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Initial Experimentation on the Nonvented Fill of a 0.14 m^3 (5 ft^3) Dewar With Nitrogen and Hydrogen

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INITIAL EXPERIMENTATION ON THE NONVENTED FILL OF A 0.14 m^3 (5 ft^3) DEWAR WITH NITROGEN AND HYDROGEN

by

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SUMMARY

A series of nonvented fills have been performed on a 0.14 m^3 (5 ft^3) stainless steel dewar. Fills have been conducted with 120° cone angle spray nozzle over a range of inflow and initial wall temperatures with both liquid nitrogen and liquid hydrogen. Fill levels in excess of 85 percent liquid were achieved for four out of four nitrogen and two out of five hydrogen tests. Previously developed analytical models have been compared to the test results and shown to have general trend agreement.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) as part of its charter to explore the solar system is investigating methodologies to resupply cryogen to orbiting spacecraft. NASA's Lewis Research Center has been studying transfer technologies for cryogenic propellants such as hydrogen and oxygen. One of the most prominent methodologies is a technique known as nonvented fill. Ground-based transfer of cryogen is normally done with a vent open to remove the boil-off gas generated during the transfer process. Leaving the vent open during a fill in a low gravity environment such as Earth orbit creates the risk of ingesting liquid into the vent due to the lack of buoyancy forces required to separate the liquid and vapor phases. Liquid venting results in the loss of large quantities of propellant (brought to orbit at a considerable cost) and causes severe attitude control problems due to unbalanced venting induced accelerations. Thrusting to produce artificial gravity, and thus phase separation, leads to excessive fuel usage for many propellant transfer operations.

To overcome these problems, a two-step procedure has been developed which enables propellant to be transferred with the vent closed during liquid inflow. First, the tank is cooled to a specified thermal energy state. At this state, energy available for transfer between the tank walls, gaseous ullage, and incoming liquid is below the amount which could result in a tank pressure rise such that the maximum tank operating pressure is exceeded during the fill. Several methods have been proposed for the chilldown of the tank. One of the most promising is to inject a small charge of liquid with the vent closed. After allowing the liquid to vaporize and reach equilibrium with the tank walls, the resultant gas is vented, and the process is repeated until the tank is cooled to the required "target" temperature (that temperature which meets the energy criteria specified above). After the target temperature is reached, the second step is to begin filling the tank. During this process spray nozzles and jets are used to promote vapor-liquid heat transfer and to insure that the majority of vapor generated collapses back into the bulk liquid. The dynamics of this process are also influenced by the amount of subcooling of the incoming liquid based on the saturation temperature at the tank's maximum operating pressure, the type of fill technique employed, and the liquid flow rate. The chill-fill procedures have been shown to be theoretically capable of fill levels in excess of 95 percent liquid by volume. However, experimental experience with the nonvented fill is extremely limited.

To gain experience with the nonvented fill, a small scale experimental rig has been constructed to fill a 0.14 m^3 (5 ft^3) dewar without venting in a 1-G environment. Some

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of the limitations of the rig are that it is incapable of simulating the flow fields found in low gravity and it is of much smaller volume than the typical spacecraft tankage expected to be filled. Even so, it is expected to produce a better understanding of the driving forces of nonvented fill and the bounding parameters under which fill to a reasonable level can be achieved. This paper will report the results of initial testing with this rig and compare the data to theoretical predictions.

EXPERIMENTAL RIG DESCRIPTION

The Liquid Transfer Cryogenic Test Facility is located in Cell 7 of the Cryogenic Components Laboratory (CCL-7) of the NASA Lewis Research Center. A photograph of the installed test rig is shown in figure 1. Operation and monitoring functions are performed in a remotely located control room, which is separated from the testing area by earth embankments. Video cameras provide continuous viewing of the rig from several nearby vantage points. The facility is designed to accommodate both nitrogen and hydrogen testing. All safety precautions required for hydrogen testing are incorporated in the rig design and test procedures. A detailed description of the test cell is given in Moran, Nyland, and Papell (ref. 1).

Hardware

Fluid handling in the CCL-7 facility is performed with a supply dewar and two interchangeable receiver dewars. Only the larger of the receiver dewars was tested in the initial experiments described in this paper. Liquid cryogen is loaded into the supply tank from an adjacent portable dewar, and thermally conditioned prior to the initiation of a test.

A schematic of the supply and one of the receiver tanks as they are installed in the test facility, is presented in figure 2.

<u>Supply dewar</u>. - The supply dewar is a vacuum-jacketed stainless steel tank containing multilayer insulation (MLI) within the vacuum annulus. The dewar is composed of a cylindrical main body with an overall height of 60 in. and a mating lid assembly. The main body is open at the top for insertion of the lid and has an inside diameter of 22 in. Both the main body and lid are flanged to accommodate a bolted, double o-ring joint. The top of the lid contains piping and instrumentation penetrations. The top is recessed to allow application of foamed insulation. Internal volume of the supply tank is approximately 18 ft^3.

<u>Receiver dewar</u>. - The construction of the large receiver is similar to that of the supply dewar. The receiver, with an overall height of 32 in. and an inside diameter identical to the supply dewar (22 in.), has an internal volume of approximately 5 ft^3. The lid assembly of the receiver is composed of a short cylindrical section with an inverted dome bottom. The assembly is evacuated and insulated with MLI to minimize heat transmission through the dome from the environment. Figure 3 presents a photograph of the receiver lid.

With the lid in place, the interior walls of the assembled receiver tank form a cylindrical storage volume with domed ends. Piping penetrations include four lines. One line provides venting, pressurization, and burst disk pressure relief. Two liquid lines are supplied for various liquid transfer configurations. Another liquid line provides for tank dump on test completion. An additional penetration is provided for the liquid level probe.

<u>Piping systems</u>. - Liquid lines are constructed of stainless steel and are vacuum jacketed or foam insulated throughout the rig. The rig is capable of transferring liquid cryogen between the dewars using a variety of fill configurations. The dump line also

allows the liquid to be returned to the supply dewar. Liquid line valves are pneumatically actuated and vacuum jacketed. Control electronics and power supplies for all the valves in the system are located in sealed, nitrogen purged cabinets.

The vent system is composed of stainless steel lines connected to each tank. An air ejector system provides sub-atmospheric pressure control in the vent lines to as low as 2 psia. Compressed air at 120 psig is used to operate the air ejectors. Vent line control valves are pneumatically operated and explosion proof. Because the valves are not designed for cryogenic temperature service, finned pipe sections are located just downstream of the tanks to insure near ambient vapor temperatures within the vent lines before reaching the control valves.

Pressurization with helium, hydrogen, or nitrogen (during liquid nitrogen tests) is available for the supply and receiver tanks. A simplified piping schematic of the test rig is given in figure 4.

Instrumentation

All power supplies and terminal blocks located within the test cell are enclosed in nitrogen purged cabinets. Rig instrumentation lines are routed to the control room via shielded cabling. Sensor signals are monitored with panel mounted LED and LCD displays in the control room. They are also displayed on the dedicated microcomputer screen when the data acquisition software is operating.

Temperature and point level measurement. - Temperature sensors are positioned throughout the rig on all tanks and selected lines and components. Temperature measurements are obtained with thermocouples and silicon diodes. Estimated measurement accuracies are 0.2 °R for the silicon diodes and 2 °R for thermocouples. Thermistors are used as point level sensors to indicate the presence of liquid or vapor. Thermistor position has been determined to 0.1 percent of tank height. Figure 5 illustrates temperature sensor and thermistor locations for the supply and receiver tanks.

Tank wall thermocouples and silicon diodes are located in the annular vacuum space of both tanks and are mounted to the inner tank wall. The supply tank contains four thermocouples vertically spaced on the wall, two at the tank bottom, and an additional four thermocouples positioned 180° circumferentially from the original array. Four silicon diodes are mounted in the same location as the first array of wall thermocouples, and one diode is positioned at the bottom of the tank. Two final silicon diodes are located on the inside lid of the supply tank.

Similarly, the receiver tank contains 10 thermocouples vertically spaced on the tank wall along the same circumferential angle. At two different vertical heights, 21 thermocouples are placed around the tank wall in 3-in. circumferential increments. Fourteen silicon diodes are mounted next to selected thermocouples, and an additional two diodes are located on the inside lid.

Within each tank is an instrument tree containing silicon diodes and thermistors at varying heights. This tree is in direct contact with the tank contents, whether liquid or vapor. The supply dewar contains a total of 6 silicon diodes and 10 thermistors on the instrument tree. Alternately, the receiver has 11 silicon diodes and 5 thermistors. Five of the tree diodes for the receiver are located near the 70 percent height level and are spaced 0.25 in. apart.

In addition to the tank wall and tree temperature measurements, other temperature sensors are placed in key locations throughout the rig. Thermocouples are positioned on the flange of each tank and on all tank vent lines. Additional thermocouples monitor the liquid dump, valve prechill, and receiver tank return lines. Silicon diodes are mounted on the tank inlet and outlet lines, as well as on all venturi flowmeters.

Pressure measurement. - Pressure transducers installed on the vent lines of both tanks and the TVS provide continuous internal pressure data on these components. Total pressure and pressure differential measurements are also available on all venturi flowmeters. Finally, a pressure sensor is installed in the exhaust line of the air ejector. Pressure measurement accuracies are 0.5 percent full scale.

Flow measurement. - Mass flow rate through the liquid inlet lines of the supply and receiver tanks is calculated with venturi flowmeters. The flowmeters are instrumented with temperature and pressure taps as previously described. The vent lines of both tanks can be routed through a mass flow measuring system. This system consists of four thermal conductivity type mass flow meters and a venturi. The particular meter used and measurement accuracy depends on the flow rate being measured.

Continuous liquid level. - Liquid height as a percentage of total tank height is measured via a commercial capacitance level probe. The probe is constructed of an outer and inner pipe which form an annular space where liquid and vapor accumulates. Holes are drilled in the outer pipe to allow inflow of cryogen into the annular space. The probe is mounted vertically within the tank, and capacitance measurements of the space between the pipes are made. The magnitude of the capacitance reading for a particular fluid is an indication of the fraction of liquid versus vapor resident in the annular space. In this way, the probe provides a measurement of the liquid height within the tank. The level probe was calibrated in place against the point level sensors. Root mean square error after calibration was 1.3 percent of tank height in nitrogen and 2.4 percent of tank height in hydrogen.

TEST PROCEDURE

Performance of a nonvented fill test involves five sequential steps:

(1) System purge: The system is pressurized to 25 psia with gaseous helium and checked for leaks. The helium is then vented through the air ejector. This purge cycle is repeated a total of four times, with leak detection performed on the first cycle only.

(2) Filling the supply dewar and conditioning the cryogen: The supply dewar is filled from the roadable dewar with enough liquid to perform the planned test. With the supply tank filled, the liquid is thermally conditioned to the desired temperature by adjusting the tank pressure to the corresponding saturation pressure for that temperature. The tank is pressurized with gaseous pressurant for conditions above atmospheric. Conversely, the air ejector system is utilized for achieving pressures below one atmosphere.

(3) Prechill of the transfer line: With the cryogen conditioned to the desired temperature, the supply tank is pressurized for liquid transfer. The transfer line and associated components (e.g., valves, fittings, etc.) are then prechilled with a low flow rate of liquid.

(4) Receiver tank chilldown: The receiver tank pressure is reduced below atmospheric with the air ejector. A charge of liquid is then loaded into the receiver tank with the vent valve closed. The vent remains closed while the liquid boils, thus removing heat from the tank walls. When the tank pressure reaches a predetermined maximum or stabilizes, the vent valve is opened. Additional cooling is achieved as the tank pressure is once again brought below one atmosphere using the air ejector system. The resulting charge-hold-vent cycle is repeated until the tank wall temperature is reduced to the desired starting condition. This step also serves to purge the receiver of residual helium from step 1.

(5) Nonvented fill: In the final step, the liquid cryogen is transferred from the supply to the receiver tank until the receiver is filled or until the pressure reaches a predetermined maximum value.

RESULTS

Four nitrogen and five hydrogen nonvented fills were performed with the CCL-7 rig in 1989. All tests were conducted using a full cone nozzle producing a conical spray of liquid droplets with a roughly 120° cone angle from the top of the large receiver tank. The outlet of the nozzle faces downward and is at the 90 percent fill level. A sketch of this filling configuration is presented in figure 6.

Experimental Data

A composite graph of pressure versus time for all nitrogen nonvented fills performed at CCL-7 in this test series is presented in figure 7. Table I lists pertinent parameters for these tests. At the completion of the nonvented fills of figure 7, all liquid fill levels were greater than 90 percent. For tests N2 and N3, the fill level met or exceeded 97 percent.

Figure 8 shows a similar composite graph of all the hydrogen nonvented fills performed at CCL-7 in this test series. Table II presents test conditions for this set of data. In contrast to the nitrogen tests, high fill levels were more difficult to achieve with hydrogen. In fact, test H2 was the only hydrogen nonvented fill to reach 90 percent, with H4 achieving the next highest final fill level of 86 percent.

Transient instrument tree temperature data for the first minute of hydrogen nonvented fill H2 is plotted in figure 9. Plot labels indicate vertical height from the tank bottom and are nominal. Tree temperatures decrease rapidly during the initial moments of this nonvented fill. In fact, one minute into the test, all tree temperature sensors are within 2 °R or less of each other and remain so for the balance of the test. This behavior is indicative of both the hydrogen and nitrogen fills performed with the inlet spray nozzle configuration. However, the time lag for convergence of the tree temperatures during nitrogen tests is somewhat longer (e.g., 5 min), and the maximum temperature difference between sensors is on the order of 10 °R.

Wall temperature data for the H2 test is presented in figure 10. The upper plot indicates temperature data for the first 1 min of the nonvented fill, while the lower plot represents the remainder of the test. Once again, plot labels denote nominal height from the tank bottom. Examination of figure 10 indicates that all but the top two wall sensors drop rapidly in temperature, much like the instrument tree temperatures. Note that the 21 in. and top sensors are located above the point where the inlet spray impinges the wall. Once again, this trend is indicative of all the nonvented fills performed to date, with a similar time lag difference between nitrogen and hydrogen tests as noted previously for the tree temperature data.

Analytical Modeling

Chato in his previous work (refs. 2 and 3) has developed theoretical models of the no-vent fill process using thermodynamic relations and heat transfer correlations. A computer code called NVFILL has been constructed to iteratively solve the model equations enabling the prediction of thermal and pressure transients for various nonvented fills. Documentation of the NVFILL code is contained in Cowgill, Chato, and Saad (ref. 4). The current paper represents the first attempt to verify the code with experimental data.

Some changes to the code were made to allow a more accurate simulation of the CCL-7 test conditions. Modifications included adaptating for use with liquid nitrogen and adding the ability to input initial tank pressures. The algorithm developed in Chato 1989 (ref. 3) for heat transfer from droplet sprays was added to replace a user input heat transfer coefficient. Finally new subroutines were added to calculate fill height as a function of liquid volume specific to the CCL-7 receiver tank, estimated input heat transfer coefficient. Finally new subroutines were added to calculate fill height as a function of liquid volume specific to the CCL-7 receiver tank, estimated droplet flight distance, and stored energy for the stainless steel wall (previous models assumed aluminum tankage).

The new code has as user inputs the following parameters: Mass to volume ratio, inflow rate, mean droplet size for spray, starting pressure, inflow temperature, and starting wall temperature. The values in tables I and II were used for the majority of inputs. Mean droplet size was calculated using the method described in Chato 1989 (ref. 3). Droplet size was 882 μm for the nitrogen runs and 523 μm for hydrogen. Tank mass-to-volume calculation proved difficult. Tank mass-to-volume for mass in direct contact with the liquid is 6.21 lbm/ft^3, but this number seems to seriously overestimate the initial tank pressure rise. By observing the test data it was concluded that the tank lid did not cool until significantly after the initial pressure rise was completed, so this mass was eliminated from the calculation. The tank bottom was also eliminated because this mass was at approximately the liquid inflow temperature at the start of all tests. The mass-to-volume ratio with these masses eliminated is 2.1 lbm/ft^3. Table I and II values for initial wall temperature were used even though these include the lid and bottom temperatures. It was the authors' opinion that, since elimination of the lid and bottom masses removed the hottest and coldest temperatures from the average calculation, the average value would not change significantly (this opinion was reenforced by the results of limited hand calculation). Figure 11 shows NVFILL predictions for LN2 runs; figure 12 shows NVFILL predictions for LH2 runs. Trend similarity between the analyses and experiment is seen in all the nitrogen and hydrogen pressure histories.

Discussion

Figure 13 illustrates a plot of the receiver tank pressure as a function of time from one of the hydrogen tests. The liquid inlet temperature for this test averaged 34 °R, with an average mass flow rate of 1.36 lbm/min. The nonvented fill was initiated with the receiver tank at 3.6 psia, with an estimated average wall temperature of 103 °R.

Nonvented fill tests conducted at CCL-7 exhibit three distinct time dependent pressure regions as indicated by the labels 1 to 3 in figure 13. The first region is a period of rapid boil off as the incoming liquid spray impinges on the tank wall and absorbs its thermal energy. This region is characterized by a steep pressure rise in the receiver tank. For the test presented, the tank pressure reaches a maximum of 18.7 psia. In the second region, the slope of the pressure curve decreases even to the extent of becoming negative for some fills. At this point in the fill process, boiling of the liquid cryogen decreases, and the effect of ullage vapor condensation onto the incoming liquid droplets becomes more evident. The magnitude and sign of the pressure curve slope in region 2 is dictated by the competing processes of condensation and boiling within the tank. For the test of figure 13, the mass transfer due to condensation is greater than that transferred by boiling, resulting in a gradual pressure decrease with time (i.e., negative pressure curve slope).

The tank pressure at the end of region 2 is 15.7 psia. Region 3 develops as the spray nozzle begins to be submerged by the rising liquid interface. As the nozzle is covered, condensation on the liquid droplets ceases, and the pressure rises suddenly as the ullage is compressed. For this test the final tank pressure reaches 16.6 psia.

A plot of liquid fill level versus time for the same nonvented fill test is presented in figure 14. The three previously described regions are marked for reference.

The liquid filling rate of figure 14 decreases with time toward the end of region 1, as indicated by a gradual reduction in the slope of the liquid level curve at this point. The rapid pressure rise in the receiver tank in this region reduces the differential pressure between the supply and receiver tanks, thus lowering the mass flow rate. Liquid level at the end of this region is 10.0 percent. In the second region, the liquid level curve is relatively linear, indicating a virtually constant flow rate. A fill level of 89.9 percent is reached at the end of region 2. Finally, in the last region, The flow rate is reduced as the pressure rapidly rises due to ullage compression. The final fill level for this hydrogen test was 90.8 percent.

The nitrogen nonvented fills represented in figure 7 all exhibit the three pressure response regions described earlier. The hydrogen nonvented fills in figure 8 all show the first two regions. Since H2 was the singular hydrogen test with a final fill level of 90 percent or greater, its pressure curve is the only one exhibiting the region 3 pressure rise corresponding to submersion of the spray nozzle. The shape of the curves and the final tank pressure vary significantly among the fills as a result of the test conditions. A primary parameter affecting the pressure history in these tests is the inlet liquid temperature. At the lower inlet temperatures, the pressure level drops in region 2. For the nitrogen tests there is a one-to-one correspondence between the inlet temperature and pressure level at the end of region 2. The lower the inlet temperature, the lower the pressure level. The same correspondence is true for the hydrogen tests with the exception of H3 and H5. Other conditions listed in tables I and II also contribute to the tank pressure response.

Agreement between the analysis and the test data is not as good as would be desirable. Trends for the analytical curves and comparable test data are quite similar. The model overpredicts the initial rate of pressure rise for the nitrogen tests. This discrepancy appears to be due to an overly optimistic estimate of the heat transfer rate between the tank walls and the incoming droplet spray. Unpublished data collected by the authors from other test rigs reinforce this assessment. Efforts are now under way to develop a wall-droplet heat transfer correlation in better agreement with the empirical data. The model underpredicts final fill pressure for all tests except H3. This second discrepancy is more difficult to explain. Attempted alternate analyses have shown similar pressure disagreement. The suspected source is the secondary heat loads into the test rig which are not included in the model. It is estimated from the hydrogen saturation curve that a 1 °R change in inflow temperature will produce about 2 psia change in pressure level. One load is heat leak into the line between the venturi where the inlet temperature is measured and the spray nozzle. If the insulation is performing to specification, this heat leak is calculated to only produce a maximum 0.2 °R temperature rise, which is insufficient to account for the pressure difference. However a similar line from the supply to the venturi shows a 2 °R rise as installed. The inner dewar walls which attach directly to a flange near ambient are another source of heat. Hand calculations estimate the steady-state heat load at approximately 150 Btu/hr for liquid hydrogen tests. If this load is assumed to be absorbed in the inflow, it will result in a 1.2 °R rise in inflow temperature at a inflow rate of 1 lbm/min.

CONCLUDING REMARKS

Initial testing completed at CCL-7 with nitrogen and hydrogen indicates that nonvented fills in excess of 90 percent full are achievable with these fluids. Using the described test configuration and procedures, 90 percent fill levels were accomplished with nitrogen at inlet liquid temperatures as high as 143 °R (19 psia saturation pressure), and an average tank wall temperature of nearly 300 °R. Hydrogen was found to be considerably more difficult to transfer without venting. The highest temperature conditions resulting in a fill level greater than 90 percent were with an inlet liquid temperature of 34 °R (10 psia saturation pressure) and an estimated tank wall temperature of slightly more than 100 °R. All tests were performed with a top mounted, 120° full cone, droplet spray nozzle. Maximum receiver tank pressure was limited to 30 psia.

The shape of the time varying pressure curve for nonvented fill tests using the fill technique described is characterized by three distinct regions. These regions are delineated by (1) an initial steep pressure rise as the incoming liquid boils rapidly due to impingement on the warm tank walls, (2) a sizable decrease and possible sign change of the pressure curve slope as boiling decreases and the effects of condensation of the ullage vapor on the incoming droplets becomes more evident, and (3) a sudden pressure rise as the liquid interface begins to submerge the inlet nozzle. Region 3 develops only in those tests which exceed the 90 percent fill level by volume for the test configuration employed.

Inlet liquid temperature appears to be a primary parameter affecting the shape and magnitude of the pressure curve for nonvented fills with both nitrogen and hydrogen. Other test conditions, however, also play a role in the pressure history.

The analyses presented show comparable trends to the test data. It should be borne in mind that the analytical model was developed prior to the test runs so even general agreement leads to some confidence in the modeling approach. Work is already underway to enhance the model in light of the empirical evidence obtained in this test series. The attempt to reconcile the model and test data has improved the authors' understanding of the hardware limitations imposed by this test rig.

Future work for this rig includes testing of alternate inlet configurations and further investigation on the effect of target temperature on the fill process. It is the authors' belief that the information contained in this paper will substantially increase the knowledge and understanding of the no-vent fill process. Work underway at NASA Lewis to conduct large-scale ground testing and orbital testing on the COLD-SAT spacecraft has been greatly aided by the initial runs of this test program.

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2. Chato, D.J., "Thermodynamic Modeling of the No-Vent Fill Methodology for Transferring Cryogen in Low-Gravity," AIAA Paper 88-3403, July 1988 (Also, NASA TM-100932, 1988).

3. Chato, D.J., "Analysis of the Nonvented Fill of a 4.96 Cubic Meter Lightweight Liquid Hydrogen Tank," ASME Paper 89-HT-10, Aug. 1989 (Also, NASA TM-102039, 1989).

4. Cowgill, G.R., Chato, D.J., and Saad, E., "CryoTran Users Manual Version 1.0," NASA TM-102468, 1989.

TABLE I. - TEST PARAMETERS FOR NITROGEN NONVENTED FILLS AT CCL-7

	Test			
	N3	N2	N1	N4
Liquid inlet temperature, average, °R	122	126	131	143
Initial wall temperature, estimated, °R	299	273	223	176
Inlet mass flow rate, average, lbm/min	11.2	10.7	7.9	7.1
Initial receiver pressure, psia	4.5	3.9	3.6	4.9
Final fill level, percent full by volume	97	98	93	90

TABLE II. - TEST PARAMETERS FOR HYDROGEN NONVENTED FILLS AT CCL-7

	Test				
	H4	H2	H1	H5	H3
Liquid inlet temperature, average, °R	34	34	38	39	41
Initial wall temperature, estimated, °R	55	103	111	90	75
Inlet mass flow rate, average, lbm/min	3.05	1.36	1.31	1.28	1.89
Initial receiver pressure, psia	3.1	3.6	3.7	4.0	3.8
Final fill level, percent full by volume	86	91	45	14	39

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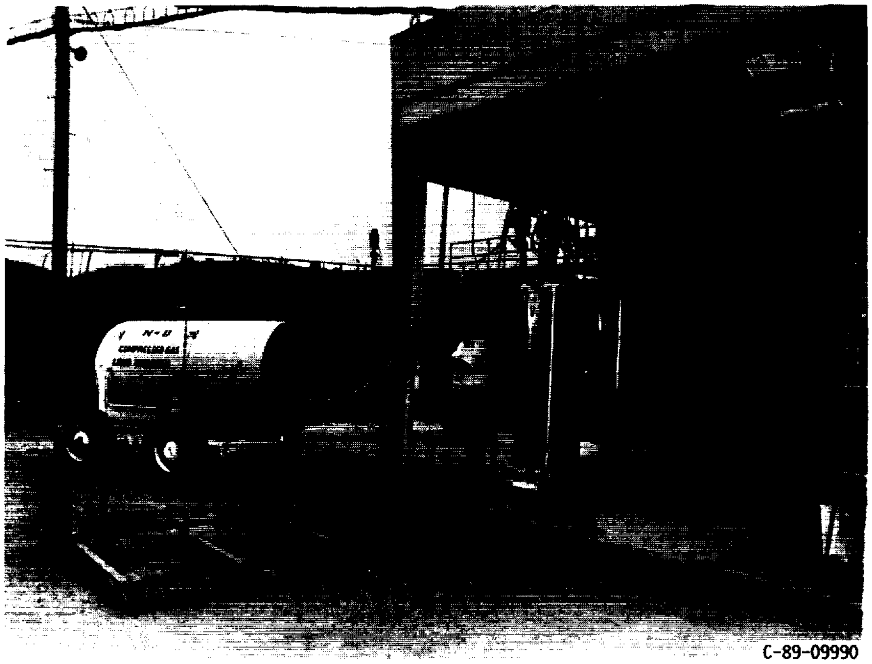

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FIGURE 1. - PHOTOGRAPH OF THE CCL-7 TEST CELL.

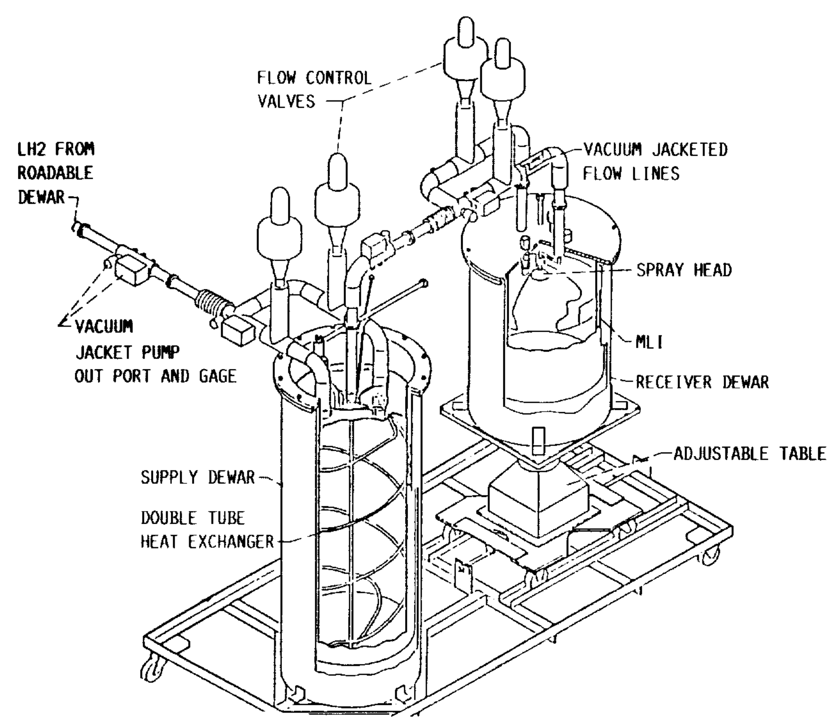

FIGURE 2. - SUPPLY AND LARGE RECEIVER TANKS AS INSTALLED IN CCL-7.

FIGURE 3. - PHOTOGRAPH OF THE LARGE RECEIVER LID ASSEMBLY.

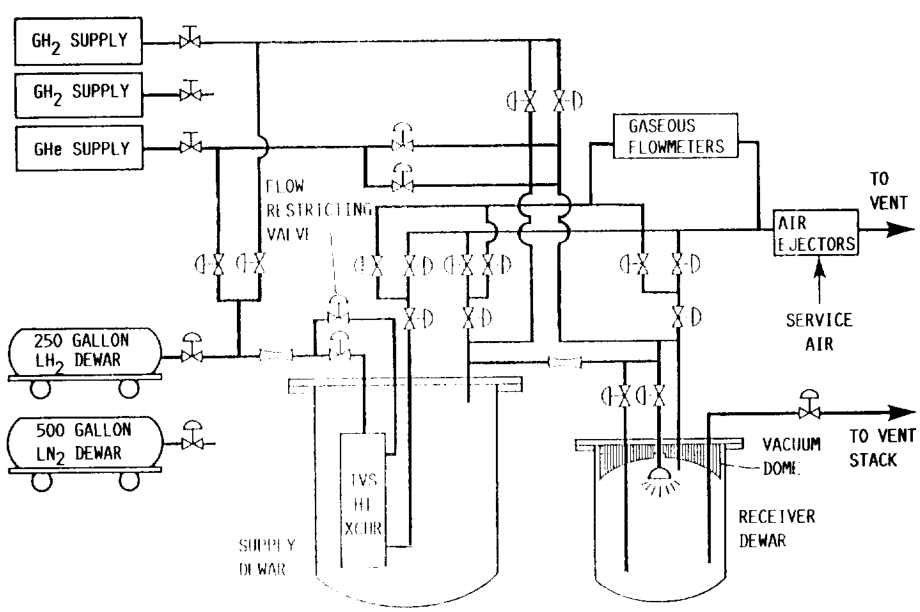

FIGURE 4. - SIMPLIFIED PIPING SCHEMATIC OF CCL-7 TEST RIG.

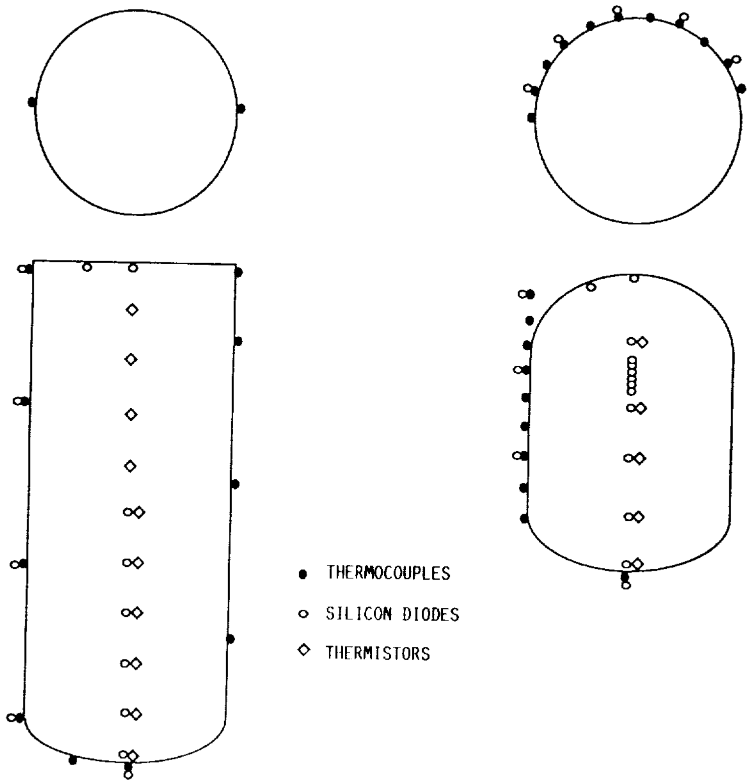

FIGURE 5. - APPROXIMATE LOCATIONS OF TEMPERATURE SENSORS AND THERMISTORS FOR THE SUPPLY AND LARGE RECEIVER TANKS.

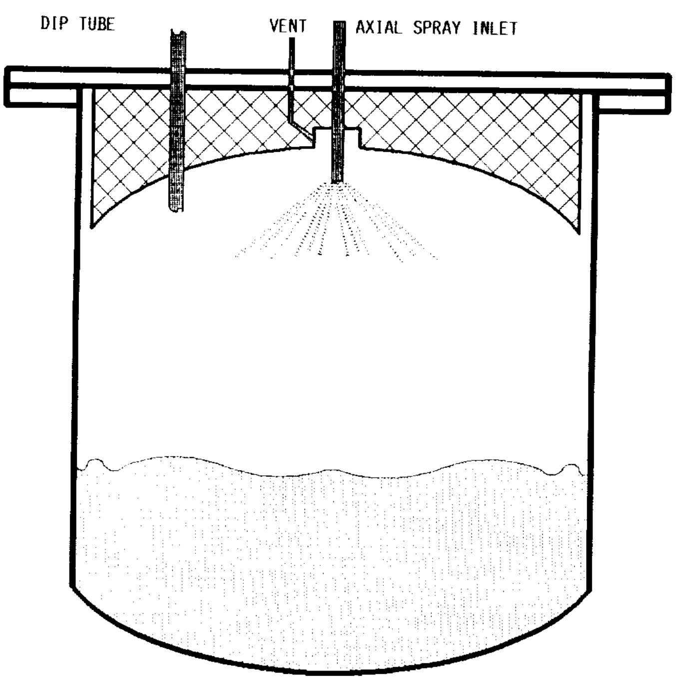

FIGURE 6. - FILL CONFIGURATION USED FOR NONVENTED FILLS IN CCL-7.

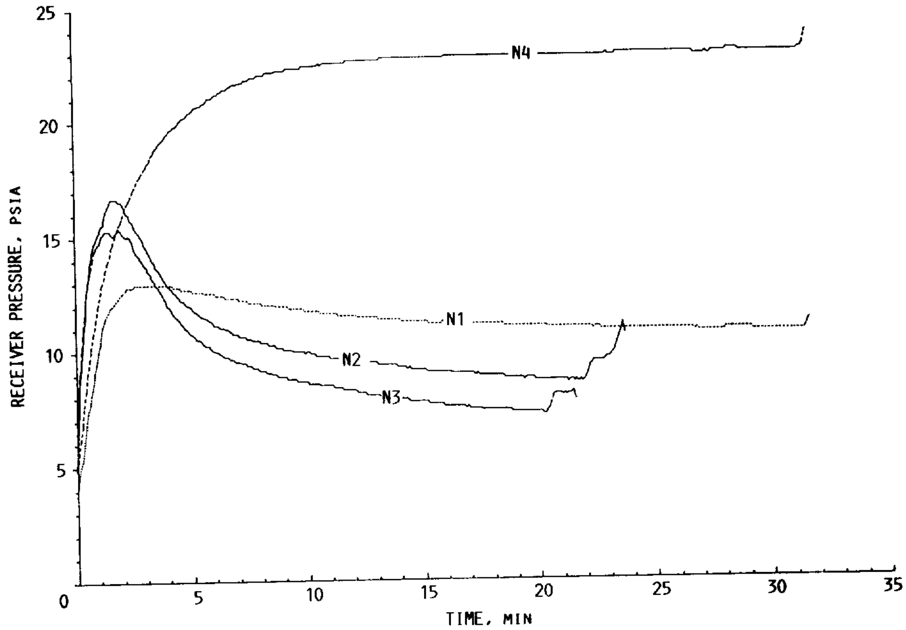

FIGURE 7. - COMPOSITE GRAPH OF RECEIVER TANK PRESSURE AS A FUNCTION OF TIME FOR NITROGEN NONVENTED FILLS AT CCL-7.

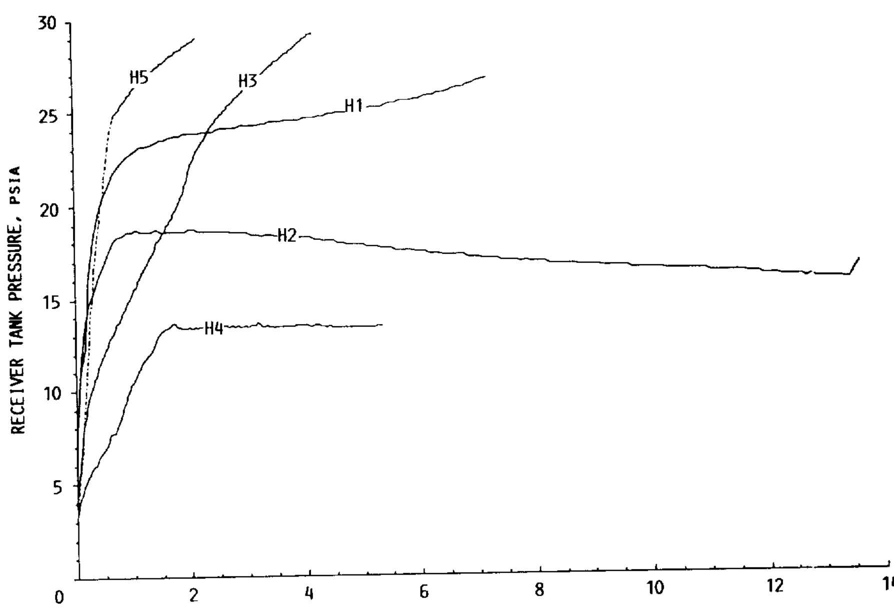

FIGURE 8. - COMPOSITE GRAPH OF RECEIVER TANK PRESSURE AS A FUNCTION OF TIME FOR HYDROGEN NONVENTED FILLS AT CCL-7.

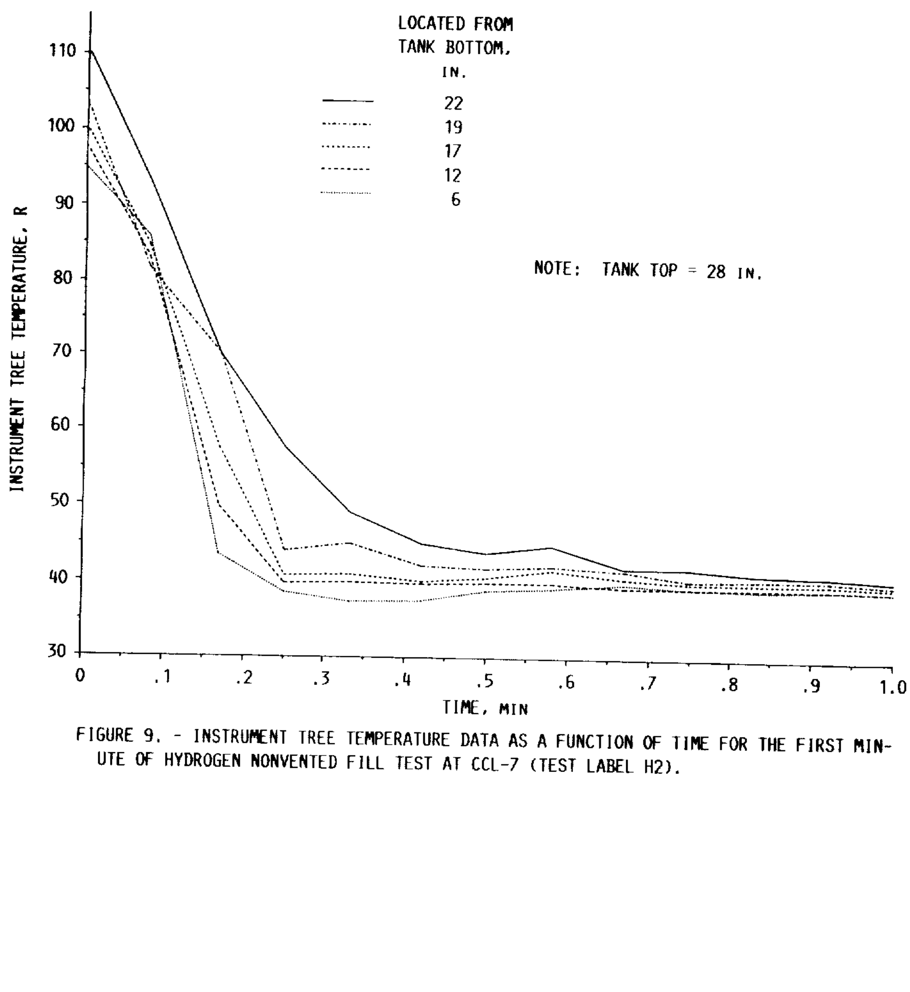

FIGURE 9. - INSTRUMENT TREE TEMPERATURE DATA AS A FUNCTION OF TIME FOR THE FIRST MINUTE OF HYDROGEN NONVENTED FILL TEST AT CCL-7 (TEST LABEL H2).

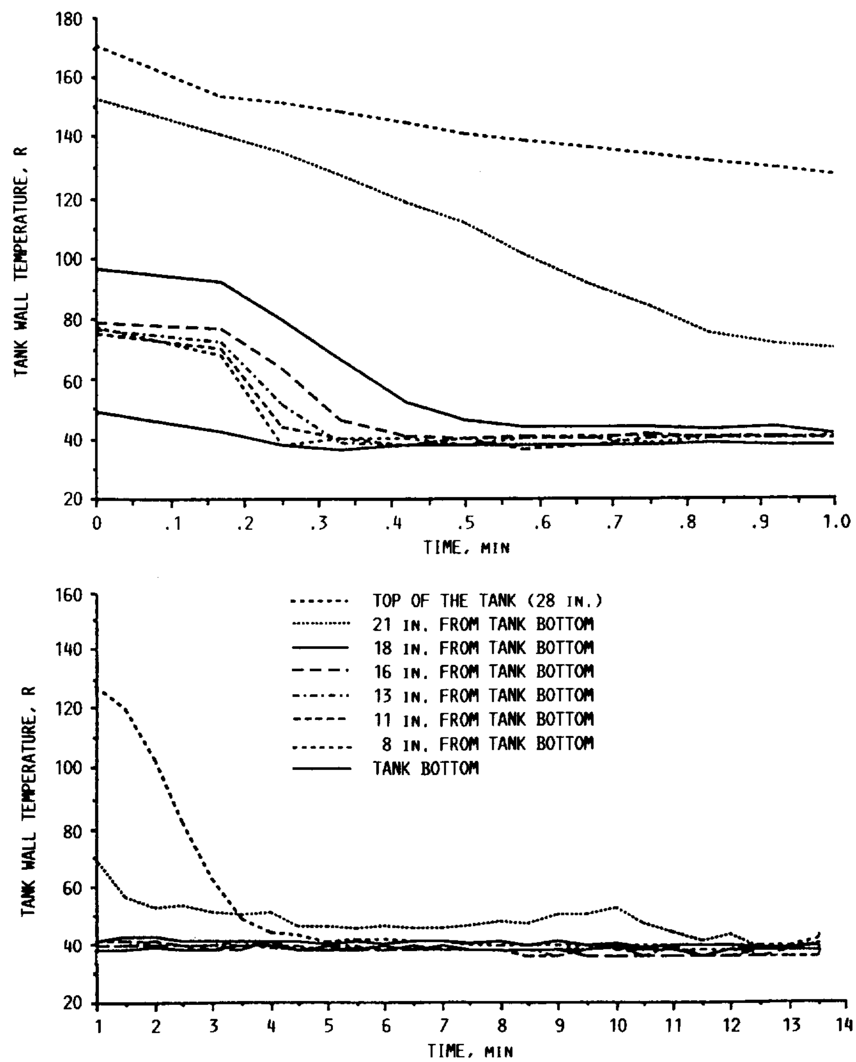

FIGURE 10. - TANK WALL TEMPERATURE DATA AS A FUNCTION OF TIME FOR HYDROGEN NON-VENTED FILL TEST AT CCL-7 (TEST LABEL H2).

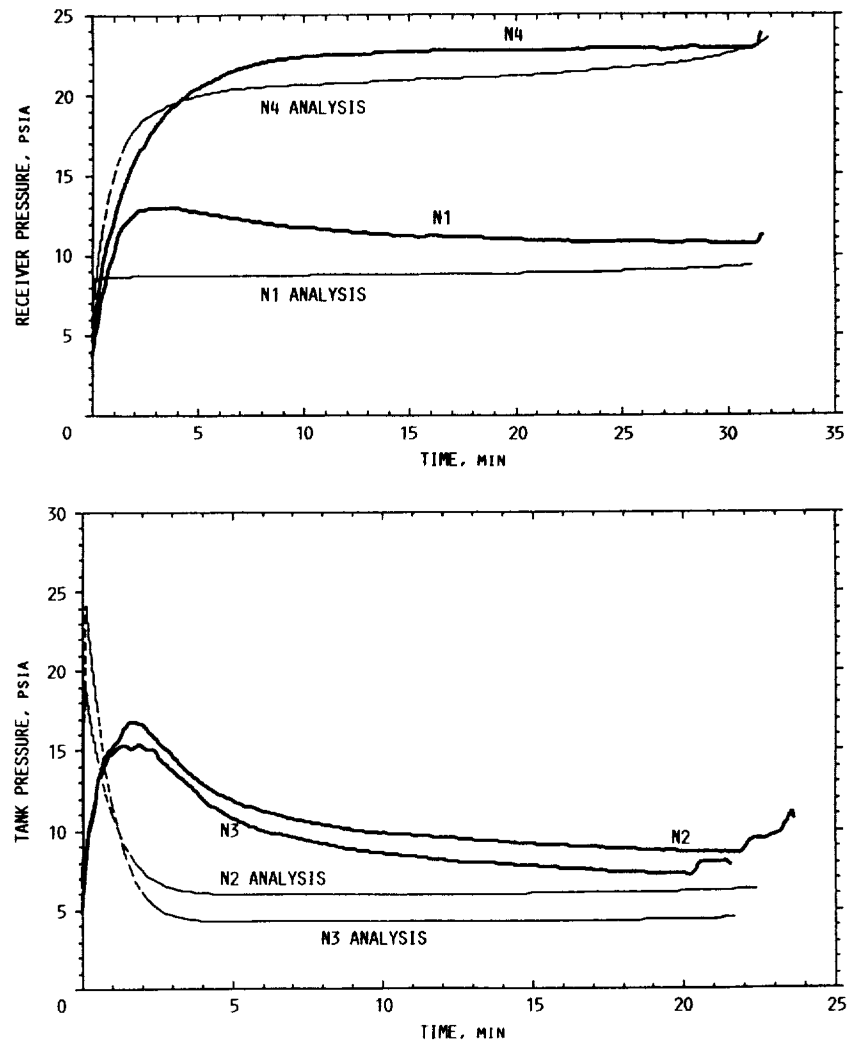

FIGURE 11. - COMPARISON OF ANALYTICAL PREDICTIONS FOR NONVENTED FILL TO CCL-7 PRESSURE HISTORIES DURING LIQUID NITROGEN TESTS.

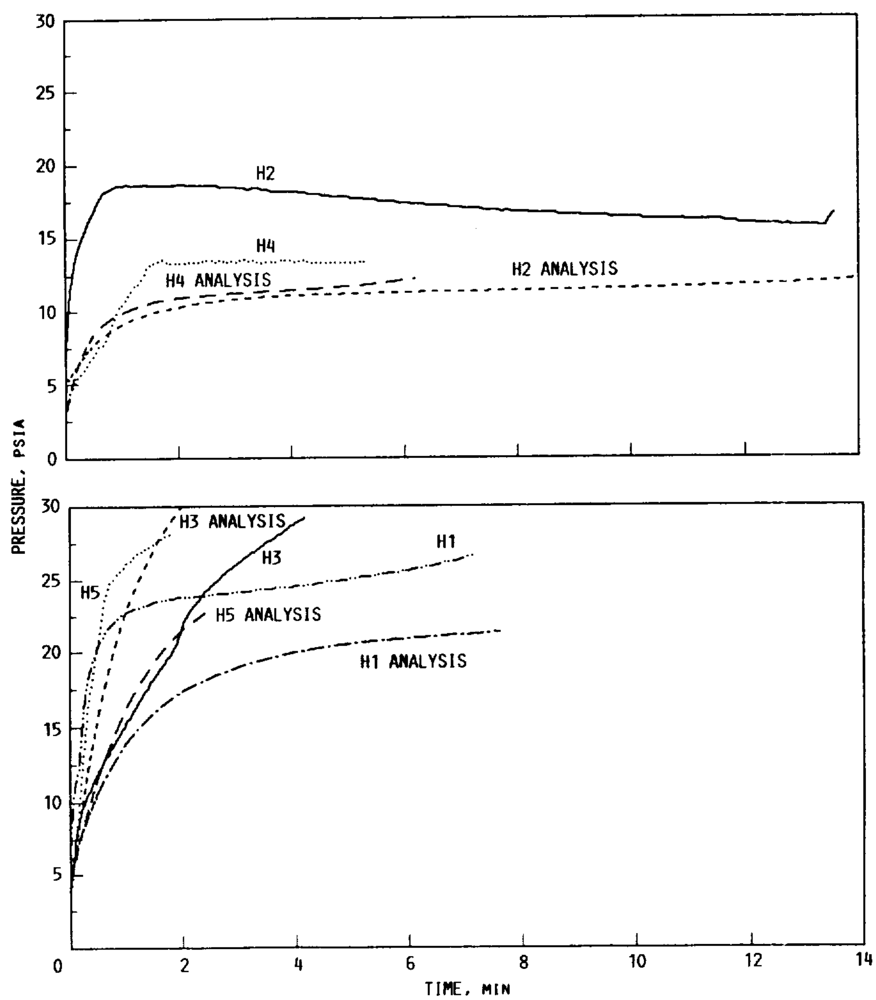

FIGURE 12. - COMPARISON OF ANALYTICAL PREDICTIONS FOR NONVENTED FILL TO CCL-7 PRESSURE HISTORIES DURING LIQUID HYDROGEN TESTS.

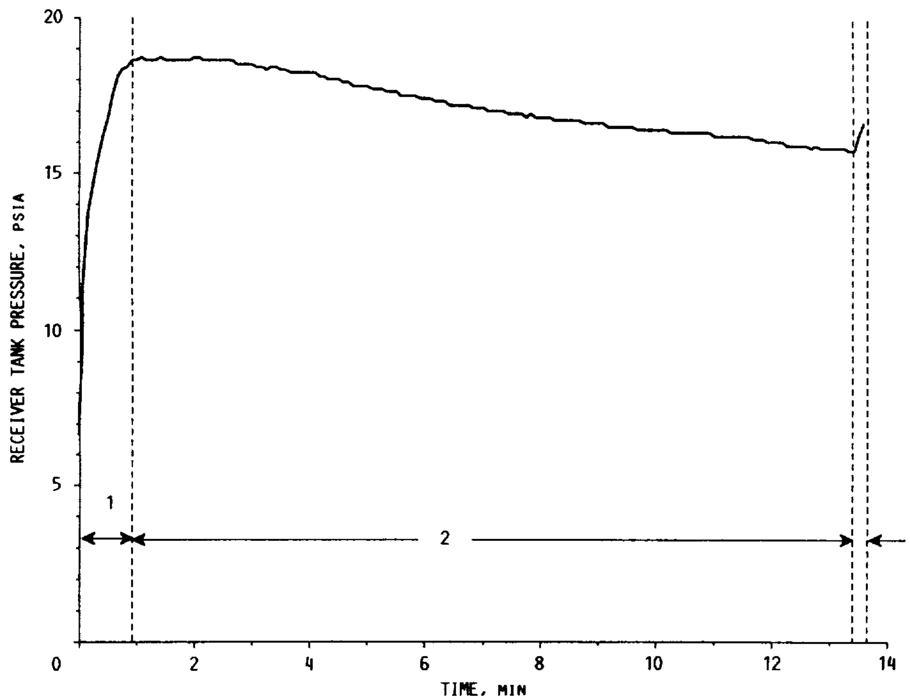

FIGURE 13. - TANK PRESSURE AS A FUNCTION OF TIME FOR HYDROGEN NONVENTED FILL TEST AT CCL-7 (TEST LABEL H2), AND THE THREE DISTINCT PRESSURE REGIONS.

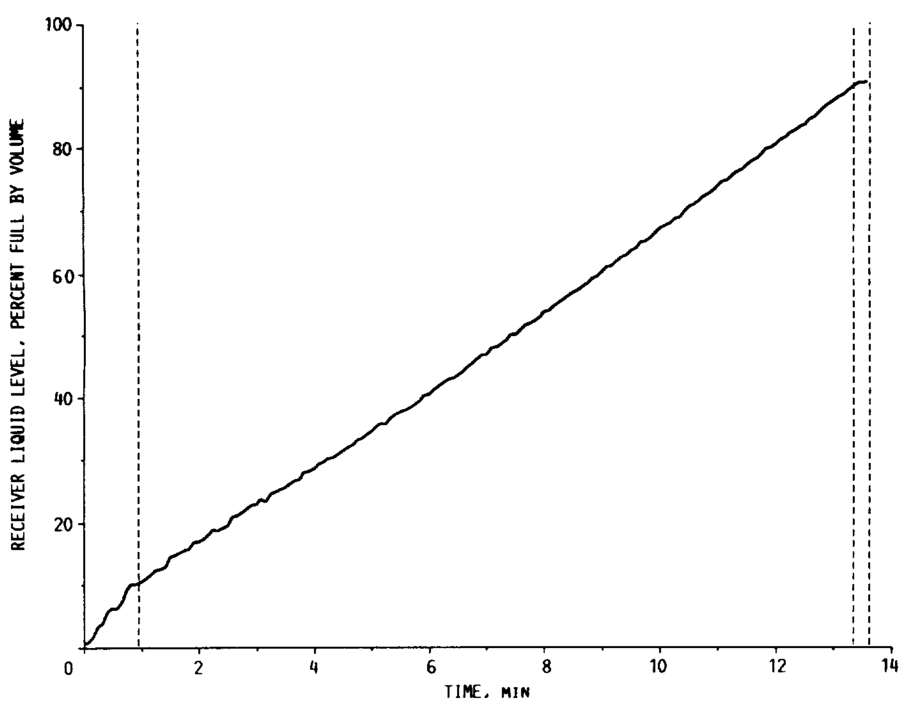

FIGURE 14. - LIQUID FILL LEVEL AS A FUNCTION OF TIME FOR HYDROGEN NONVENTED FILL AT CCL-7 (TEST LABEL H2), AND THE THREE DISTINCT PRESSURE REGIONS.

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16. Abstract

A series of nonvented fills have been performed on a 0.14 m^3 (5 ft^3) stainless steel dewar. Fills have been conducted with 120° cone angle spray nozzle over a range of inflow and initial wall temperatures with both liquid nitrogen and liquid hydrogen. Fill levels in excess of 85 percent liquid were achieved for four out of four nitrogen and two out of five hydrogen tests. Previously developed analytical models have been compared to the test results and shown to have general trend agreement.

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