VALIDATION CASE: LINE CHILLDOWN USING LIQUID HYDROGEN

In 1988, just two years after FLUINT was first introduced, Brent Cullimore (then at Martin Marietta) wrote a memo* documenting the comparison of SINDA/FLUINT (Version 2.2 perhaps) with a 1966 test by the National Bureau of Standards (NBS, now National Institute of Standards and Technology, NIST).

This validation case revisits that comparison, taking advantage of the numerous developments available in the last 16 years, as incorporated into SINDA/FLUINT Version 4.7. This work also makes use of C&R's Thermal Desktop® and FloCAD® to facilitate model building and postprocessing. The Thermal Desktop drawing and property files are available separately, so this document need not contain those details. Instead, it focusses on a description of the test, on the comparison with predictions, and on the explorations of alternate methods and models since those discussions provide guidance for modeling similar chilldown systems.

V.1 Test Description

Information in this section was taken from the 1988 memo, since regrettably the original NBS report† has been lost. Fortunately, the 1988 memo contained pages copied from the 1966 report, so there is little concern that any errors of significance have been introduced by using an intermediate source. Unfortunately, the original source itself lacked descriptions of important components and properties, so treatment of those uncertainties will be taken up in a later section.

In the NBS tests, a pressurized LH2 tank was used with a volume (300 liters) sufficient to assure nearly constant supply temperature and pressure. The tank was isolated from an empty line (open to the atmosphere) by a series of valves. The line was vacuum-jacketed 3/4" and made with an unspecified copper alloy. At time zero, a valve was opened (presumably the furthest downstream) and LH2 was allowed to flow until the line was completely full and liquid hydrogen was discharged from exhaust end of the pipe.

The relevant characteristics of the comparison case are as follows:

LH2 Source (pressurized):
- Pressure . . . . 2.5 atm. (absolute)
- Temperature 19.5K

Inlet Valves
- 3/4" ball valve, 1" globe valve, and 1" gate valve, all of unknown design

* B. Cullimore, "FLUINT Demonstration: Transient Cooldown Simulation of a Cryogenic Hydrogen Transfer Line," Martin Marietta Space Systems white paper, February 9, 1988.

† J.A. Brennan et al, "An Experimental Report on Cooldown of Cryogenic Transfer Lines," for NASA by NBS, November 1966.

Transfer line (vacuum jacketed, copper, open to atmosphere):

Inner diameter. . . . . 1.59 cm (3/4" nominal)
Outer diameter . . . . 1.90 cm
Line length . . . . 200 ft. (61m)
Initial line/shield temperature 276K

Ambient

Pressure . . . . 0.82 atm (absolute)

Thermocouples were attached to the pipe wall (inside of the vacuum jacket) at four axial stations that were 20, 80, 141, and 198 feet from the inlet. The best estimate of this temperature history data, as measured using published curves from the original report, is provided in Figure V-1.

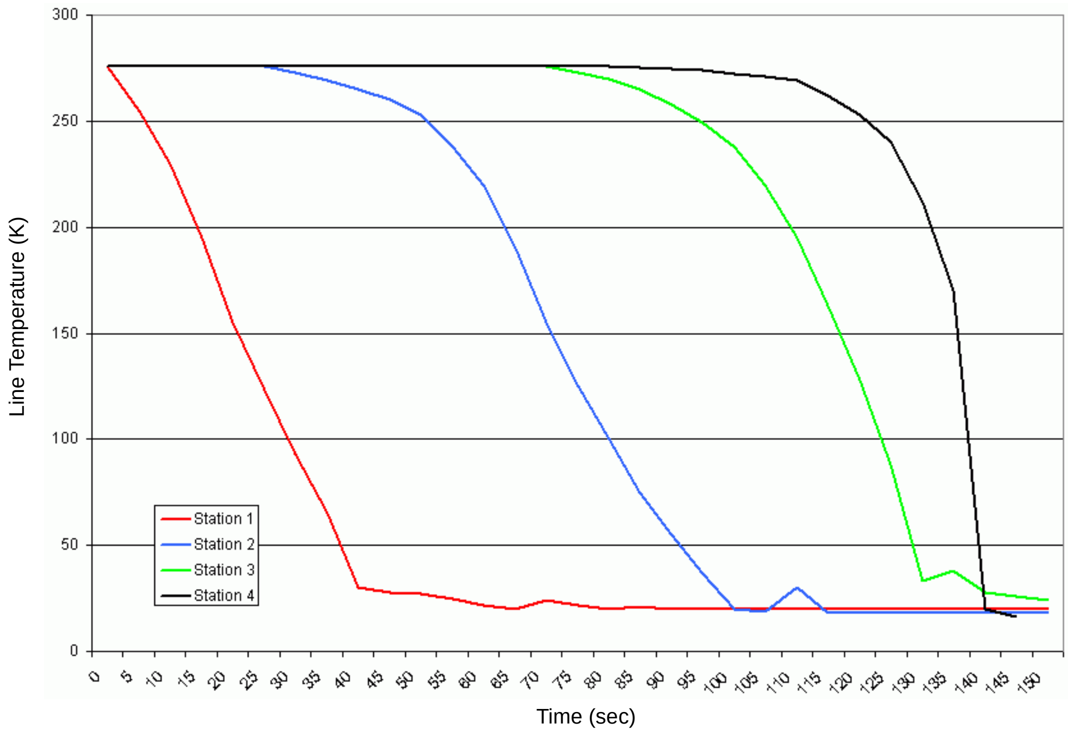

Figure V-1: Data from 1966 NBS Tests

V.2 Baseline Thermal/Fluid Model

C&R's Thermal Desktop® was used to develop a thermohydraulic model, as depicted by the postprocessed FloCAD pipe in Figure V-2. The model was parameterized, facilitating easy exploration of uncertainties as described in Section V.4. Results are described in the next section.

The fluid properties used were contained within a 6000 series (full tabular two-phase) description available at www.crtech.com. This description was produced using NIST's REFPROP program.

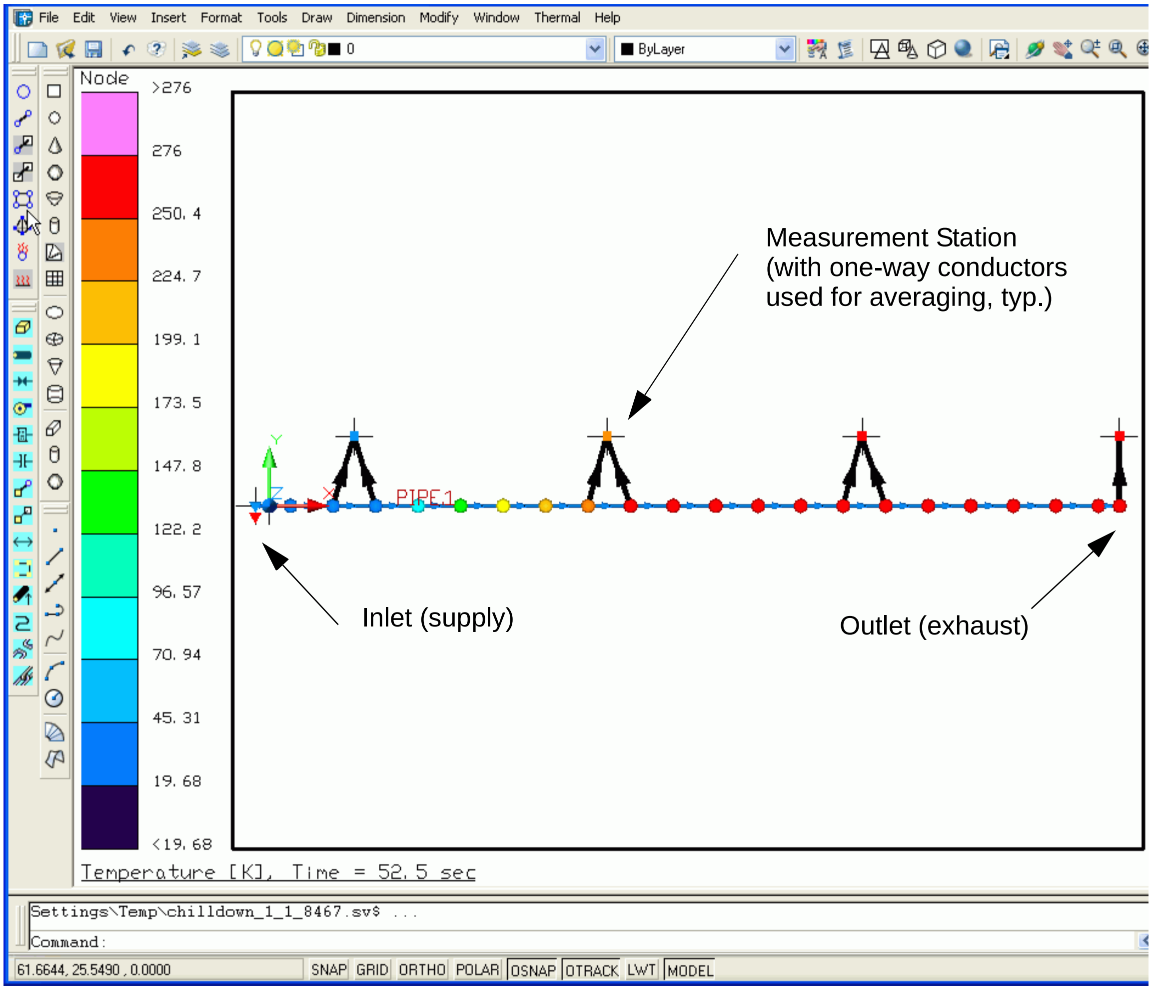

Figure V-2: Thermal Desktop Depiction (postprocessed in middle of run) of Model

The supply tank and atmospheric exhaust were both modeled using stagnant plena (FLUINT lumps of infinite volume, with LSTAT=STAG to designate negligible velocity as well). The FloCAD pipe used an axial resolution of 20 applied for both the wall model and the fluid model, which corresponds to a SINDA/FLUINT HX macro with NSEG=20. The line consisted of FLUINT junctions and tubes (flow inertia was included, but the mass/volume of each fluidic control volume was neglected -- see Section V.4). Homogeneous flow and perfect mixing within control volumes were both assumed, permitting fast executions. Gravity was applied laterally, but likely had little to no effect on the flow regimes since the two-phase zone is short: slug and annular flow are dominant.

It was discovered that one of the key missing inputs was the specific heat (C_p) of the copper alloy as a function of temperature. Lacking any data about the nature of the alloy used, NIST data for OFHC copper* was employed, as shown in Figure V-3 (the Thermal Desktop property data window). The conductivity of the copper, while uncertain, had little effect on the answers.

* http://cryogenics.nist.gov/NewFiles/OFHC_Copper.html

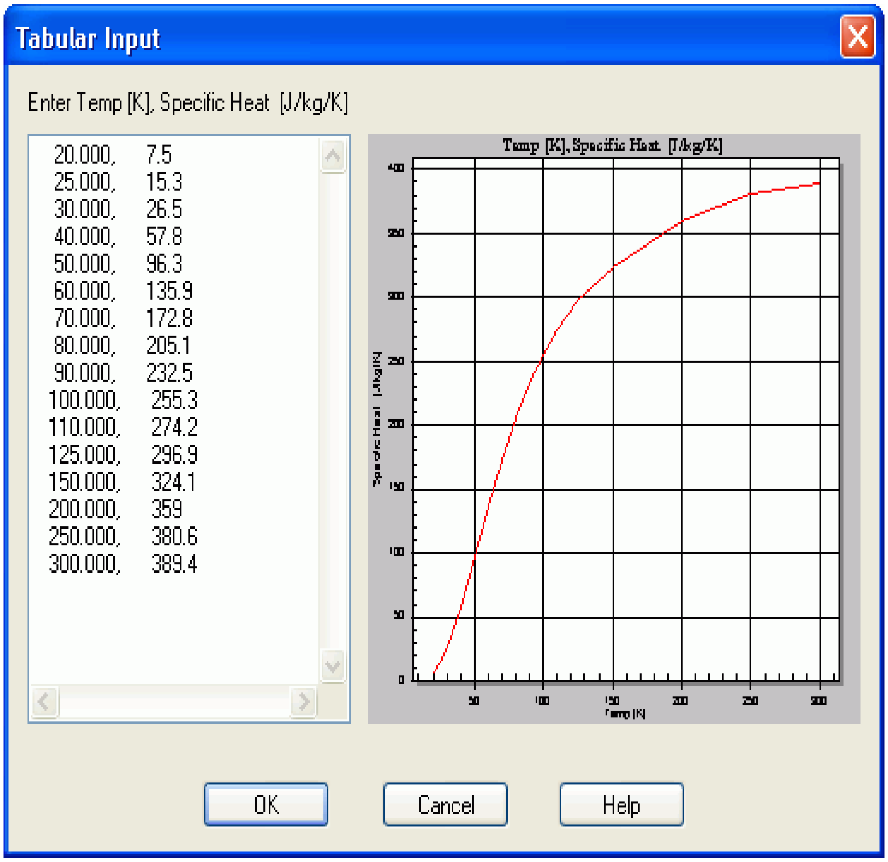

Figure V-3: C_p vs. Temperature Data Employed

The nature of the vacuum jacketing was also unknown. For the purposes of modeling, the outer diameter of the pipe was presumed to radiate (with a guessed emissivity of 0.1) to a constant shield temperature of 276K. The roughness of the pipe was assumed to be $\varepsilon/D = 4.0e-4$ (see Section V.4).

While the line was initially full of air, it was analytically convenient to avoid the complexities of a mixture and consider it full of GH2 instead at 276K and 0.82 atm. It was calculated that the air would be purged from the line in the first fraction of a second given the initial boil-off rate.

The valves at the inlet of the transfer line represented the largest concern given that they could causing flashing, choking, etc. In the end, the FloCAD FK calculator was used to tally up a total K-factor of approximately 8, and only a slight constriction (throat area) was assumed for choking. Departures from these assumptions had little effect, as detailed in Section V.4.

In order to facilitate comparisons with test data, four arithmetic (massless) nodes, representing the measurement stations, were placed at 20, 80, 140, and 200 feet (rounding the last two station locations to even distances for convenience). Since these positions sometimes fell between control volume locations, averages of adjacent temperatures were sometimes used. While such averaging could have been done in user logic or expressions, one-way SINDA conductors (which extract information without affecting results) were used to provide a geometric depiction of the measuring stations. These conductors are the black arrows depicted in Figure V-2.

The Thermal Desktop drawing and property files are available upon request if they were not included in the packet containing this document.

V.3 Comparison with Test Data

Figure V-4 presents the main results of this paper: a comparison of SINDA/FLUINT predictions with NBS test data. The predictions show the inlet side of the line filling slightly faster than actually happened in test, but overall the comparison is excellent, especially for the parameter that matters most: the total time (and therefore LH2 expended) to completely chill down the line.

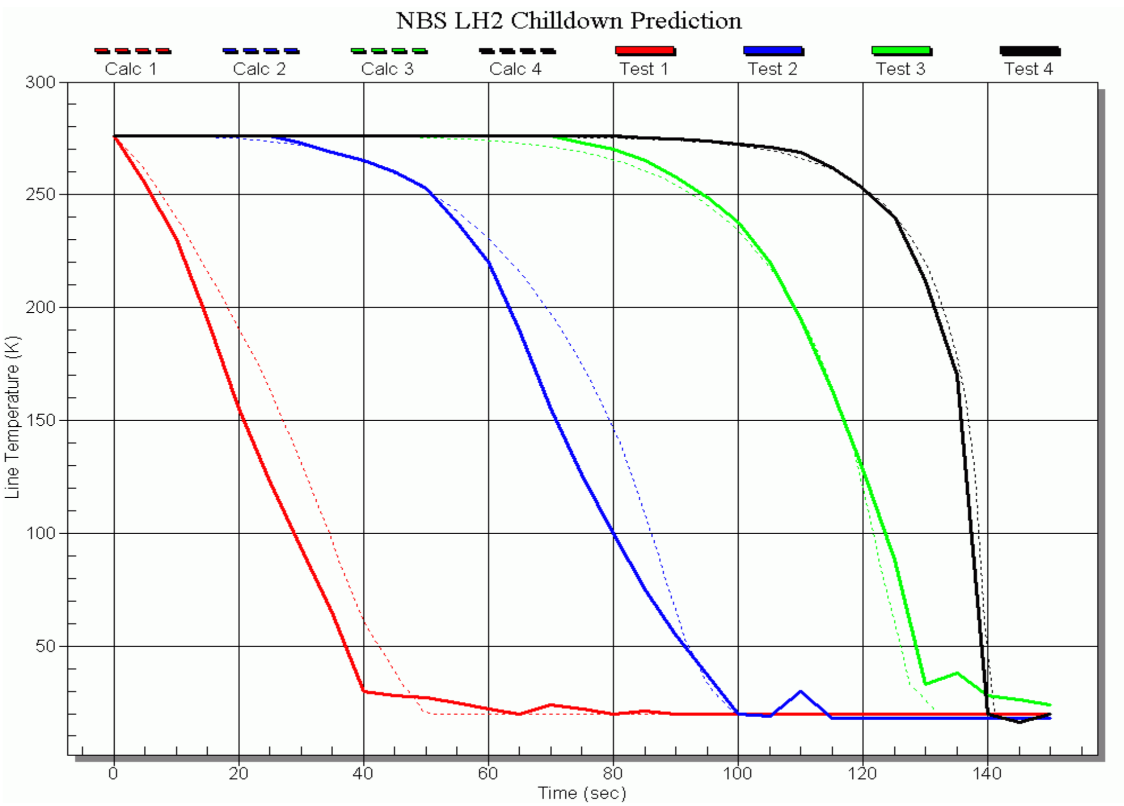

Figure V-4: Comparisons of SINDA/FLUINT Predictions with Test Data

V.4 Model and Parameter Variations

It is notoriously difficult to make comparisons with tests performed by third parties in advance of analysis. This case turns out to be the exception: almost all uncertainties turned out to have little to no effect on the final results. The two exceptions to this statement are therefore treated first, then a simple list is made of uncertainties and variations that had little effect on results, and finally a brief summary of modeling variations that were not needed (and therefore not explored) is provided for completeness.

Specific Heat--Variation of specific heat with temperature was critical to achieving a successful comparison. This sensitivity is to be expected considering the nature of the problem: the quenching of the pipe wall over a 250K range of sensible cooling. This model used a C_p vs. T profile for OFHC (oxygen free high conductivity) copper, a specialty alloy not normally available for the off-the-shelf tubing that was almost certainly used by NBS. Nonetheless, lacking better data no adjustments to this data were made. Scaling factors applied to this profile will, however, cause the final temperature histories to shift noticeably left and right (in time).

Wall Roughness--Another nonnegligible uncertainty was wall roughness, although it had a small effect. The results shown in the prior section were made using $\varepsilon/D = 0.0004$ (WRF in FLUINT). This value is only slightly higher than should be experienced in off-the-shelf copper tubing (ε/D of about 10^{-4}), but this higher value may be justified on the basis of joints or seams not described in the NBS report. Note that assuming a smooth wall ($\varepsilon/D=0$) speeds up the chill-down time by only 3.5%, so the uncertainty in this parameter is still not significant.

Variations that Had Little Effect--One of the surprises of this comparison was that seemingly important variations (both in modeling assumptions and inputs) turned out to have little effect on the final results. One of these choices (the choice of control volume type, tank vs. junction) is described in more detail below. Otherwise, a simple list will suffice. The following variations were verified to be unimportant:

1. *Gravity.* Because the line was horizontal, the only effect of gravity would be a change of flow regime (e.g., stratified instead of annular). Because of the shortness of the two-phase zone, such effects were unimportant. Slip flow ("twinned tubes" in FLUINT) can therefore be expected to be unnecessary as well.
2. *Wall emissivity and shield temperature (other than initial temperature).* Radiation is simply too weak to compete with a rush of LH2.
3. *Axial conduction.* The long thin aspect ratio of the lines meant that little energy flowed axially within the pipe wall compared to advection.
4. *Valve models.* Liquid fills the inlet portions of the line so quickly, and has such a low velocity compared to that of the vapor, that the total flow rate is largely determined by pressure drop in the vapor portion of the line and not in the inlet valves. Adding an unrealistically large K-factor (say, 100) had little to no effect on the results. Similarly, because the in-flowing liquid was subcooled, adding a significant restriction (small throat area, such that choking was more likely) proved inconsequential unless the restriction was unrealistically small (1% or less of available flow area).
5. *Resolution.* The axial resolution (discretization) of the model had little effect on the results, at least above the meager 20 segments the baseline model uses: models with more than twice the resolution produced nearly identical results.
6. *Tanks vs. Junctions.* FLUINT offer the choice of whether or not to include the storage and release of mass/energy within each control volume: whether filling or emptying of each control volume is significant ("tank," or finite volume control volume) or negligible (volumeless "junction"). This distinction is important enough that it will be described next in a separate subsection.

Tanks vs. Junctions--SINDA/FLUINT is perhaps unique amongst thermohydraulic solvers in that it permits the user to choose the degree of fidelity to the underlying physics. Flow inertia can be excluded or included (tube vs. STUBE connector), for example, as can assumptions such as homogeneous vs. slip flow.

Similarly, the ability to exclude energy/mass *storage* (not to be confused with *conservation*[*]) exists by choosing *junctions* instead of *tanks*, and thereby speeding up solutions. For example, if liquid in a coolant loop recirculates every 20 seconds, and if the event time of interest is on the order of tens of minutes or hours, then it makes no sense to monitor temperature lags within the loop (as long as no lag-sensitive control systems are present, such as thermostatic by-pass valves). If, on the other hand, a start-up transient of the same coolant loop were desired (e.g., an event on the order of seconds or tens of seconds), then FLUINT tanks would be required.

It was surprising, therefore, that tanks were *not* required in this comparison with a fast event: junctions gave almost exactly the same *thermal* response in a fraction of the solution time. To understand why this was true, consider that the transit time for a particle of vapor within the line was a fraction of a second (about 0.1 to 0.3 seconds) which is negligible compared to an event time of 150 seconds. Because of the approximate 700 fold increase in liquid density over vapor density, the transit times for a particle of liquid *was* on the order of the solution time: about 70 to 200 seconds. However, by the time a section of pipe had completely filled with liquid, all of the action (energy removal, specifically) was finished.

The above conclusion should not be extended to the hydrodynamic (pressure/flow-rate) response. When junctions are used, the mass flow rate is the same all the way along the line, though it varies with time. Figure V-5 shows the pressure response along the pipe for the baseline (junction-based) model. It can be seen from this figure that the inlet pressures rise quickly as they fill with slow-moving liquid (which helps explain why different valve models had so little effect). As the fraction of the pipe containing liquid increases, the flow rate also increases and the majority of the pressure drop occurs near the exit of the line, where the vapor approaches sonic velocities. At the very end of the run (past 140 seconds), the line contains 100% liquid and the pressure drop quickly becomes uniform along the line as the mass flowrate increases dramatically.

This graph is to be contrasted with the fully hydrodynamic (tank-based) solution presented in Figure V-6, which uses an expanded vertical scale. Despite producing the same temperature history, the pressures and flow rates oscillate violently as liquid hits the hot wall and boils almost explosively. Indeed, the pressures can easily exceed the source pressure and fluid can be pushed back into the supply tank: flows can reverse (as was reported by NBS in the original tests). Almost all of the conclusions of this document are based on the *thermal* response, which is important for estimating the quantity of the cryogen that must be expended to chill down a warm line. The *hydrodynamic* response, which is clearly more uncertain, will likely be very sensitive to valve models, resolution, two-phase assumptions, and other factors that are otherwise dismissed elsewhere in this document as being irrelevant to the *thermal* response of this particular test case.

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* Junctions balance energy flows and so conserve energy, they just neglect the dU/dt and dM/dt (storage) terms in the energy/mass equations.

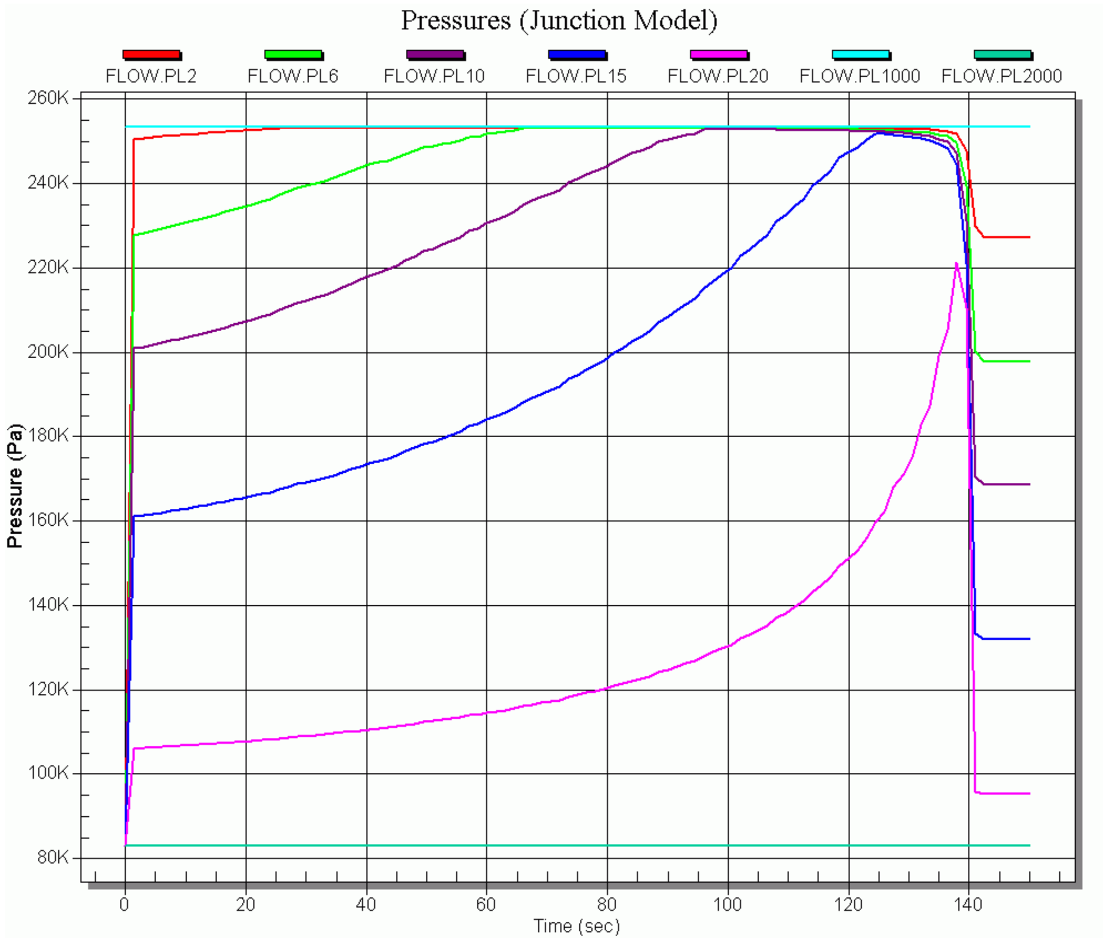

Figure V-5: Pressure Histories in Baseline Model at Selected Points

Variations not yet Explored--SINDA/FLUINT enables additional phenomena and complexity to be explored. While these extra options were clearly not required for this comparison, they are listed below since such a conclusion might not be the case in another scenario.

1. *Slip flow and nonequilibrium.* As was noted above, the abbreviated two-phase zone means that advanced two-phase effects such as slip flow (vapor velocities different from liquid velocities at the same cross-section) and phasic nonequilibrium (vapor temperatures different from liquid temperatures at the same cross-section) are of questionable value in this model, compared to potentially much slower solution times. This might not be true in other systems (especially larger diameter horizontal lines) or if more accuracy were required in peak pressure predictions. SINDA/FLUINT twinned tubes and twinned tanks could be employed if necessary for full two-fluid thermohydraulic modeling.

2. *Mixtures, including dissolved pressurant.* The air initially in the line was neglected, as mentioned above. It could have been modeled if it had not been negligible, though this would require SINDA/FLUINT to track multiple species through out the transient event even though they are only relevant at the very beginning. Perhaps more relevant would

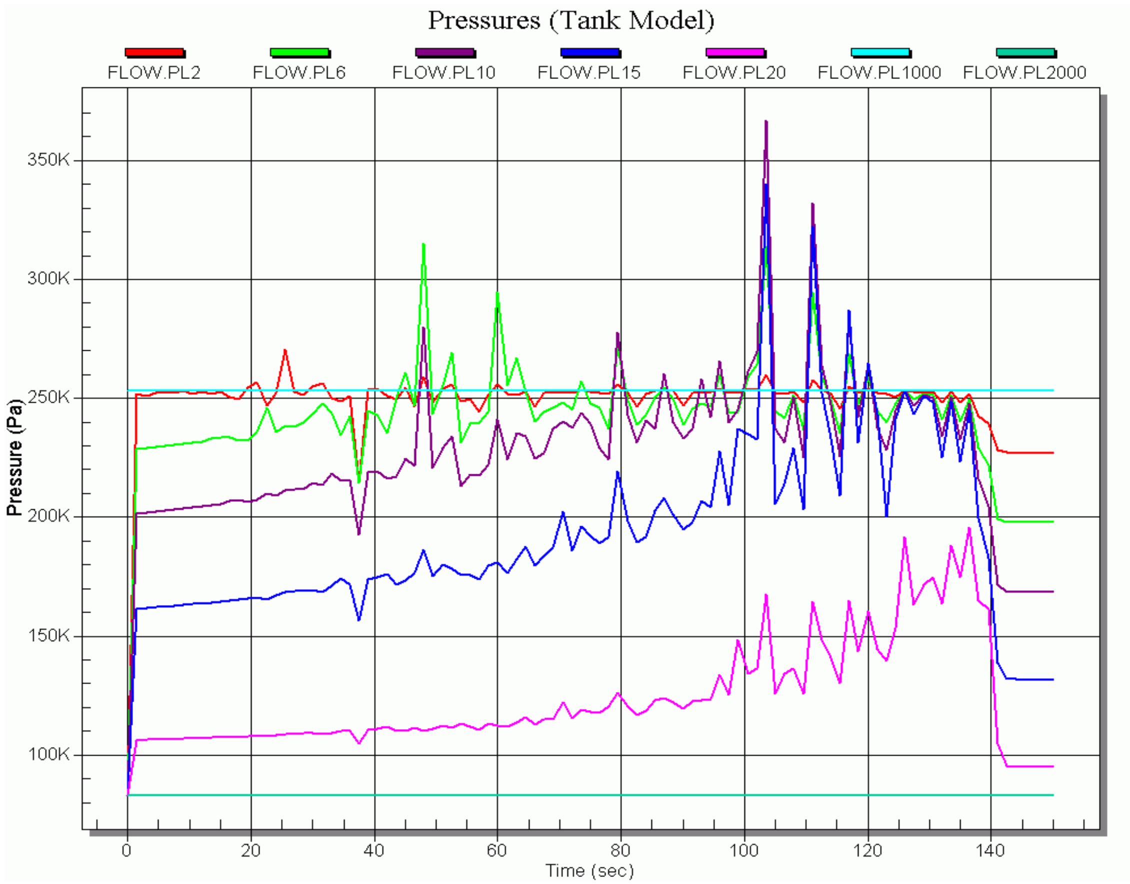

Figure V-6: Pressure Histories with Full Hydrodynamics (Tanks instead of Junctions)
Note: Expanded vertical scale from Figure V-5

be dissolved helium (presumably the pressurant used by NBS), which could similarly be included within SINDA/FLUINT's MIXTURE DATA if equilibrium solubility data is available. It is possible that this helium would come out of solution downstream of the control valves, and hence affect the response.

3. *Circumferential pipe resolution.* In a large diameter cryogenic transfer line that stratifies, it may be necessary to subdivide the wall model circumferentially (and perhaps radially) as well as axially. This would require extra modeling effort to "explain" to the software which wall nodes are above or below the liquid level, since otherwise nodes do not have an orientation with respect to gravity.

4. *Wall roughness effects on heat transfer, and entrance length effects.* These factors could be included, but are likely to be negligible considering the relative importance of boiling over single-phase convection.

5. *Alternate CHF and post-CHF heat transfer.* The default correlations for critical heat flux (CHF) and post-CHF heat transfer were employed. Although the wall *was* hotter than nucleate boiling could support as the liquid front reached each section, the effect was transient and highly localized, so adjustments to these correlations are unlikely to affect results. Similarly, other default correlations were used for flow regime mapping,

single- and two-phase heat transfer and pressure drop, high speed heat transfer, etc. They are all available for modification, but were left in their default state for this analysis, and were apparently adequate to the task.

6. *Supply tank response*. If the tank could not be assumed to be an infinite supply, then the depletion of the tank and perhaps the operation of the gas control system could be simulated if necessary. Refer to the stratified tank auxiliary problem at www.crtech.com for more details.