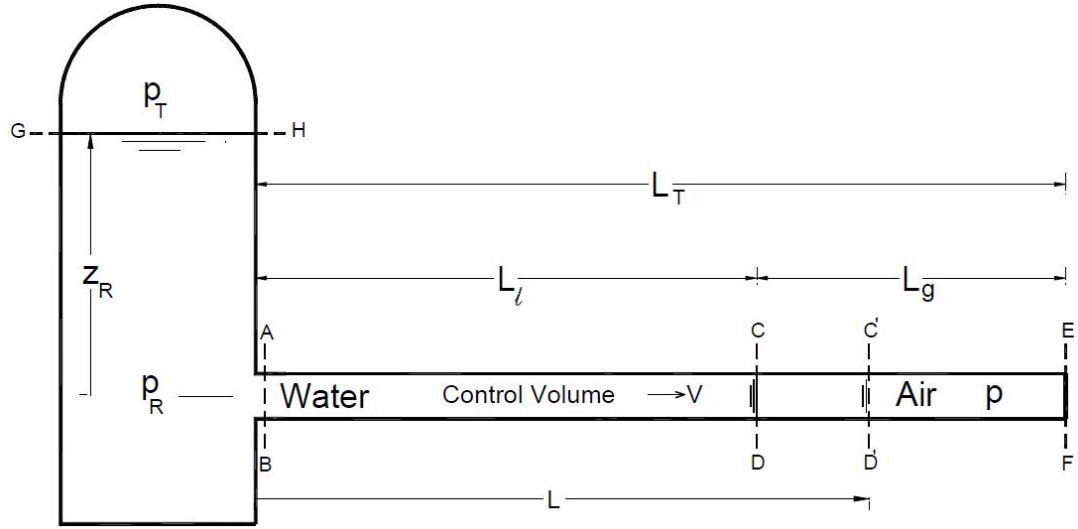
Flowrate & Pressure History





- Initially flow oscillation occurs due to instabilities of two-phase flow
- Flowrates gradually increases as pipes chilldown and vapor starts condensing
- Pressure difference in the pipe diminishes as more and more liquid flows through the pipe

Fluid Transients in Pipes Due to Sudden Opening of Valve (EXAMPLE 26)



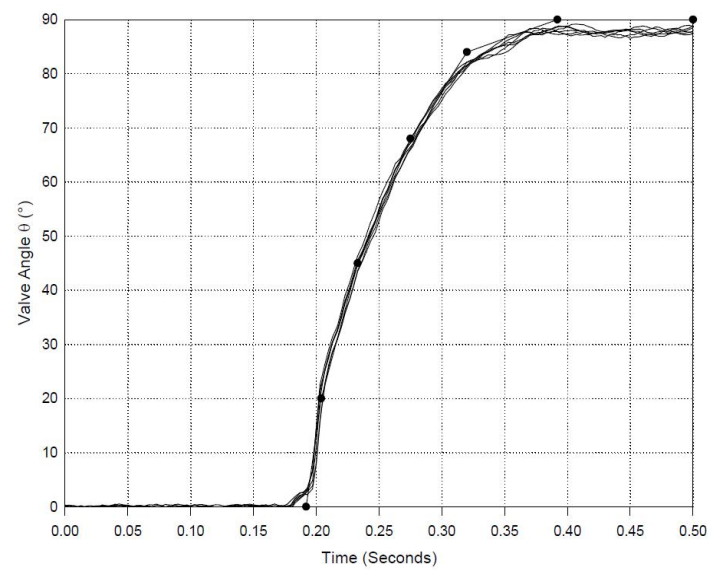
Schematic of the Pipeline System with ball-valve location (C-D).

Parameters:

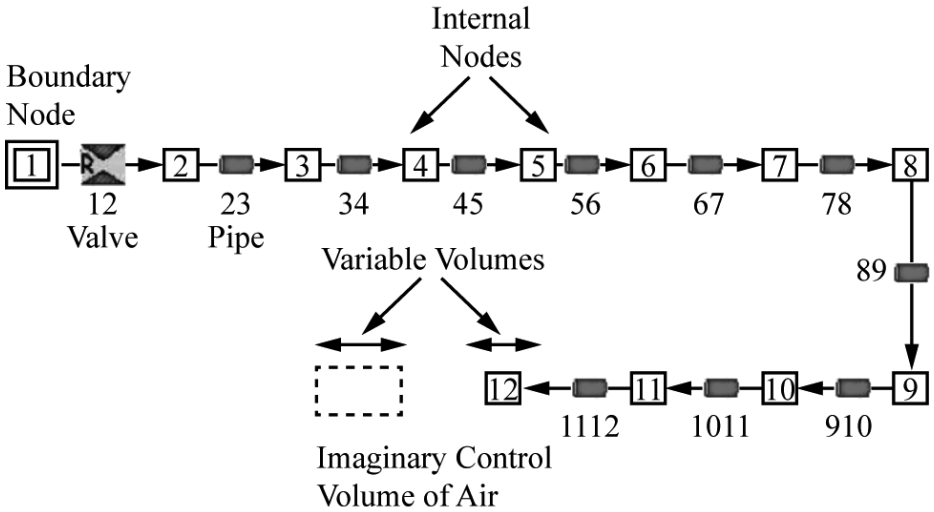
$\alpha = L_g/L_T$

$P_R = p_R/p_0$

Ball-Valve Opening History



GFSSP MODEL



Pipe Length = 20 ft

Pipe Diameter = 1.025in

- Node 1: Reservoir pressure = 29.4 to 102.9 psia
- Node 12: Volume change due to change in entrapped air volume.
- Air pressure at the end of node 12 is calculated using Adiabatic gas expansion relation for ideal gas.
- The valve opening area is based on ball-valve opening of the original problem.
- Momentum Source due to pressurization of water column due to air pressure.

Modeling Interaction between Water and Air Column

•Volume Change with time for pseudo node 12 due to air pressure:

$$\Delta V_w = -\Delta V_{air} = m_{air} R_{air} T_{12} \Delta p / p_{12}^2$$

$$\Delta p = (p_{12} - p_{12}^*)$$

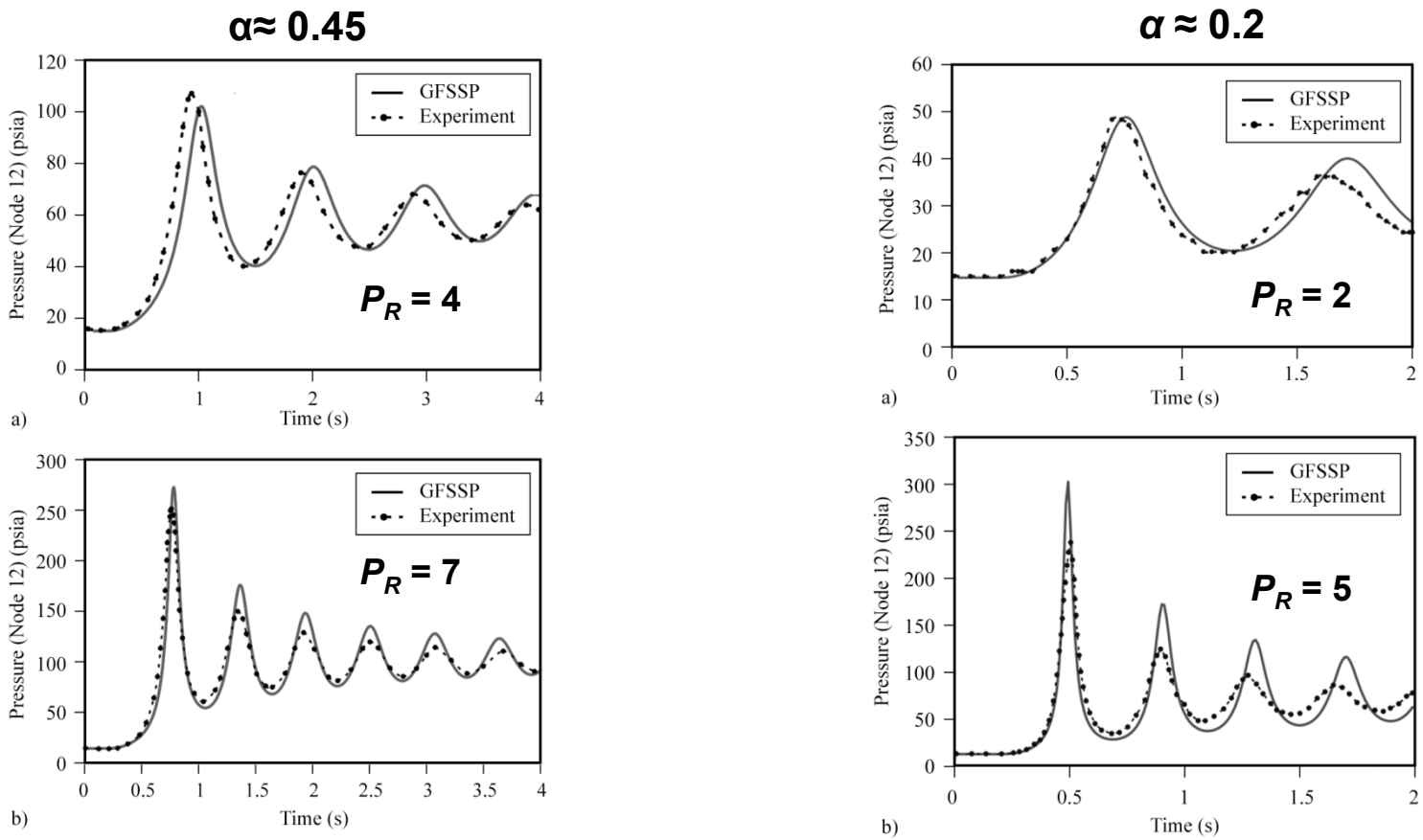
•Air Pressure Calculation: (Using Adiabatic Gas Relation):

$$p = \left(p^* V + p^* V^* \left[\left(\frac{V^*}{V} \right)^{\gamma - 1} - 1 \right] \right) / (V + \Delta V)$$

•p, V etc indicates pressure and Volume at the current time step and p^*, V^* indicates pressure and volume at the previous time step. The volume and pressure changes are with respect to time.

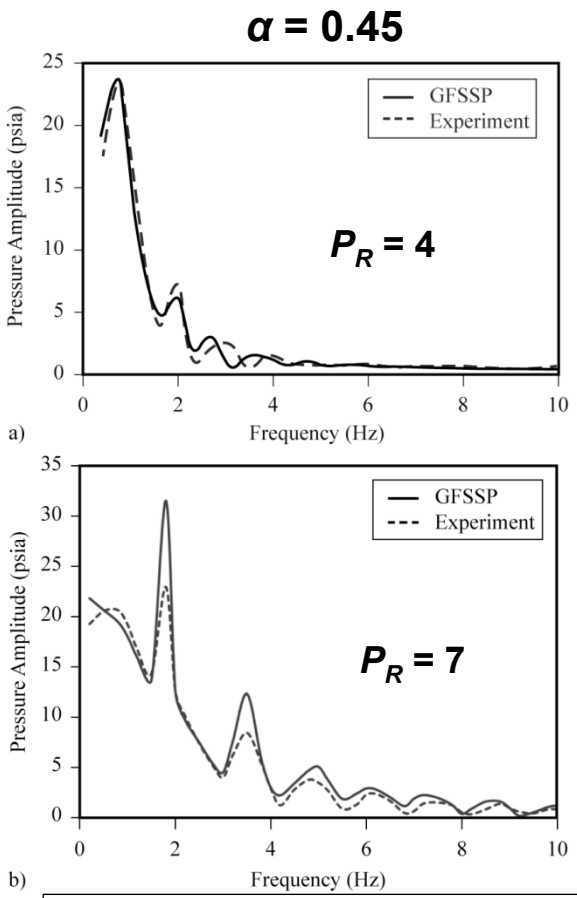
•Momentum Source in Node 12: $-(p_{air}-p_{12})A$

Comparison of GFSSP and Experimental Data



Bandyopadhyay, A. and Majumdar, A., "Network Flow Simulation of Fluid Transients in Rocket Propulsion System" submitted to *Journal of Propulsion and Power* for publication

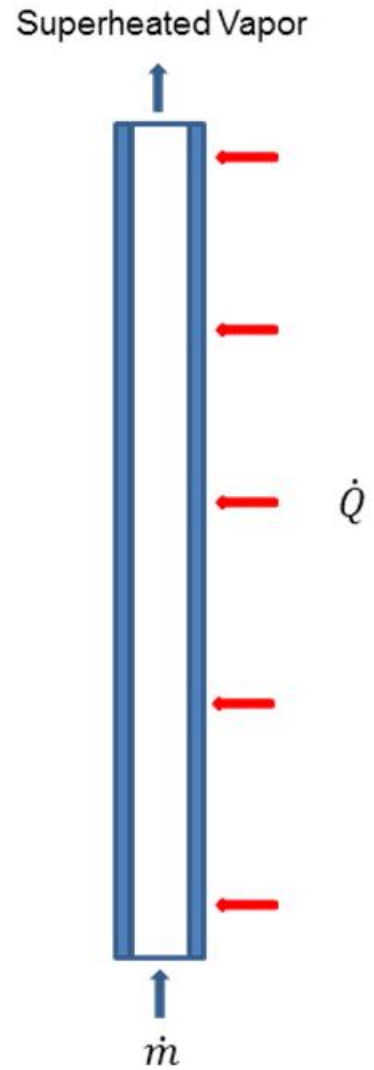
Fast Fourier Transform (FFT) of the Pressure Oscillations



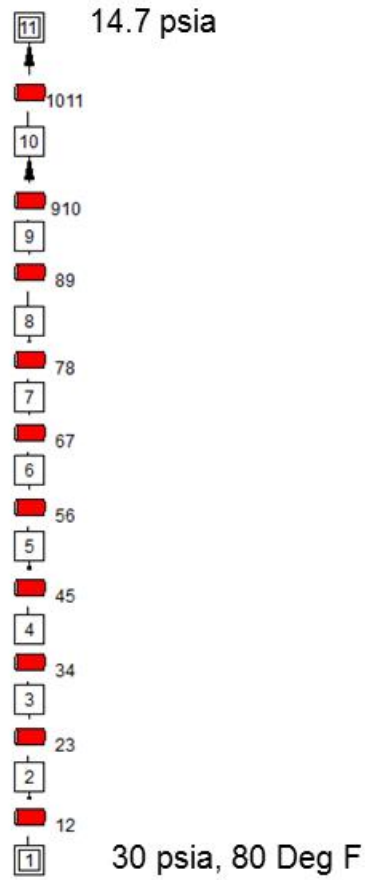
- FFT Analysis transforms the time domain pressure oscillations into the frequency domain
- A Fortran Program, “FFT Multiple.for” has been developed based on Danielson and Lanczos algorithm is available in Example 26 Folder in GFSSP Installation Directory
- The program reads “p_t.txt” which contains time in first column and pressures in subsequent columns
- The output is stored in “p_f.xls”

Danielson, G. C. and Lanczos C., “Some improvements in practical Fourier analysis and their application to X-ray scattering from liquids”, *Journal of Franklin Institute*, vol. 233, pp 365-380 and 435-452

Boiling Water Reactor (Example 27)

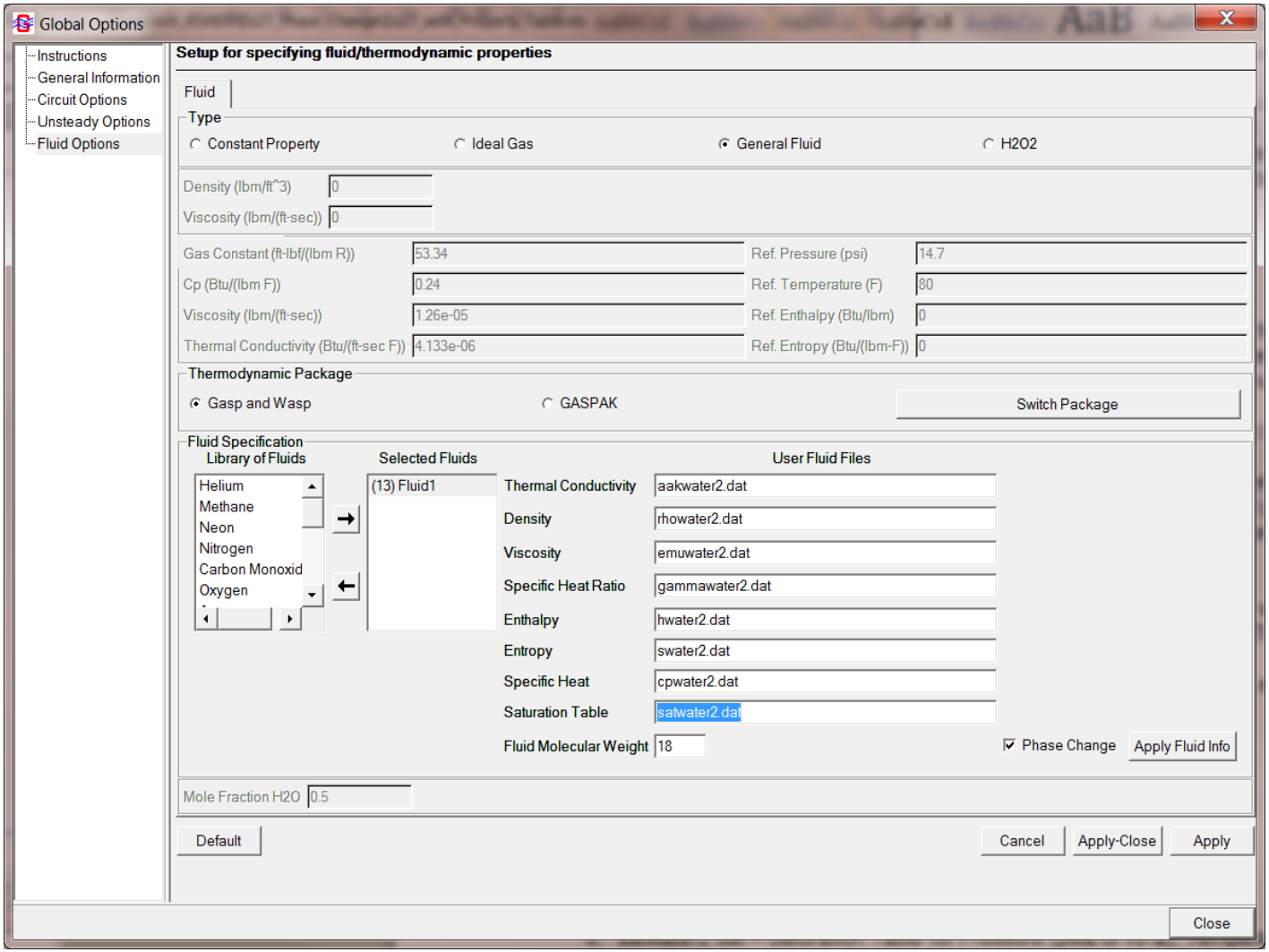


a. Problem Schematic



b. GFSSP Model

Fluid Option in VTASC for User Specified Fluid

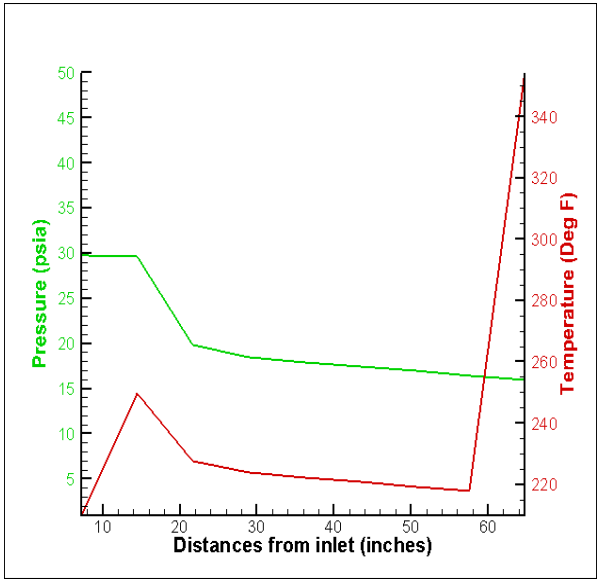


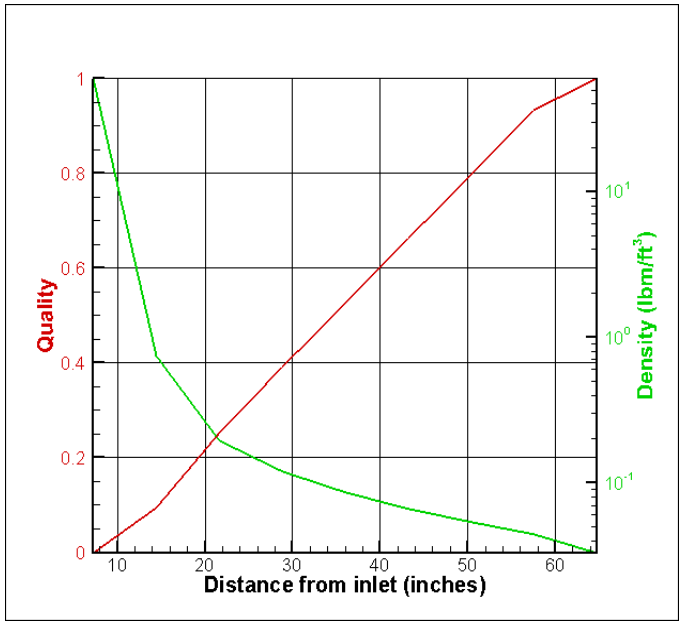
Comparison between solutions with WASP and Property Table generated by REFPROP

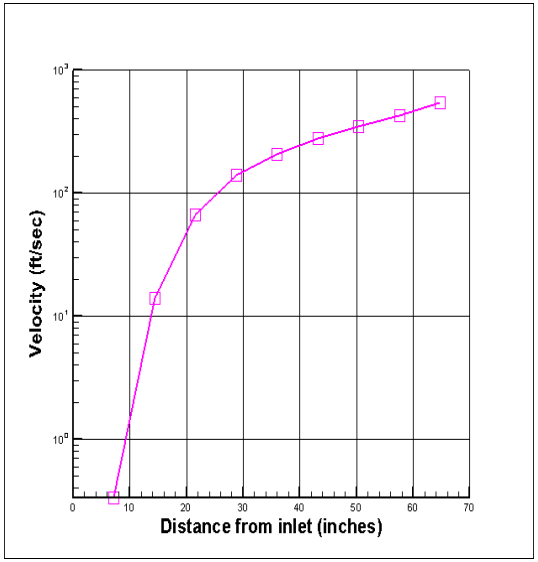
Variables	WASP	Property Table	% Difference
Flowrate (lbm/sec)	0.1125	0.1131	0.5333
P_2 (psia)	29.745	29.747	0.00672
P_5 (psia)	18.517	18.536	0.103
P_{10} (psia)	15.946	15.935	0.069
T_2 (°F)	209.99	209.59	0.191
T_5 (°F)	223.88	223.02	0.384
T_{10} (°F)	354.39	352.55	0.519
X_2^{**}	0.00	0.00	0.00
X_5	0.3906	0.3909	0.077
X_{10}	1.00	1.0	0.00

** x is the vapor mass fraction or quality

Results


Pressure (psia)
Temperature (Deg F)
Distances from inlet (inches)


Quality
Density (lbm/ft^3)
Distance from inlet (inches)


Velocity (ft/sec)
Distance from inlet (inches)

No-Vent Tank Chill & Fill Model (Example 28)

- **K-site Test Tank - The LH2 chilldown test was run on February 15, 1991**

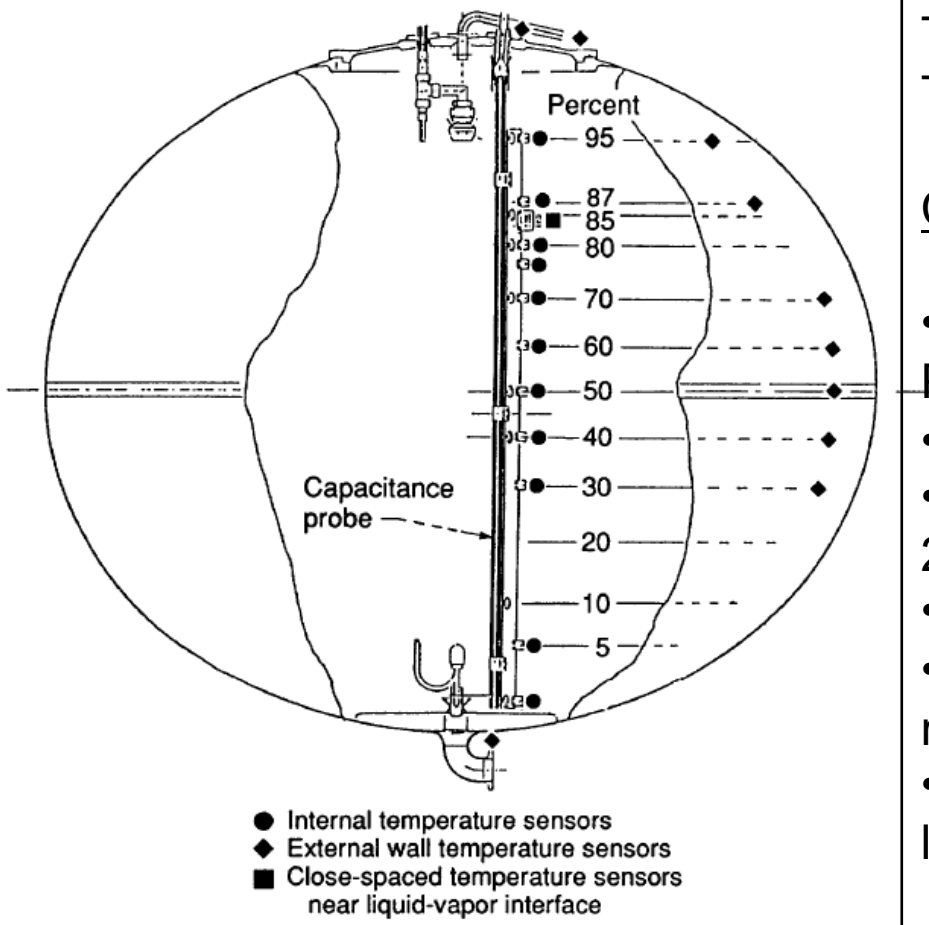


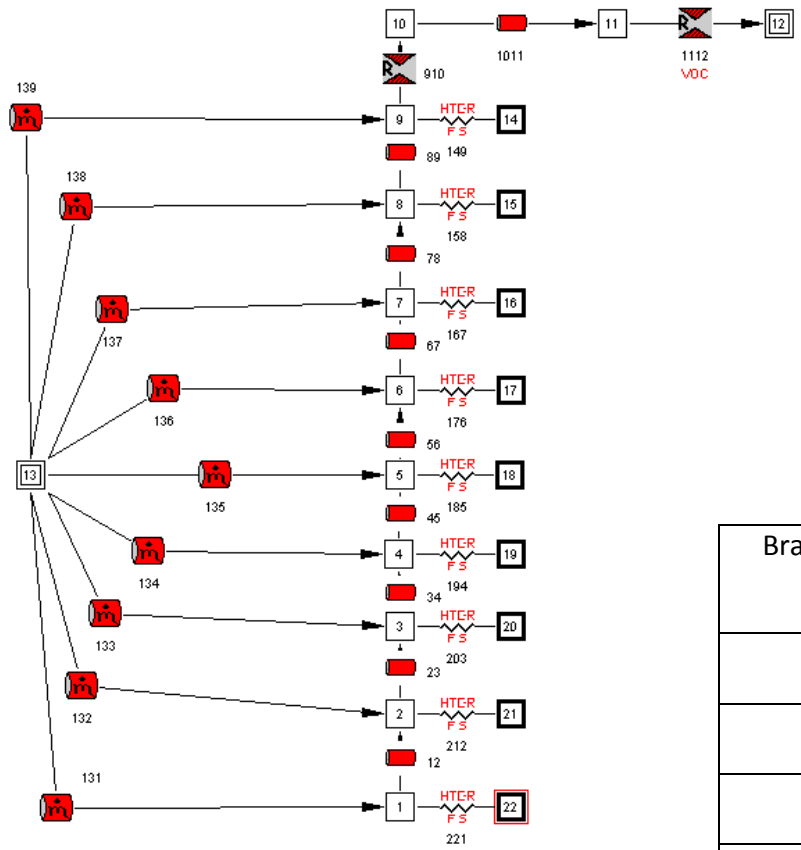
Figure 6.—Tank instrumentation.

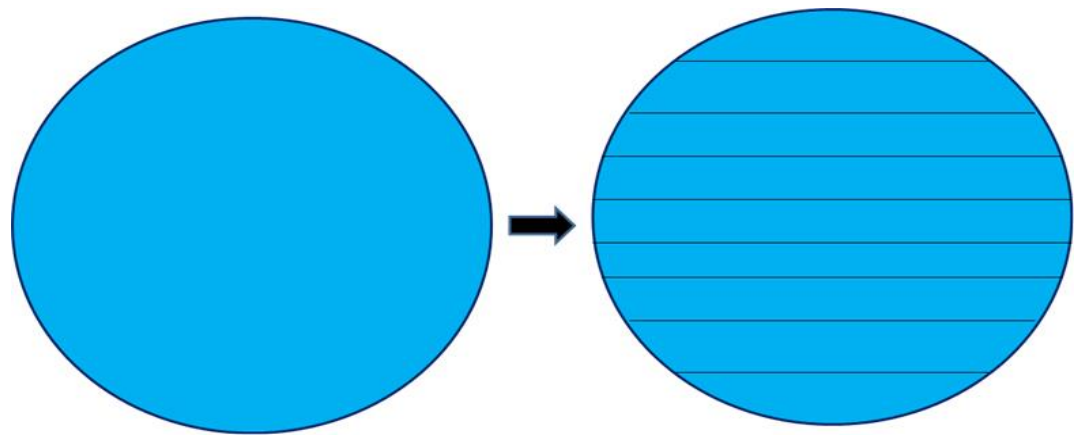
Tank Material – 2219 Aluminum
Tank Volume = 175 ft^3 (87 x 72.5 inch)
Tank Weight = 329.25 lbs
Tank Insulation – 34 layers of MLI

<u>Chilldown Method:</u>

- 6 Cycles of Charge-Hold-Vent Process
- Injection rates were measured
- 714.35 lbs of LH2 was injected in 2.35 hrs
- Tank was filled to 94%
- Fluid and wall temperatures measured
- Estimated consumption of LH2 = 32 lbs

GFSSP Nine Node Tank Model



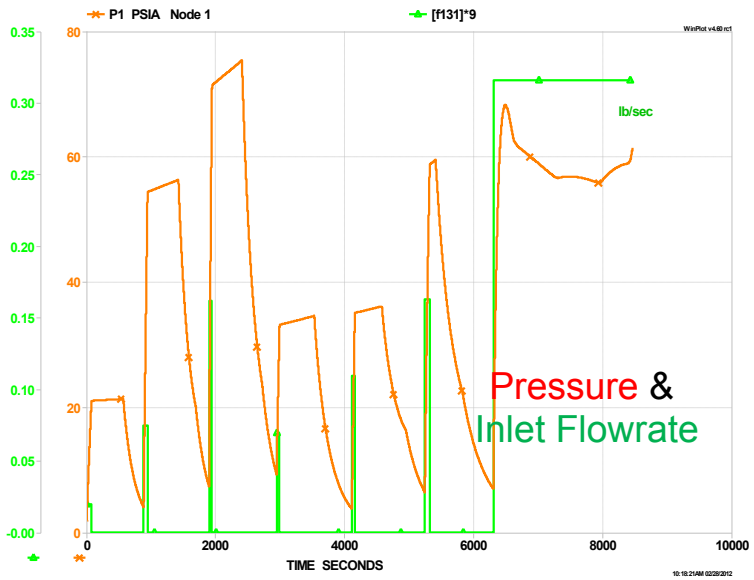


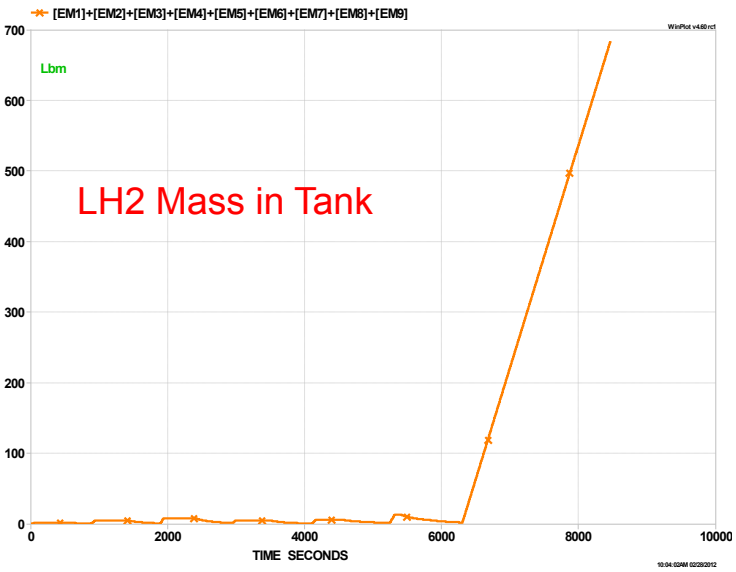
- No heat leak was assumed
- Initial Tank Pressure = 2 psia
- Initial Tank Temperature = -20 º F

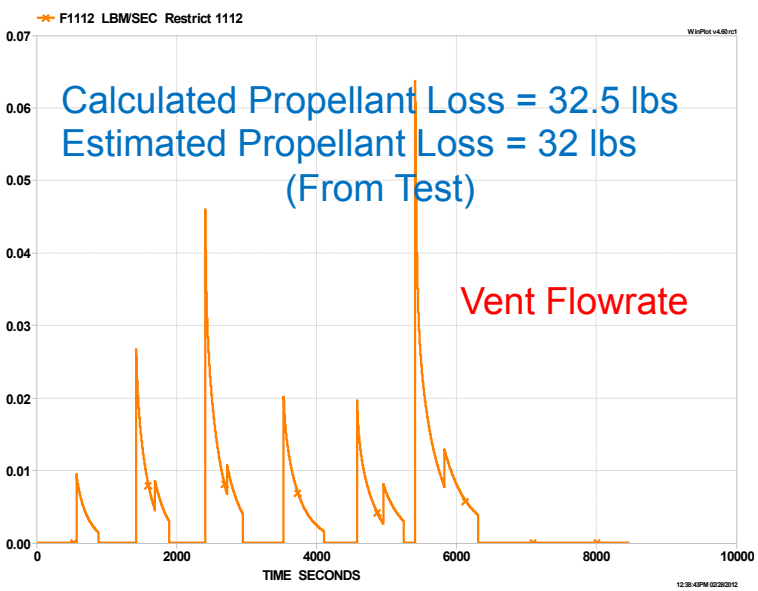
Table 3.4.1. Internal Model Tank Parameters

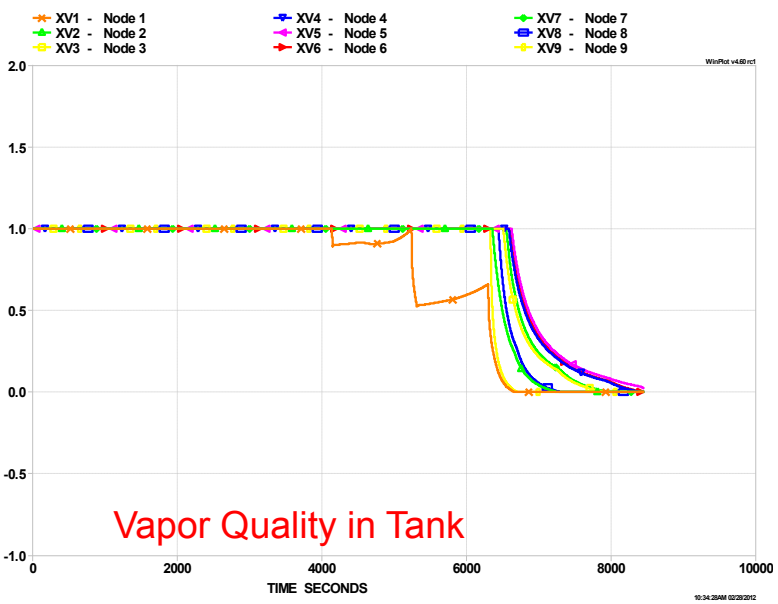
Branch Number	Branch Length (in)	Branch Diameter (in)	Branch Volume (in^3)
12	11.063	38.59	4,118.72π
23	11.063	62.71	10,876.43π
34	11.063	74.61	15,395.96π
45	11.063	79.88	17,647.73π
56	11.063	79.88	17,647.73π
67	11.063	74.61	15,395.96π
78	11.063	62.71	10,876.43π
89	11.063	38.59	4,118.72π

GFSSP Model Results

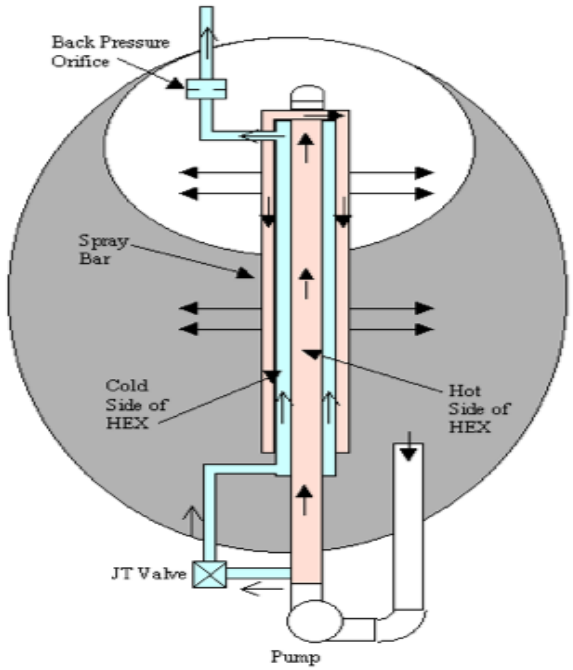




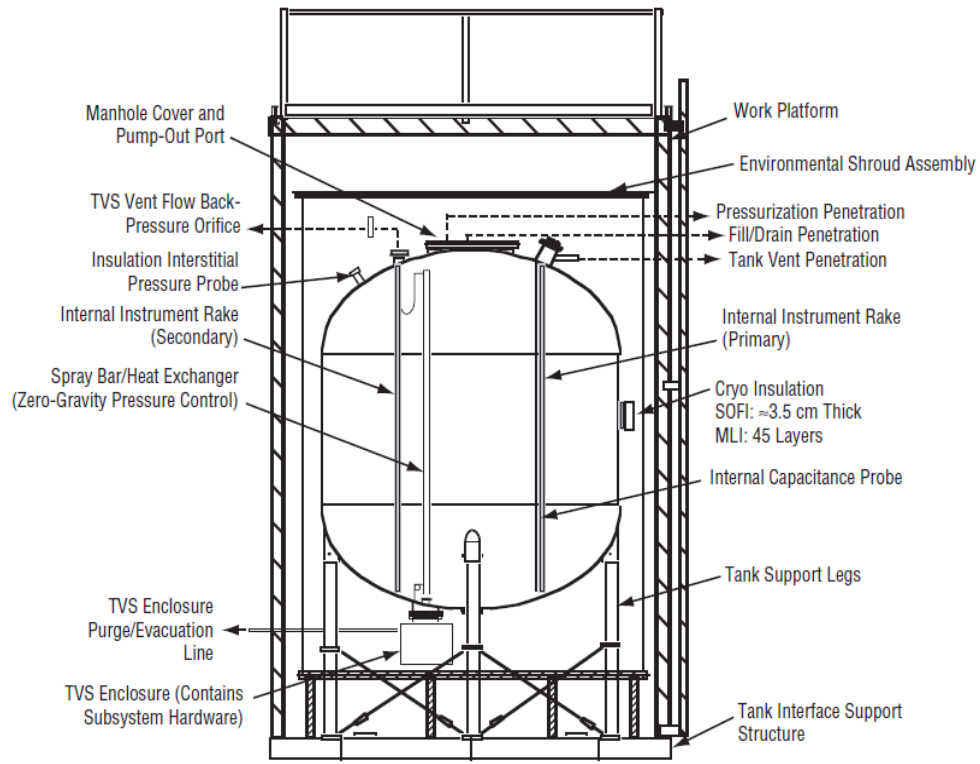




Self-Pressurization of a Cryogenic Propellant Tank Due to Boil-off (Example 29)



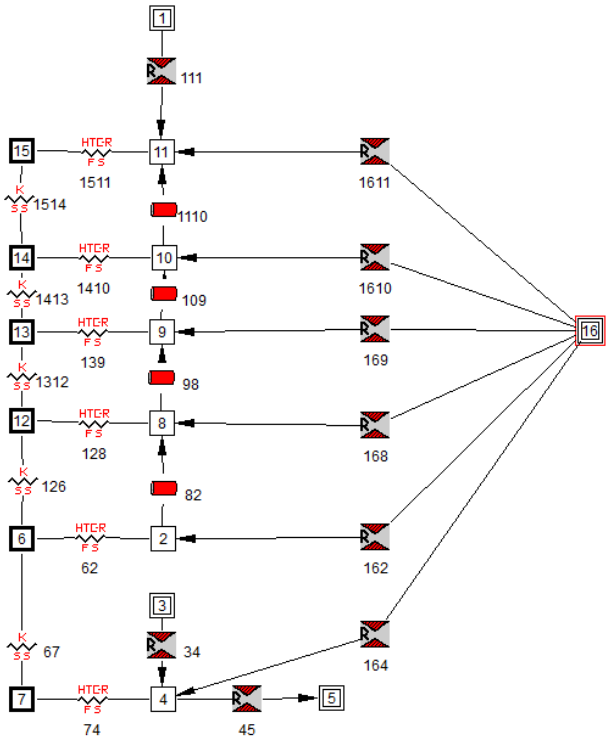
Thermodynamic Vent System in MHTB Tank



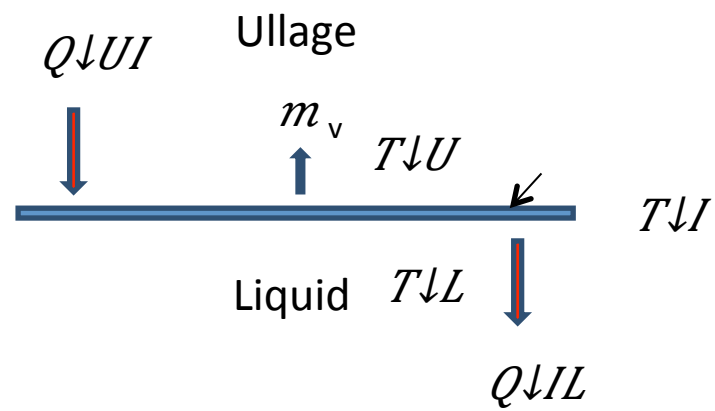
MHTB Test Tank and Supporting Hardware Schematic

GFSSP Model & Evaporative Mass Transfer

GFSSP Model



Evaporative Mass Transfer at Liquid-Vapor Interface



- Ullage to Interface heat transfer, Q_{UI}

$$Q\downarrow UI = h\downarrow UI\, A(T\downarrow U - T\downarrow I),$$

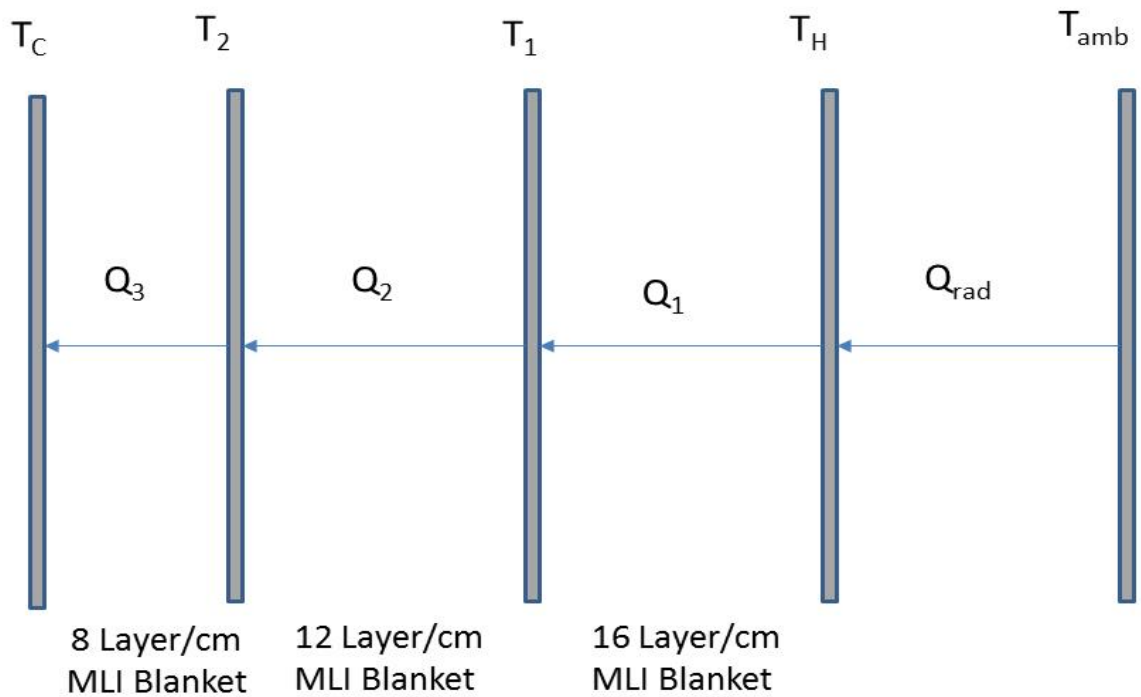
- The Interface to Liquid heat transfer, Q_{IL}

$$Q\downarrow IL = h\downarrow IL\, A(T\downarrow I - T\downarrow L)$$

- The evaporative mass transfer

$$m = Q\downarrow UI - Q\downarrow IL / h\downarrow fg$$

Heat transfer thru MLI blankets



Radiative Heat Transfer

q=$\sigma(T\downarrow amb\uparrow 4 -$

Modified Lockheed Equation

Hastings, L. J., Hedayat, A., and Brown, T. M., *Analytical Modeling and Test Correlation of Variable Density Multilayer Insulation for Cryogenic Storage*, NASA/MSFC, NASA/TM-2004-213175, May 2004.

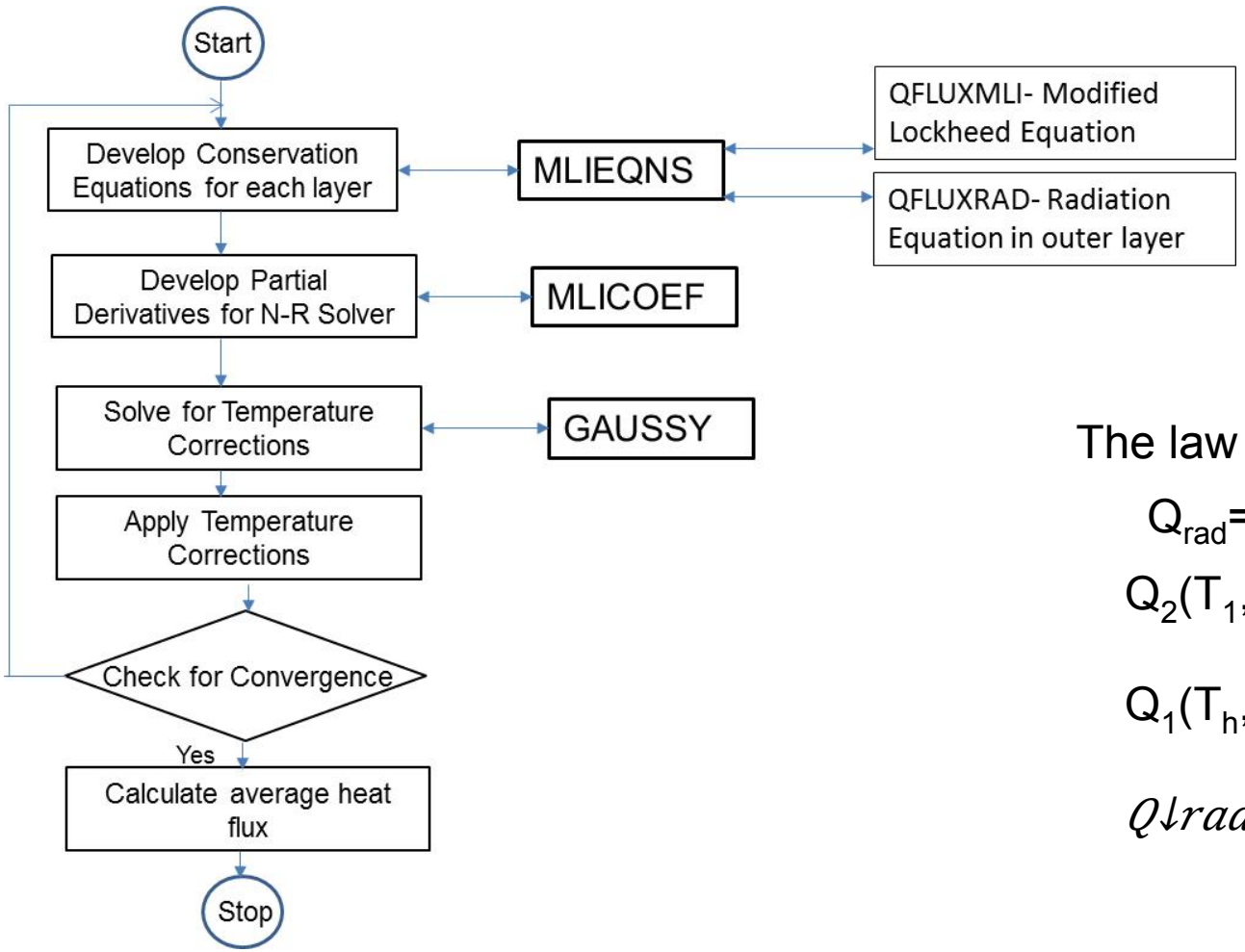
$$q = \left[\frac{C_s(0.017 + 7.0E-6*(800.0 - T_{avg}) + 2.28E-2*\ln(T_{avg}))(N^*)^{2.63}(T_h - T_c)}{} + \frac{C_r \varepsilon (T_h^{4.67} - T_c^{4.67})}{N_s} + \frac{C_g P (T_h^{0.52} - T_c^{0.52})}{N_s} \right]$$

N* MLI layer density, layers/cm
N_s number of MLI layers
ε MLI layer emissivity, ε = 0.031
P interstitial gas pressure, torr

Variables and units

q heat flux through MLI, W/m²
T_h hot boundary temperature, K
T_c cold boundary temperature, K
T_{avg} average of hot and cold boundary temperatures, K

Modeling of MLI Heat Transfer in GFSSP



$q=\sigma(T\downarrow amb\uparrow 4 - T\downarrow out$

The law of energy conservation

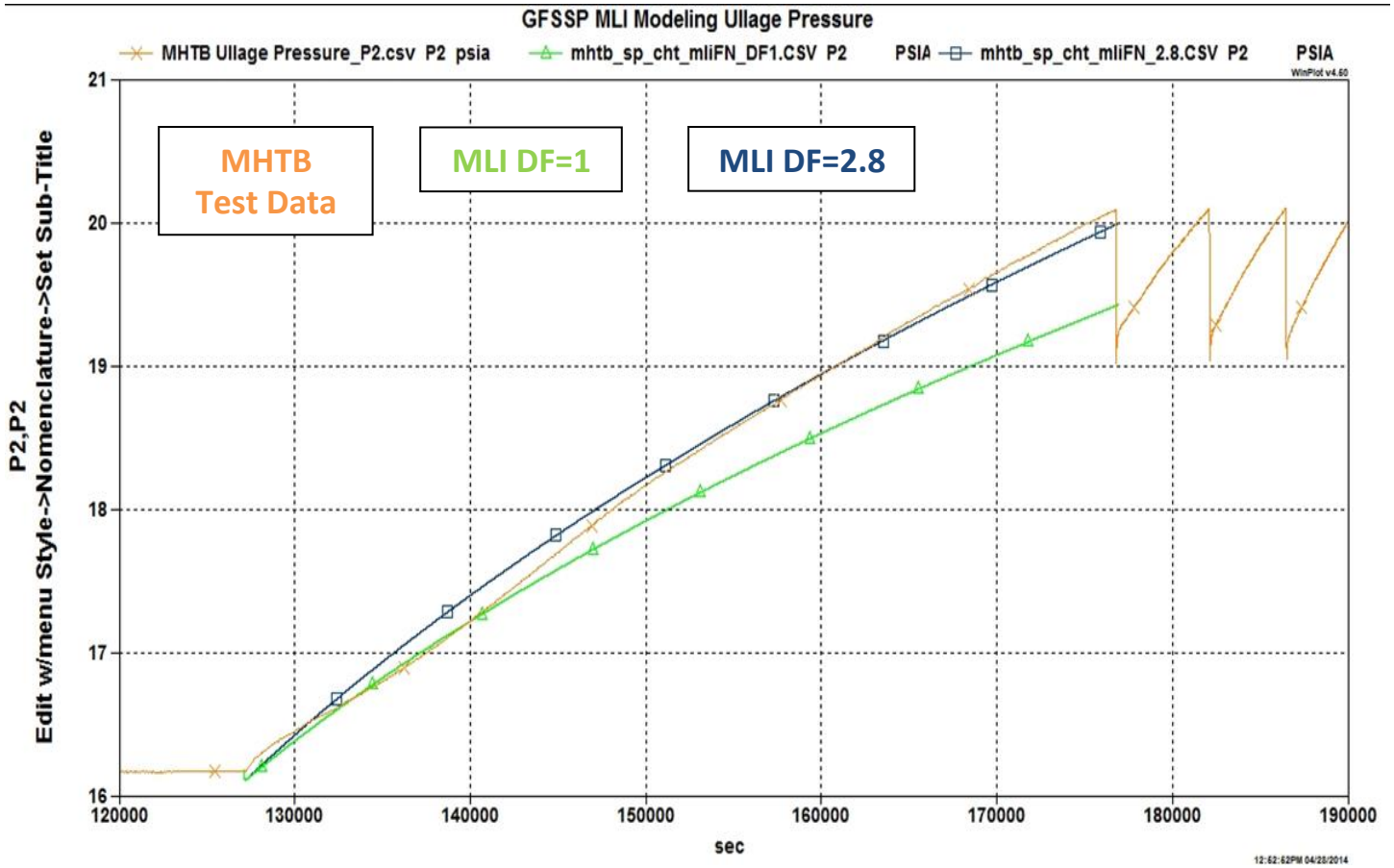
$Q_{rad} = Q_1 = Q_2 = Q_3,$

$Q_2(T_1, T_2) - Q_3(T_2, T_c) = 0$

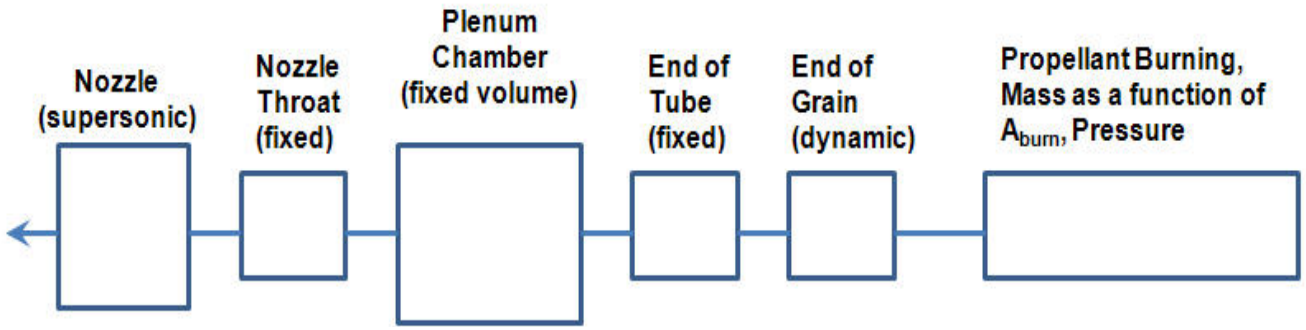
$Q_1(T_h, T_1) - Q_2(T_1, T_2) = 0$

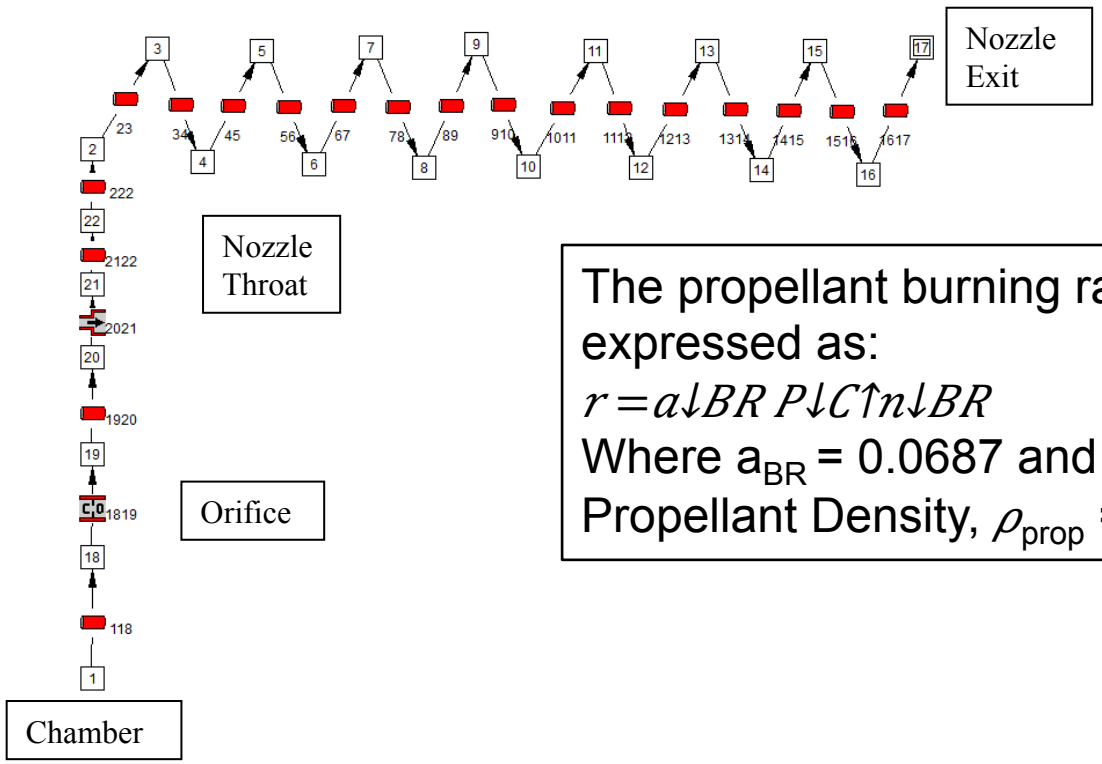
$Q\downarrow rad\ (T\downarrow amb, T\downarrow H) - Q\downarrow 1\ (T\downarrow H,$

Application Results for MHTB Self Pressurization Model



Modeling Solid Propellant Ballistic with GFSSP (Example 30)





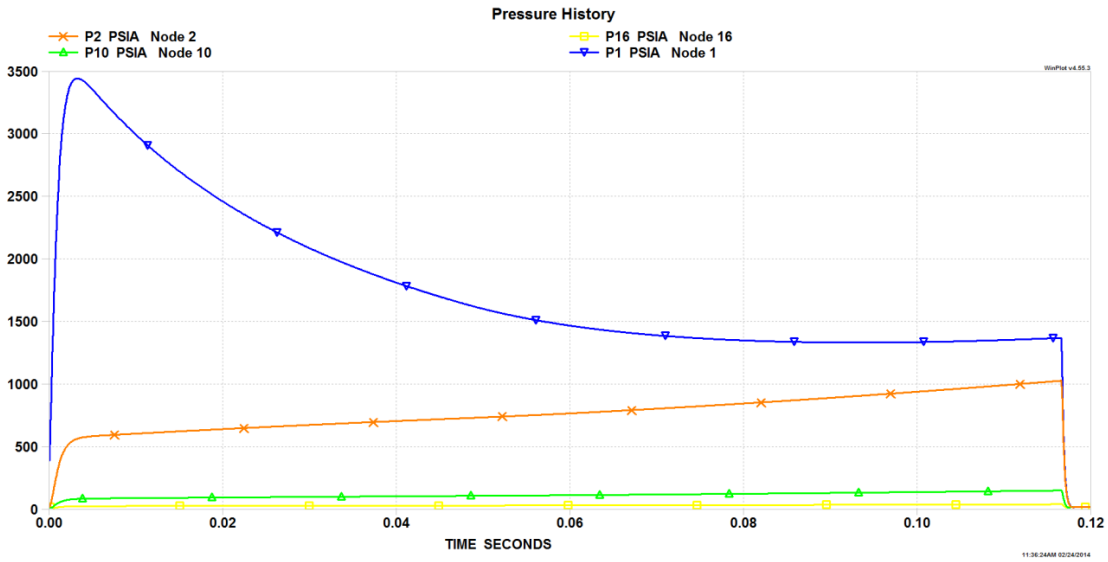
The propellant burning rate (in/sec) was expressed as:

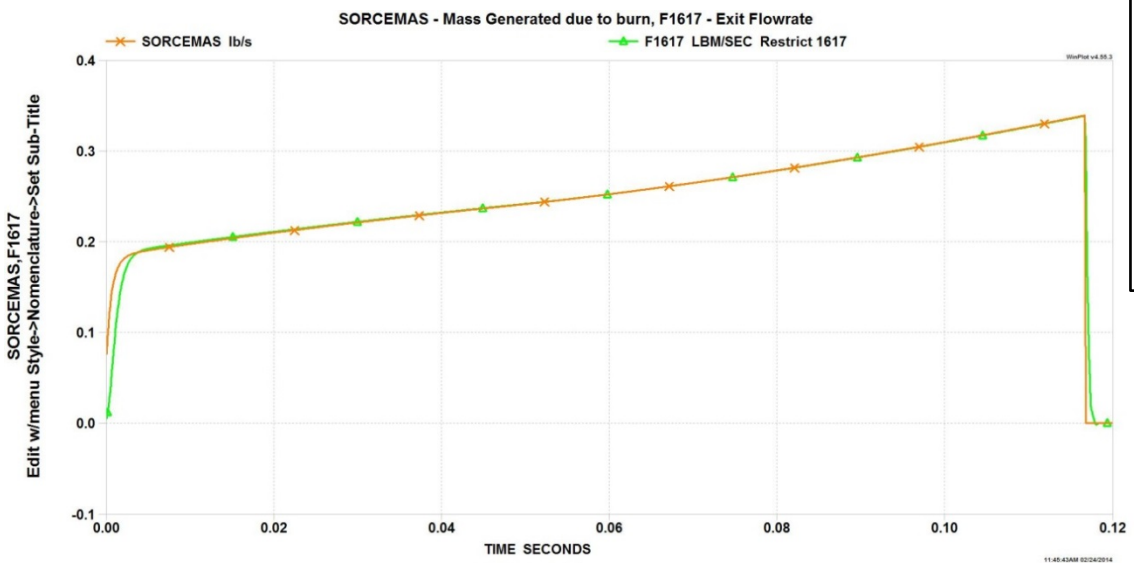
$$r = a_{BR} P_C^{n_{BR}}$$

Where a_{BR} = 0.0687 and n_{BR} = 0.3

Propellant Density, ρ_{prop} = 0.06 lbm/in^3

Results & Computational Details





Numerical Control Parameters:

Very Small Time Step:
(DTAU = 0.0001 sec)

Stringent Convergence Criterion
(CC = 1e-07)

Heavy Under-Relaxation on Density
(RELAXD = 0.05)

During Tail-Off, RELAXNR was set to 0.3 in User Subroutine

Summary & Future Work

- Version 605 is the final release of Version 6
- Supplementary Documentation released with this version describes all additional capabilities and example problems
- There is a plan to merge the Version 604 User's Manual with the Supplementary Documentation into an updated User's Manual
- All existing models should be migrated to Version 605
- The planned Version 701 will include:
  - Psychrometric Properties
  - Significant improvement in Computational Efficiency

Acknowledgement

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  - Kyle Schafer /ER43-Summer Intern
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- Example Problems
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  - Juan Valenzuela /ER24
  - Ali Hedayat /ER24
  - Johnny Maroney/ ER43-ESSSA