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Hydrogen No-Vent Fill Testing in a 5 Cubic Foot (142 Liter) Tank Using Spray Nozzle and Spray Bar Liquid Injection

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available for the test tanks. Fig. 1 shows a schematic flow diagram of the test facility.

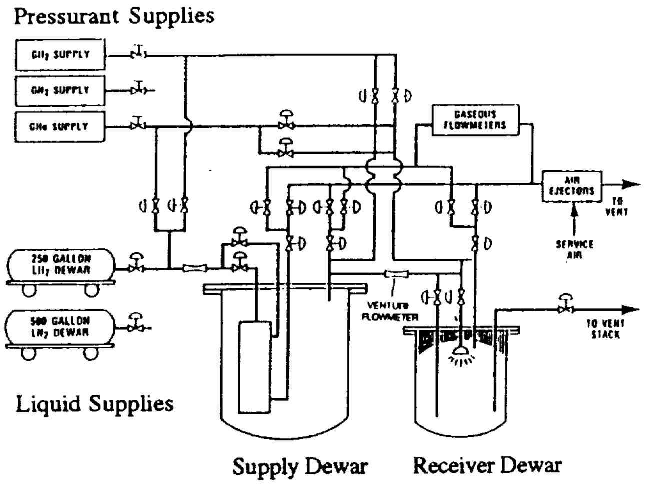

Fig. 1. Test facility flow schematic.

Test Dewars

Fluid handling tests are performed with a supply dewar and two interchangeable receiver dewars. The supply dewar is a vacuum jacketed stainless steel tank that contains multi-layer insulation (MLI) within the vacuum annulus. The dewar is cylindrical, with an internal height of 54 inches and an inside diameter of 22 inches. Internal volume of the supply tank is approximately 10.8 cubic feet. The receiver dewar used for this test series is similarly constructed. With an internal height of 28 inches and an inside diameter of 22 inches, it has an internal volume of approximately 5.0 cubic feet. The lid is composed of a flat flange which supports a short cylindrical section with an inverted dome bottom. The space between the flange and cylindrical section is evacuated and insulated with MLI to minimize heat transmission through the dome from the environment. With the lid in place, the interior walls of the assembled receiver tank form a cylindrical storage volume with domed ends.

Heat transfer from the environment is a function of liquid fill level for the supply and receiver tanks. This is due to the disproportionate heat flux entering from the tank top as a result of various lid mounted penetrations and the coupling of the lid walls to ambient temperatures at the tank flange. The overall heat flux for the tanks was experimentally determined, and ranges from 1 to 10 Btu/hr·ft^2 depending on the fill level and test fluid (nitrogen or hydrogen).

Instrumentation

Temperature sensors are positioned throughout the rig and on the tank walls, selected fluid lines, and components. Temperatures are measured with type T (copper-constantan) thermocouples and silicon diodes; thermistors are utilized to indicate the presence of liquid or vapor. Tank wall sensors are located in the annular vacuum space of the supply and receiver tanks, and are mounted to the inner tank wall. Within each tank is an instrument tree with silicon diodes and thermistors attached at various heights. This tree is in direct contact with the tank contents, whether liquid or vapor. Silicon diode sensors are accurate to within ± 0.2 °R, whereas, the thermocouples are accurate to within ± 2 °R. Fig. 2 illustrates temperature sensor and thermistor locations for the supply and receiver tanks

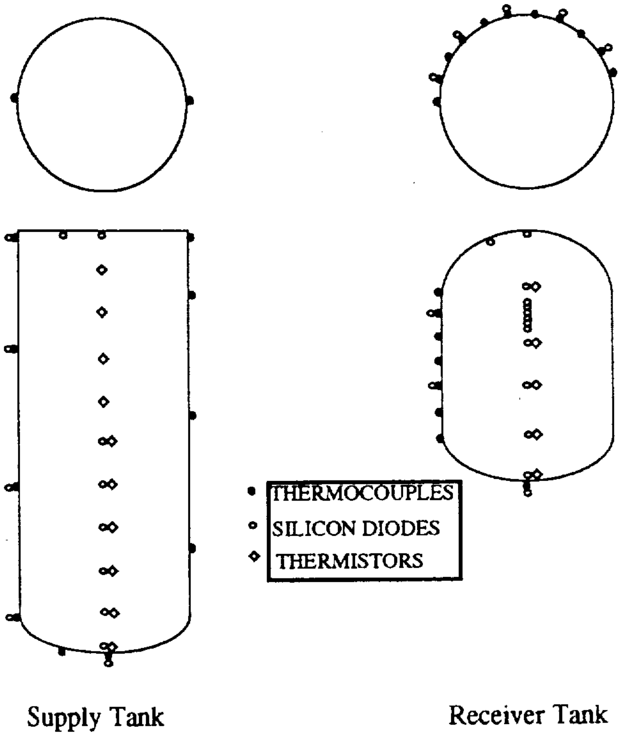

Fig. 2. Approximate locations of temperature sensors and thermistors for the supply and receiver tanks.

Transducers provide continuous pressure measurement throughout the system with an estimated accuracy of ± 0.5 percent. Each tank is equipped with a capacitance type level probe which is used to calculate the liquid fill level. The level probe in the receiver tank was calibrated in liquid hydrogen against point sensors (thermistors) and found to agree within one inch for liquid levels greater than 10 percent.

Liquid Injection Hardware

A sketch of the two liquid injection techniques used is given in Fig. 3. The spray nozzle configuration utilized various size nozzles mounted at the top near center of the tank to produce liquid droplets. Tested nozzle sizes included manufacturer designations 4.3W, 5.6W, 14W, 27W, and 50W which indicate flow capacity in tenths of gallons per minute of water at a 10 psi pressure differential. The spray nozzles produce a 120 degree solid cone pattern of droplets with a median volume droplet diameter of 1140 microns at 10 psid.

Conversely, the spray bar was installed axially in the tank with drilled holes to discharge the liquid streams radially toward the tank walls. Twelve circumferential rows of four holes each were spaced at 2 inch increments with a rotated offset of 45 degrees per row. Initial tests were conducted with a hole size of 0.024 inches and then enlarged for succeeding tests to 0.040, and 0.052 inches. The spray bar was constructed of 1/2 inch pipe with an overall length of 25.6 inches.

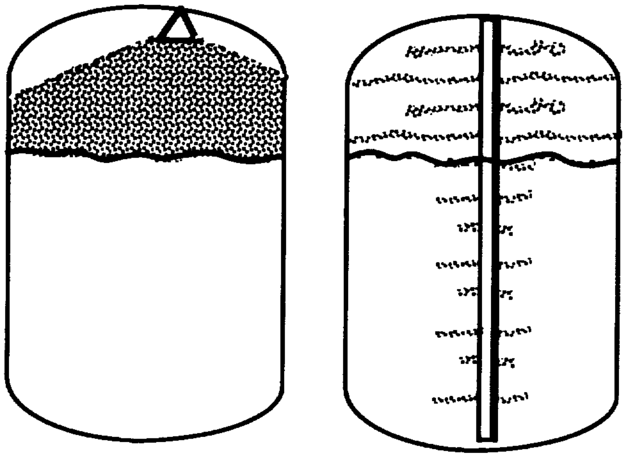

Fig. 3. Spray nozzle and spray bar liquid injection techniques.

Test Procedure

Performance of a no-vent fill test involves five sequential steps (refer to Fig. 1). First, the facility is pressurized to 25 psia with gaseous helium and monitored for leaks. The helium is then vented through the air ejectors. This purge cycle is repeated a total of four times. Second, 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 by controlling the tank pressure with the air ejector system. Third, 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 flowrate of liquid which vaporizes and is vented through the receiver tank. In the fourth step, the receiver tank pressure is reduced below atmospheric with the air ejectors. A charge of liquid is then loaded into the receiver tank with the vent valve closed. The vent remains closed while the liquid vaporizes, thus removing heat from the tank walls. When the receiver 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. The receiver tank pressure is then reduced to an initial starting pressure, nominally 3 to 5 psia, and the vent valve is closed. In the fifth and final step, the liquid cryogen is transferred from the supply to the receiver tank with the vent valve closed until the receiver is filled to the desired level or until the pressure reaches a predetermined maximum value. A more detailed test procedure can be found in Ref. 1.

Results and Discussion

A total of 38 no-vent fill tests were performed in this test series using various size spray nozzles and a spray bar with different hole sizes. Table I lists all of these tests and includes the primary initial and averaged test parameters.

Characterization of Spray Nozzle and Spray Bar

The top spray nozzle configuration exhibited the same characteristic tank pressure profile documented during previous no-vent fill test programs. Receiver tank pressure and fill level as a function of time for one of the top spray nozzle no-vent fill tests is shown in Fig. 4.

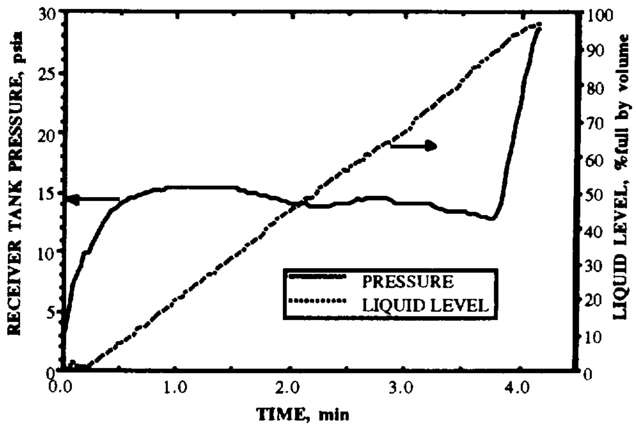

Fig. 4. Receiver tank pressure and fill level history for one of the spray nozzle tests (91266b)

Table I. Primary initial and averaged test parameters

Fill Config;* Test Number	Inlet Venturi Temperature (°R)	Supply Tank Liquid Temp (°R)	Temperature Difference** (°R)	Equiv Initial Wall Temp (°R)	Inlet Flow (lbm/min)	Initial Tank Pressure (psia)	Pressure @ 90% full† (psia)	Final Fill level (% by vol)
sb024; 91265a	34.3	33.2	1.1	115	2.6	4.4	30	87
sb024; 91266a	34.9	32.0	2.9	95	2.9	4.2	25	92
sb024; 91267a	35.4	31.7	3.7	88	2.8	8.5	28	90
sb024; 91267b	35.8	34.2	1.6	85	2.5	5.0	30	88
sb040; 91273c	33.4	31.5	1.9	110	4.2	4.2	26	91
sb040; 91273b	34.4	33.0	1.5	82	4.3	4.4	29	90
sb040; 91272c	34.5	32.9	1.6	116	3.9	4.0	29	86
sb040; 91272a	35.2	33.6	1.6	137	3.2	4.2	31	77
sb040; 91275	37.1	34.0	3.0	125	3.2	3.3	31	68
sb040; 91274a	37.6	33.2	4.3	66	4.0	4.1	29	86
sb052; 91281c	33.2	31.7	1.5	109	5.8	3.7	28	90
sb052; 91280c	33.5	31.4	2.1	138	5.5	4.2	29	90
sb052; 91279a	33.8	32.8	1.0	77	4.8	4.3	26	92
sb052; 91281a	36.9	31.7	5.3	128	5.0	4.1	29	79
sb052; 91280a	37.2	31.7	5.4	129	5.5	4.3	29	81
ts4.3; 9153	34.7	32.5	2.2	82	1.0	6.0	23	93
ts5.6; 91274b	34.0	31.9	2.1	54	1.9	4.2	14	99
ts5.6; 91272b	35.3	32.6	2.6	58	1.6	4.7	21	97
ts5.6; 91273d	36.3	33.1	3.2	53	1.5	4.2	22	82 ††
ts5.6; 91273a	36.6	32.6	4.0	52	1.7	4.1	20	98
ts14; 91281d	33.8	32.2	1.6	65	3.6	4.2	22	94
ts14; 91280b	33.8	32.2	1.6	55	3.6	4.2	20	96
ts14; 91279b	33.8	32.9	0.9	90	3.5	3.7	21	95
ts14; 91280d	34.6	32.2	2.4	76	3.6	4.3	18	80 ††
ts14; 91281b	34.7	33.7	1.1	64	3.3	4.1	26	91
ts27; 91266b	33.4	30.7	2.7	127	5.2	3.1	13	97
ts27; 91267c	33.7	31.9	1.8	63	5.2	4.4	14	97
ts27; 91265b	33.8	32.8	1.0	111	5.3	4.1	15	96
ts27; 91266c	34.4	33.0	1.4	91	5.1	4.0	16	95
ts27; 91267d	35.7	34.2	1.5	65	4.8	4.8	23	90
ts50; 91258a	33.0	31.4	1.6	134	6.0	3.5	10	95
ts50; 91258b	33.5	32.7	0.8	136	6.1	2.9	12	96
ts50; 91254c	33.6	31.7	1.9	145	5.5	3.3	12	79 ††
ts50; 91254b	34.8	33.7	1.1	114	5.2	3.2	14	94
ts50; 91254a	36.8	35.2	1.6	101	3.6	4.1	23	90
ts50; 91259	37.2	33.8	3.4	120	6.5	3.5	15	96
ts14&sb052; 91282	35.1	31.9	3.2	94	6.8	4.0	24	82 ††
ts5.6&sb040; 91274c	33.9	33.3	0.6	65	6.1	3.9	27	91

* Fill configurations: sb### - spray bar (hole size in thousandths of an inch); ts## - top spray (nozzle size designation).

** Temperature difference measured between the liquid in the supply tank and the venturi flowmeter located in the transfer line between the tanks; an indication of the liquid sensible heat gain in the transfer line.

† Receiver tank pressure when the 90% fill level was reached; or the final pressure for tests not reaching the 90% fill level.

†† Test ended prematurely for operational reasons (e.g. reduction of supply tank pressure; insufficient liquid supply)

Initially, the receiver tank rises rapidly in pressure as the incoming liquid flashes. This rapid pressure rise is followed by a tapering off of the tank pressure as the effect of ullage condensation on the incoming liquid droplets becomes more evident. Finally, the pressure profile rises steeply toward the end of the test as the liquid level reaches the tank lid and compresses the remaining ullage vapor. Internal and tank wall temperature responses also parallel previously published data[1,2]. Internal tank temperatures drop rapidly to saturated hydrogen value at the initiation of the no-vent fill process (Fig. 5). The tank lid sensors drop more slowly than the internal temperatures as seen in Fig. 6, but eventually approach saturation temperature. The effect of ullage compression near the end of the run is evidenced by an increase in the same two top dome temperature sensors.

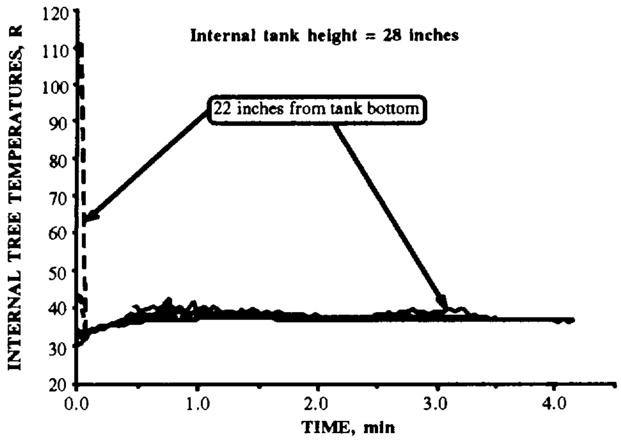

Fig. 5. Internal tank temperatures for one of the spray nozzle tests (91266b)

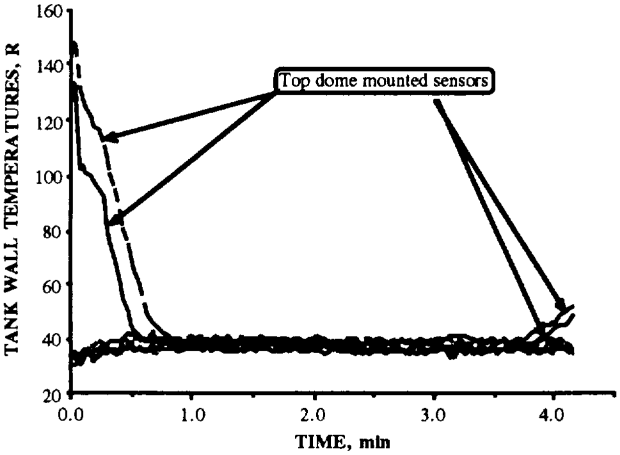

Fig. 6. Tank wall temperatures for one of the spray nozzle tests (91266b)

A similar pressure response is exhibited in Fig. 7 for one of the spray bar tests. The pressure profile in Fig. 7 is indicative of all of the test runs performed with this configuration. An initially rapid tank pressure rise is followed by a leveling off of the pressure history curve as vapor condenses onto the discharging liquid streams. Unlike the spray nozzle configuration, however, an oscillation of the tank pressure toward the end of a fill is observed. The maximum peak-to-peak magnitude of the pressure oscillation observed during all of the test runs was less than 4 psia. This response is presumably caused by an agitated liquid interface produced by the spray bar. Lower magnitude fluctuations of the tank pressure are also seen throughout much of the test. Finally, ullage compression causes a sharp pressure increase as the liquid level rises into the upper dome of the tank.

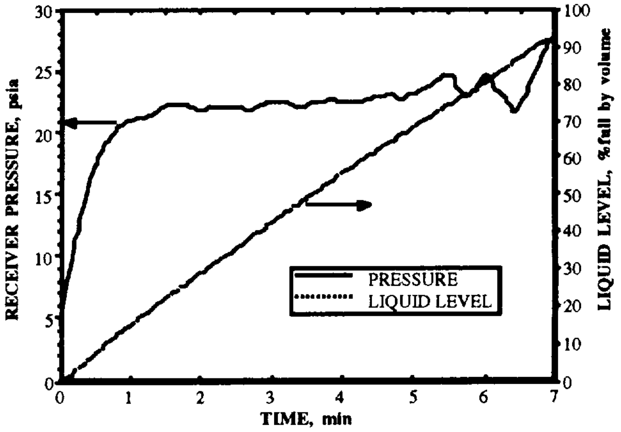

Fig. 7. Receiver tank pressure and fill level history for one of the spray bar tests (91266a).

Internally mounted sensors indicate a rapid drop in temperature inside the tank at the initiation of the same test (Fig. 8). However, saturated hydrogen temperature is not reached until the individual sensors become submerged in the rising liquid. The fluctuations in tank pressure during the test result in fluctuating vapor temperatures as indicated by the corresponding temperature sensors.

The wall mounted sensors cool rapidly during this test in a manner similar to the spray nozzle configuration as shown in Fig. 9. However, the uppermost sensor cools more slowly for this configuration, never quite reaching saturated hydrogen temperature. As with the spray nozzle tests, the two top dome sensors rise in temperature slightly as the ullage is compressed near the end of the test.

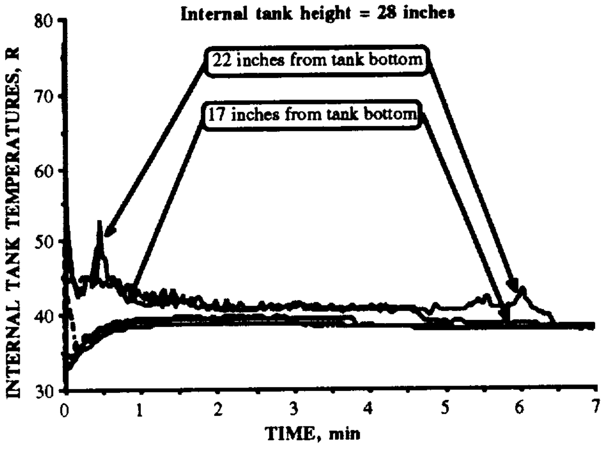

Fig. 8. Internal tank temperatures for one of the spray bar tests (91266a)

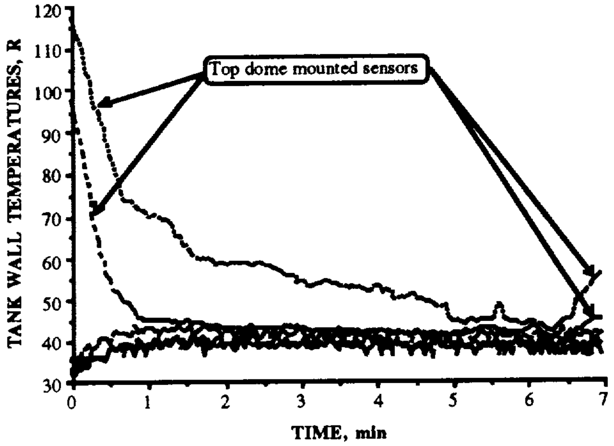

Fig. 9. Tank wall temperatures for one of the spray bar tests (91266a)

Pressure Response Comparisons

Comparisons between different spray nozzle sizes and between the spray nozzle and spray bar configurations can be made by isolating test parameters of interest. Primary test parameters identified in previous test programs include inlet liquid temperature, inlet flowrate, and initial equivalent wall temperature. The effect of these primary test parameters on the pressure history during a no-vent fill operation have been documented[2], and are consistent with the results observed during the current test series. Secondary test conditions which affect the tank pressure response to a lesser degree include initial tank wall temperature distribution, tank fill profile as a function of time, and liquid sensible heat gain in the transfer line. Fig. 10 illustrates the pressure response as a function of fill level for two identically configured spray nozzle tests with well matched primary and secondary test parameters. The maximum discrepancy in tank pressure for the two tests is less than 3 psi, providing a measure of the repeatability achievable with this test series.

A comparison of the pressure versus fill level history of two different spray nozzle sizes, 50W and 27W, is shown in Fig. 11. The break in the pressure plot line for one of the tests indicates missing data for those sample times. Although the 50W nozzle indicates a slightly lower tank pressure throughout the test, the difference is less than 3 psia and consequently inconclusive. No other tests with different size spray nozzles could be adequately matched for comparison. Therefore, the effect of variable nozzle sizes could not be completely addressed by this test series. However, examination of Table I shows that the lowest receiver tank pressures at the 90% fill level were achieved with the larger flow capacity nozzles.

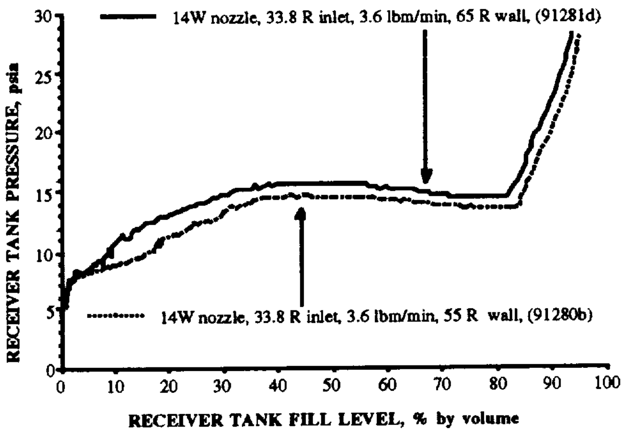

Fig. 10. Pressure response for spray nozzle tests with nearly identical test parameters and same nozzle size (91281d, 91280b).

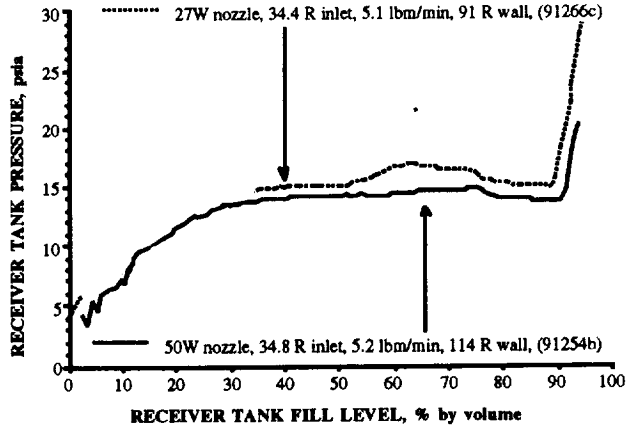

Fig. 11. Pressure response for two different size spray nozzle tests with matched test parameters (91266c, 91254b)

Comparison of the spray bar configuration with the spray nozzle arrangement is given in Fig. 12. It can be seen from Fig. 12 that the spray nozzle test outperforms the spray bar test to a significant degree in terms of lower receiver tank pressure with nearly equivalent test conditions. The lower receiver tank pressure profile observed with the spray nozzle tests illustrate that the droplet spray generated by this injection technique condenses more vapor than the liquid streams produced by the spray bar configuration during a no-vent fill.

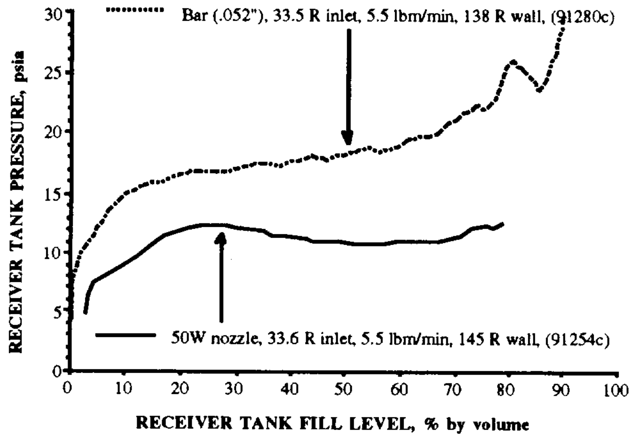

Fig. 12. Pressure response for one spray nozzle and one spray bar test with matched test parameters (91280c, 91254c).

Fig. 13 illustrates the best and worst pressure responses exhibited with the spray bar tests. The lower pressure profile and higher final fill level of test label 91266a is primarily due to the 2.2 °R lower inlet liquid temperature compared to test label 91275. This lower liquid temperature provides a greater sensible heat sink for energy exchange with the tank wall and also establishes a larger differential temperature for condensation between the vapor and incoming liquid. The result is a final fill level of 92% by volume and a receiver tank pressure of 25 psia at the 90% fill level. By comparison, test label 91275 achieves a final fill level of only 68% with a corresponding final tank pressure of 31 psia.

A similar comparison of best and worst receiver tank pressure responses for the spray nozzle tests is given in Fig. 14. Once again, inlet liquid temperature is primarily responsible for the lower pressure response of test label 91258a, although the higher inlet flowrate also contributes to produce the lower receiver tank pressure. The effect of both inlet liquid temperature and flowrate on the tank pressure response has been investigated in previous test programs[2] and is consistent with the current results. Both tests in Fig. 14 achieve fill levels in excess of 90% (91% for 91281b and 95% for 91258a).

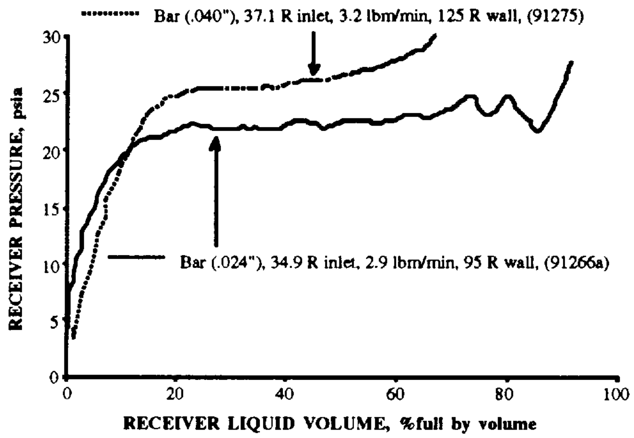

Fig. 13. Pressure response for the best and worst spray bar no-vent fills (91275, 91266a).

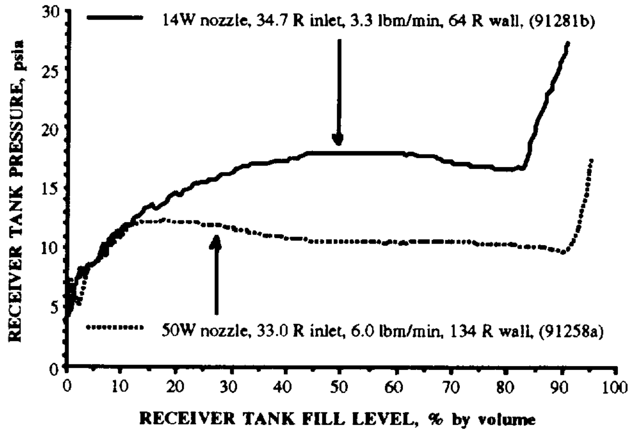

Fig. 14. Pressure response for the best and worst spray nozzle no-vent fills (91258a, 91281b).

Summary of Results

The spray nozzle no-vent fills demonstrated tank pressure and temperature responses comparable to previous test series. Initially, the receiver tank rises rapidly in pressure and then tapers off as the effect of ullage condensation becomes more evident. Near the end of the test the pressure profile rises steeply as the ullage vapor is compressed. Internal and wall tank temperatures drop rapidly at the initiation of the no-vent fill process and remain at saturated hydrogen conditions throughout the test. The tank lid sensors drop more slowly, eventually approaching saturation temperature.

In general, receiving tank pressure response for the spray bar configuration was similar to the spray nozzle technique. Initially the tank pressure rises rapidly and then levels off as vapor condenses onto the discharging liquid streams. The spray bar configuration, however, produces an oscillation of the tank pressure toward the end of a fill, presumably caused by the agitated liquid interface as the tank fills. Near the end of the test, the spray bar configuration again parallels the spray nozzle tests as a sharp pressure increase is observed due to ullage compression. Internal and tank wall sensors for the spray bar also react in a manner similar to spray nozzle tests, although individual sensors do not reach saturated hydrogen temperature until submerged in the rising liquid interface. This indicates that the spray bar configuration did not induce saturated conditions in the ullage during a no-vent fill operation, whereas, the droplet spray created by the spray nozzle reduced most of the ullage to saturation temperature.

Comparisons between spray nozzle tests using different size nozzles were inconclusive due to the difficulty in matching test parameters for these tests. In contrast, comparisons between the spray nozzle and spray bar configurations for well matched test conditions show a significant and repeatable trend. The spray nozzle injection technique is more effective in minimizing the receiving tank pressure throughout a no-vent fill compared to the spray bar configuration tested. The significance of this result for low gravity application is difficult to assess since ullage position in such an environment is generally uncertain. Injection of the droplet spray directly into the tank vapor for the spray nozzle configuration is key to the success of this technique. By comparison, the effectiveness of the the spray bar arrangement is much less sensitive to ullage position. Therefore, an effective liquid injection technique for low gravity might incorporate a hybrid of these two configurations.

Finally, plots of the best and worst tests for each injection configuration indicate the range of pressure response observed in this tests series for variable primary test parameters. Both configurations achieved fill levels in excess of 90% under various test conditions.

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13. ABSTRACT ***(Maximum 200 words)***

A total of 38 hydrogen no-vent fill tests were performed in this test series using various size spray nozzles and a spray bar with different hole sizes in a 5 cubic foot receiver tank. Fill levels of 90% by volume or greater were achieved in 26 of the tests while maintaining a receiver tank pressure below 30 psia. Spray nozzles were mounted at the top of the tank, whereas, the spray bar was centered in the tank axially. The spray nozzle no-vent fills demonstrated tank pressure and temperature responses comparable to previous test series. Receiver tank pressure responses for the spray bar configuration were similar to the spray nozzle tests with the pressure initially rising rapidly, then leveling off as vapor condenses onto the discharging liquid streams, and finally ramping up near the end of the test due to ullage compression. Both liquid injection techniques tested were capable of filling the receiver tank to 90% under variable test conditions. Comparisons between the spray nozzle and spray bar configurations for well matched test conditions indicate the spray nozzle injection technique is more effective in minimizing the receiving tank pressure throughout a no-vent fill compared to the spray bar under normal gravity conditions.

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