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Thermal–Fluid Analysis of the Fill and Drain Operations of a Cryogenic Fuel Tank

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ABSTRACT

The Generic Research Cryogenic Tank was designed to establish techniques for testing and analyzing the behavior of reusable fuel tank structures subjected to cryogenic fuels and aerodynamic heating. The Generic Research Cryogenic Tank tests will consist of filling a pressure vessel to a prescribed fill level, waiting for steady-state conditions, then draining the liquid while heating the external surface to simulate the thermal environment associated with hypersonic flight. Initial tests of the Generic Research Cryogenic Tank will use liquid nitrogen with future tests requiring liquid hydrogen. Two-dimensional finite-difference thermal–fluid models were developed for analyzing the behavior of the Generic Research Cryogenic Tank during fill and drain operations. The development and results of the two-dimensional fill and drain models, using liquid nitrogen, are provided, along with results and discussion on extrapolating the model results to the operation of the full-size Generic Research Cryogenic Tank. These numerical models provided a means to predict the behavior of the Generic Research Cryogenic Tank during testing and to define the requirements for the Generic Research Cryogenic Tank support systems such as vent, drain, pressurization, and instrumentation systems. In addition, the fill model provided insight into the unexpected role of circumferential conduction in cooling the Generic Research Cryogenic Tank pressure vessel during fill operations.

NOMENCLATURE

DFRF	Dryden Flight Research Facility, Edwards, CA
FILLDRAN	FLUINT submodel in NONEQFIL and NONEQDRN
FLUINT	FLUid INTegrator
GRCT	Generic Research Cryogenic Tank
LHSTF	Liquid Hydrogen Structural Test Facility, Edwards, CA
NONEQDRN	nonequilibrium drain model
NONEQFIL	nonequilibrium fill model
SINDA'85	Systems Improved Numerical Differencing Analyzer
TWODIM	SINDA'85 submodel in NONEQFIL and NONEQDRN
2-D	two-dimensional

INTRODUCTION

In 1988, a program was initiated by the Aerostructures Branch of NASA Dryden Flight Research Facility (DFRF) to develop the test capability to subject reusable primary structures for transatmospheric vehicles to combined loading and heating in the presence of cryogenic fuels such as liquid hydrogen. Testing reusable primary structures, such as transatmospheric vehicle fuel tanks, has been the subject of past experimental programs [1-4] because of the impact the fuel tank has on the flight-vehicle airframe and propulsion concepts.

The short-term goals of the DFRF program were to design, fabricate, and instrument a cryogenic tank to serve as a test article for analytical code evaluation and test technique development. The long-term goal was to develop the Liquid Hydrogen Structural Test Facility (LHSTF) to test full-scale and subscale flight vehicle components in simultaneous cryogenic and high-temperature environments combined with mechanical loads. The cryogenic tank will be tested with liquid nitrogen in the Thermostructural Laboratory and will eventually be tested with liquid hydrogen in the LHSTF.

In 1989, PRC Inc. was tasked to design a cryogenic tank, called the Generic Research Cryogenic Tank (GRCT), per DFRF requirements. As a research tank, the GRCT was to qualitatively simulate the thermal response of a transatmospheric vehicle fuel tank exposed to the environment of hypersonic flight. The objectives required by NASA for the GRCT included

(1) Develop test and operational procedures which will be applied to future test support of flight-weight fuel tanks.

(2) Develop thermal–fluid and structural analysis models that predict the behavior of cryogenic fuel tanks exposed to the environment of hypersonic flight.

(3) Obtain experimental data on the behavior of cryogenic fuel tanks subjected to hypersonic flight conditions for comparison to analytical predictions.

(4) Test and develop instrumentation which will provide accurate and continuous measurements of temperature, pressure, strain, heat flux, and liquid level for future cryogenic test structures.

(5) Provide a test bed to examine the performance of different insulation systems proposed for transatmospheric-vehicle fuel tanks.

(6) Allow for the possible examination of the effects of slosh dynamics when coupled with the aerodynamic heating of cryogenic fuel tanks due to hypersonic flight.

Several numerical models which simulate the behavior of the GRCT were created to support the design, research, and testing of the GRCT [5,6] such as defining subsystem and test requirements. This paper reviews recent efforts to develop two-dimensional (2-D) thermal–fluid models that provide performance predictions for the fill and the combined heating and draining test scenarios for the GRCT. In addition, extrapolation of the 2-D model results to predict the requirements of the full-scale GRCT are presented.

THE GENERIC RESEARCH CRYOGENIC TANK DESIGN

Figure 1 shows the GRCT suspended below a steel support structure, without the piping and heat lamps required for testing. The GRCT support structure was composed of carbon steel I-beams and was 7.3-m (24-ft) long, 3.6-m (12-ft) high, and 3.6-m (12-ft) wide. In addition, Figure 1 shows the heat shield locations and the fibrous insulation surrounding the stainless-steel pressure vessel. The requirements for the GRCT design were to

- keep construction simple, using inexpensive, well characterized, and available materials
- size the pressure vessel to minimize scale effects when extrapolating to larger test articles
- provide for liquid nitrogen and liquid hydrogen testing
- provide the capability for longitudinal and circumferential nonuniform heating up to 1089 K (1960 °R)

- meet specified heat flux requirements
  - (1) steady-state heat flux to the GRCT pressure vessel was to be approximately 94.6 W/m^2 (30 BTU/ft^2-hr) (ground hold condition)
  - (2) peak heat flux to the pressure vessel was to be at least an order of magnitude increase from the steady-state conditions (approximately 946.1 W/m^2 (300 BTU/ft^2-hr)) and occur within a 3000-sec heating period
- provide the capability for a controlled cryogen drain while heating
- operate at a maximum pressure of 308.1 kPa abs (44.69 psia) and include a relief valve and vent system
- allow the test article to be portable
- adhere to the American Society of Mechanical Engineers Division 2 pressure-vessel code

Figure 2 shows a cut-away view of the GRCT along its centerline and a section view through the cylindrical section. The GRCT consists of a 7.9-mm (5/16-in.) thick, 304 stainless-steel pressure vessel which was composed of a 3.05-m (10-ft) cylindrical section and two hemispherical ends of 0.76-m (2.5-ft) radius. The cylindrical section of the pressure vessel will be surrounded by 76 mm (3 in.) of fibrous alumina-silica ceramic insulation of 128.1 kg/m^3 (8 lbm/ft^3) density which will then be surrounded by a 0.76-mm (0.030-in.) thick Inconel® heat shield. A purge liner of 0.13-mm (0.005-in.) nickel foil was located within the insulation at 38 mm (1.5 in.) from the pressure vessel. Helium purge gas will be pumped into the end bells of the GRCT and channeled into the inner 38 mm of insulation.

DESCRIPTION OF THE TEST SCENARIOS

During test operations, a clamshell quartz lamp heater will be placed around the suspended GRCT. The heater will radiate directly to the cylindrical section and provide a high-temperature boundary condition on the GRCT heat shields. Four heat shield quadrants, composed of a top, bottom, and two side quadrants, were defined on the GRCT. Figure 3 shows the proposed heating profiles to be applied to the heat shield quadrants. These temperature profiles are composed of representative hypersonic thermal profiles and will be applied in several combinations to test the GRCT and for use in the 2-D drain-model simulations. For "even-heating" simulations, the high-temperature profile (peak temperature of 1089 K (1960 °R)) was applied uniformly to the heat shields. To simulate transatmospheric vehicle flight profiles, the two heating profiles shown in Figure 3 were applied nonuniformly to the GRCT. For "hot-top" simulations, the high-temperature profile was applied to the GRCT upper heat shield quadrant while the low-temperature profile (peak temperature of 700 K (1260 °R)) was applied to the lower quadrant. For "hot-bottom" simulations, the profiles were reversed. During nonuniform heating, the side heat shield quadrants follow a heating profile composed of the average of the high- and low-temperature profiles. During the GRCT experimental tests in the Thermostructural Laboratory and the LHSTF, the quartz lamps will be turned off at the end of the peak heating period and the GRCT will gradually return to room temperature. Therefore, the cooldown profiles in Figure 3 may not be strictly maintained as shown. However, in the numerical simulations, the cool-down profiles could be duplicated exactly as shown.

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The thermal–fluid models were used to evaluate proposed GRCT test scenarios to predict the behavior of the GRCT, identify unexpected issues, and provide data to size support systems. The GRCT fill procedure consists of a cooling stage and a fill stage. During cooldown, the GRCT pressure vessel (and fill–drain system) will be taken from room temperature to the cryogen saturation temperature. At the saturation temperature, liquid can be maintained in the vessel and the fill stage can be initiated. During the fill stage, an active control method will be used to control the liquid flow rate into the pressure vessel. The active fill control will monitor the temperature gradients being generated in the vessel wall and the amount of boiloff generated to ensure the integrity of the vessel will not be compromised. Once the liquid reaches the desired fill level, the fill control will be turned off and a ground hold will be entered until the desired steady-state conditions are obtained. Some of the issues associated with the GRCT fill process which the thermal–fluid models answered were

(1) What are the circumferential temperature gradients in the pressure-vessel wall associated with a moving liquid interface?

(2) How much liquid cryogen must be made available to cool and fill the pressure vessel to a prescribed fill level?

(3) What will be the boiloff rate for the vent system?

(4) Once filled to a prescribed level, how long will it take for the GRCT to reach steady-state conditions?

A nonequilibrium fill model (NONEQFIL) of the GRCT was designed to address the previous questions and to simulate various GRCT fill scenarios.

After the GRCT is full of cryogen and steady-state conditions have been reached, the draining and heating tests can be initiated. The procedure for a drain test consists of closing the GRCT vents, pressurizing the vessel to eliminate boiling, starting the drain and heating profiles, ending the drain profile at low fill level, and opening the vent to boil away the remaining liquid in the vessel. An active control system will maintain constant pressure while draining the vessel. Pressurized fluid transfer or pump-assisted fluid transfer have been the two proposed methods to remove liquid from the pressure vessel. For either method, self-pressurization or an independent pressurization system have been identified as the two methods for providing the pressure needed to drain the vessel. Scheduling the start of the heating and the drain profiles will affect the degree of self-pressurization, the peak temperatures, and the maximum temperature gradients that will result in the vessel wall. Some of the issues associated with the GRCT drain process were

(1) How much pressurant is required to run prescribed drain profiles? Is self-pressurization possible?

(2) What will the ullage (the unfilled portion of the vessel) pressure be during the drain process?

(3) What are the circumferential temperature gradients in the pressure-vessel wall associated with a moving liquid interface?

(4) What are the effects of the heating and drain scheduling on the response of the GRCT?

(5) If heating the GRCT, will the liquid cryogen absorb enough heat to raise the bulk liquid temperature enough to induce boiling?

A nonequilibrium drain model (NONEQDRN) of the GRCT was designed to address the previous questions and to simulate the GRCT combined drain and heating scenarios.

DESCRIPTION OF THE FILL AND DRAIN MODELS

The GRCT 2-D thermal–fluid models provided detailed design guidance and a way to predict the behavior of the GRCT under various test conditions. Figure 4 shows the pressure-vessel node and lump layout for the NONEQFIL and the NONEQDRN models. In both models, the GRCT was modeled as a 0.3-m (1-ft) wide portion of the cylindrical-vessel section divided in half along the vertical axis. The fluid inside the pressure vessel was modeled by two fluid regions (or lumps), one for liquid and one for vapor. The pressure-vessel wall was modeled by 12 wall sections (or nodes) spaced at 15°-intervals.

The 2-D thermal models of the GRCT were created using the Systems Improved Numerical Differencing Analyzer and Fluid Integrator (SINDA'85/FLUINT) [7]. These thermal models were developed to simulate the flow of heat from the heat shield, through the insulation and pressure vessel, to either liquid hydrogen or liquid nitrogen contained in the vessel. The SINDA'85/FLUINT code uses a finite-difference solution method to analyze thermal–fluid systems. SINDA'85/FLUINT is composed of two analysis codes, one code for modeling thermal systems (SINDA'85) and one code for modeling flow systems (FLUINT), which can be run separately or together. The NONEQFIL and NONEQDRN models were composed of two submodels that simulated the thermal and fluid characteristics of the GRCT. The thermal characteristics of the pressure-vessel wall, insulation, and heat shield are simulated in the TWODIM submodel which requires the use of the SINDA'85. The fluid characteristics of the vapor and liquid within the pressure vessel are simulated in the FILLDRAN submodel which requires the use of FLUINT.

Pressure Vessel Fill Simulation Using NONEQFIL

The NONEQFIL model was designed to simulate the GRCT beginning warm, dry, and empty, followed by cooling and filling the vessel with a variable flow rate of liquid nitrogen. As NONEQFIL simulates the fill process, the FILLDRAN submodel determines which tank-wall sections are submerged in liquid, which sections are exposed to vapor, and which section is at the liquid–vapor interface. Depending on the fluid in contact with the vessel, appropriate wall-to-fluid heat-transfer coefficients were assigned to account for either vapor- or liquid-free convection or liquid boiling. Heat-transfer coefficients for liquid- and vapor-free convection were calculated using the Nusselt equation [8], and boiling heat-transfer coefficients were determined from the Kutateladze correlation [9]. Boiloff flow originated in the liquid and traveled upward through the vapor and into a vent plenum. A connector was defined between the liquid and vapor regions which allowed a calculated mass flow of boiloff to be vented from the model at a rate determined by dividing the total heat input to the liquid region by the heat of vaporization for nitrogen.

Vessel fill rates were set by controlling the volume of fluid incrementally added during each time step. Two different fill-control algorithms were created to simulate the fill process. The first algorithm, called boiloff control, added liquid to the GRCT based on the boiloff rate. The boiloff control mechanism was equivalent to a constant heat-transfer rate from the wall to the incoming fluid. If the boiloff rate was above a prescribed set point, no fluid was added during the time step and conversely, if the boiloff rate was less than or equal to the set point, then an incremental amount of fluid was added to the liquid lump. The second fill control algorithm, called rate control, began adding fluid to the vessel at a constant slow rate and then changed to a linearly increasing rate until a maximum constant rate was reached.

In the NONEQFIL model, the adjustable model parameters were the method of fill control, the fill rate, the vapor heat-transfer coefficient, and the allowable boiloff rate. NONEQFIL predicted fill times and profiles, boiloff rates, and temperature gradients around the vessel wall and through the insulation. Heat fluxes and total heat inputs to the fluid were also available as results.

Pressure Vessel Drain Simulation With Heat Using NONEQDRN

The NONEQDRN model was designed to simulate the GRCT at a constant fill level and steady-state conditions, followed by a transient drain of the pressure vessel subjected to external heating. After the GRCT equilibrated at a constant fill level, several steps were required to drain the vessel. First, pressurant gas was introduced into the ullage at a fixed rate to increase the vessel pressure and suppress boiling by subcooling the liquid. The vessel pressure was allowed to increase until a prescribed pressure difference between the vessel and the pressurant source was reached (currently 6.89 kPa (1 psi)) and draining was initiated. The vessel was drained by a volumetric flow connector which allowed a prescribed liquid mass to be removed during each time step. The pressurant flow rate was varied to maintain constant pressure as the liquid level dropped. The bulk liquid temperature was monitored to determine if boiling would be initiated when the liquid reached the saturation temperature for the prescribed drain pressure. Heating profiles (Fig. 3) could be impressed on the heat-shield boundary nodes as a function of time before, during, or after the draining process was initiated.

In the NONEQDRN model, the adjustable model parameters were the initial fill level, drain pressure, rate of pressurization, drain rate, heating profile applied to the heat shields, and internal wall-to-fluid heat transfer coefficients. NONEQDRN predicted pressurization rates, wall-temperature gradients, insulation temperatures, and drain profiles. Heat fluxes and total heat inputs to the fluid were also available as results.

ANALYSIS OF TEST SCENARIOS

The simulation of numerous fill and drain scenarios are available using the NONEQFIL and NONEQDRN models. The following scenarios represent the capabilities of the two models.

Seventy-Five-Percent Fill Simulation Using NONEQFIL

The NONEQFIL model was developed to investigate cooldown and fill profiles. A characteristic measure of these processes was the pressure-vessel wall temperatures and boiloff rate. The following results refer to a 75-percent fill of the GRCT using liquid nitrogen. The vessel started at room temperature 294 K (530 °R) as liquid nitrogen at 137.9 kPa abs (20 psia) pressure and 80 K (144 °R) was introduced into the vessel. The boiloff fill-control algorithm was used in this example and the allowable boiloff rate was set at 9.07 kg/hr (20 lbm/hr).

Figure 5 shows the pressure-vessel temperature at prescribed wall positions while filling the GRCT to 75 percent. The temperature response for each wall location followed a three-step behavior. First, wall cooling was accomplished through vapor-free convection heat transfer as shown by the initial sloped line for node 900 (0 to 1.4 hr). As the liquid interface contacted the node adjacent to node 900, circumferential conduction within the vessel wall coupled with vapor-free convection caused the node 900 temperature to drop more rapidly (1.4 to 1.7 hr). As the liquid front reached node 900, boiling heat transfer caused the node 900 temperature to "plunge" toward the liquid nitrogen saturation temperature (1.7 to 2.2 hr). This behavior was observed for all wall locations in every fill run, regardless of fill rate, vapor heat-transfer coefficient, or fill-control method. The fill time was estimated from the curves in Figure 5; the final fill level of 75 percent required a cooldown and fill time of approximately 4 hr. The wall sections in the ullage region were always in contact with vapor and their temperatures continued to decline slowly (shown by node 300). One of the unexpected issues discovered by the NONEQFIL model was that circumferential conduction had no influence on the wall temperatures until the liquid front was within 20.3 cm (8 in.) of a node.

Figure 6 shows the total nitrogen added and the amount of stored liquid (equivalent to fill level) versus time. The difference between the two curves corresponds to the amount of boiloff produced during each time step. The total nitrogen added provides an estimate of the amount of nitrogen required to fill the GRCT to the prescribed level. This quantity accounted for filling the GRCT pressure vessel and did not include the amount of nitrogen required to cool the fill–drain subsystem attached to the GRCT. More than 1 hr was needed to accumulate significant quantities of liquid in the GRCT because of the time required to cool the bottom of the pressure vessel to the liquid saturation temperature. The nitrogen flow rate into the GRCT is the slope of the upper curve in Figure 6.

Vapor heat-transfer effects on the wall cooling process were evaluated (Fig. 7) by running two cases with vapor heat-transfer coefficients of 5.7 and 22.7 W/m^2 K (1 and 4 BTU/ft^2-hr-°R). In Figure 7, the temperature histories for the upper wall section (node 100) and the vapor region were examined. The results showed that wall cooling was significantly influenced by vapor heat transfer, and hand calculations verified that vapor heat transfer was the primary mechanism of wall cooling until the liquid front was within 20.3 cm (8 in.) of a node. Raising the vapor heat-transfer coefficient lowers the wall-to-vapor temperature difference and speeds up wall cooling, thus reducing the amount of nitrogen required for cooling. The effects were large enough that calculated heat-transfer coefficients could be verified from future GRCT experimental data. At the end of the fill process (3.5 to 4 hr), the vapor temperature increases because the desired fill level has been reached, which causes the fill level to remain stationary and the volume of boiloff to be reduced. The reduced amount of cool boiloff gas entering the ullage causes the vapor temperature to increase.

Seventy-Five-Percent Drain Simulation Using NONEQDRN

For the drain test case, the GRCT was 75-percent full of liquid nitrogen and at steady-state conditions before initiating a 45-min drain. Before draining, the GRCT vessel was pressurized from 137.9 kPa abs (20 psia) to 179.2 kPa abs (26 psia) by injecting warm nitrogen pressurant gas (at 294 K (530 °R)) into the ullage. A hot-bottom heating profile was started at 0.0 hr and the drain profile was initiated when the vessel had been pressurized to 179.2 kPa (26 psia) which required 0.6 hr. The vapor heat-transfer coefficient was set to 22.7 W/m^2 K (4 BTU/ft^2-hr-°R).

Figure 8 shows temperature versus time for two wall sections as well as the vapor and liquid regions during a 75-percent fill–45-min drain simulation. The uppermost section (node 100) was exposed to vapor during the entire run while a lower section (node 900) was in contact with liquid nitrogen until 1.2 hr, when the liquid interface passed and the section was exposed to vapor. In general, the vapor temperature was less than the wall temperature as the vessel was pressurized. However, when draining was initiated at 0.6 hr, the vapor temperature increased because of a large amount of warm pressurant gas being injected into the vessel to maintain constant pressure while draining. The temperature of node 100 became greater than the vapor temperature at 0.8 hr because of the effects of the applied heating profile reaching the pressure vessel. As the vessel was drained, the temperature difference between node 900 and the liquid increased due to the effects of liquid-free convection heat transfer and the applied heating profile. As the liquid interface passed node 900, the wall section was exposed to vapor which decreased the wall-to-fluid heat transfer and caused the wall temperature to increase. Once subcooled, the bulk temperature of the liquid nitrogen did not increase to the saturation temperature corresponding to the vessel pressure, thus preventing boiling from occurring while draining.

Figure 9 is the time history of the vessel pressure and the pressurant flow rate into the vessel. As shown, the vessel pressure increased from 137.9 kPa (20 psia) to approximately 179.2 kPa (26 psia) within 0.6 hr. During this time, the pressurant flow rate into the vessel was relatively small. The drain process was initiated after 0.6 hr, which caused a slight drop in pressure and a large increase in the pressurant flow rate. The increase in the pressurant flow rate was required to maintain constant pressure while draining.

Figure 10 shows the heat input to the vapor and liquid regions of the pressure vessel as a function of time. As soon as warm pressurant gas was added to the vessel (0 hr), the wall-to-liquid heat transfer changed from boiling to free convection and the vapor temperature increased, so there was an initial drop in the liquid and vapor heat input. The rapid increase in the wall-to-liquid heat input, before draining (0.6 hr), was caused by the effects of the applied heating profile reaching the pressure vessel. When draining began at 0.6 hr, the wall-to-vapor heat input became negative as the receding liquid interface exposed sections of the cold vessel wall to the warm vapor region. As draining progressed, the total wall-to-liquid heat input decreased because the volume of liquid in the vessel decreased.

APPLICATION OF THE TWO-DIMENSIONAL MODEL RESULTS

The fill and drain models were developed to predict the behavior of the GRCT under various test conditions and to define the GRCT subsystem requirements. Of particular interest was extrapolating the 2-D model results to represent the requirements of the entire GRCT, which could then be used to size the GRCT subsystems. Two factors, one for volume and one for area, were required to extrapolate the 2-D model results to the entire GRCT. Filling was a volume-dependent phenomenon, but cooling and boiloff were area-dependent. The volume of the entire GRCT pressure vessel was 7.4 m^3 (262 ft^3) while the model volume was 0.28 m^3 (9.817 ft^3), which yielded a volume factor of 26.7. The inner surface area of the GRCT pressure vessel was 21.9 m^2 (236 ft^2) while the model volume was 0.73 m^2 (7.85 ft^2), which yielded an area factor of 30.1.

Fill Process

Table 1 contains an estimate of the maximum and minimum fill rates for a 75-percent and 90-percent fill of the GRCT. The results correspond to a range of parameters and fill-control methods evaluated with NONEQFIL. Clearly, the minimum fill rate could be as slow as the fill system could trickle liquid nitrogen into the pressure vessel. Likewise, the maximum fill rate was the maximum evaluated by NONEQFIL, not necessarily the maximum possible rate. Actual fill rates will be limited either by boiloff flow from rapid vaporization or by thermal stress limits in the pressure-vessel wall. The values in Table 1 define a representative range for the GRCT performance which can be further evaluated when actual test conditions are defined. As a point of reference, the 75-percent fill of the GRCT will require 5.3 hr to fill using the minimum flow rate and 2 hr to fill using the maximum flow rate (Table 1). At 75-percent full, the GRCT holds 4831 kg (10,650 lbm) of liquid nitrogen. The NONEQFIL simulations predicted 5815 kg (12,820 lbm) of liquid nitrogen will be required to fill the GRCT to a 75-percent fill level. This translates into 984 kg (2170 lbm) of liquid nitrogen being required to cool the pressure vessel from room temperature (294 K (530 °R)).

The boiloff and venting rates listed in Table 2 are also representative values obtained during NONEQFIL runs. Depending on the type of fill-control algorithm, the boiloff was either nearly constant or fluctuated considerably during the run. Consequently, the values in Table 2 were not necessarily observed for an entire cooldown–fill run, but they were typical for what might be expected when full-scale testing of the GRCT begins. The vent-gas temperature was approximately 167 K (300 °R) when it left the GRCT, but the gas warms as it travels down the vent pipe which causes the volumetric flow rate to increase.

Drain Process

The model results were multiplied by the volume scale factor (26.7) to estimate pressurant requirements for the entire GRCT (Table 3). The minimum and maximum pressurization times and flow rates were determined for a representative range of initial fill levels and drain times. All cases were subjected to the hot-bottom heating conditions and a vapor heat-transfer coefficient of 22.6 W/m^2 K (4 BTU/ft^2-hr-°R). The vessel was pressurized from 137.9 kPa (20 psia) to 179.2 kPa (26 psia) before draining within a 10- to 60-min period. The range of pressurization times was a function of the initial ullage volume; a small ullage required a smaller pressurization time. A wide range of pressurant flow rates was predicted (23 kg/hr (51 lbm/hr) to 187.8 kg/hr (414 lbm/hr)) depending on the drain time. With a direct correlation between pressurization flow rates and the prescribed drain times, decreasing the required drain time by a factor of six decreased the pressurant flow rate requirements by a factor of five. The value of the vapor heat-transfer coefficient and the applied heating profile had a slight effect on the pressurant requirements. For a vapor heat-transfer coefficient of 5.7 W/m^2 K (1 BTU/ft^2-hr-°R) and a hot-bottom simulation, the pressurant requirements of Table 3 were reduced by 10 percent. For a "hot-top" applied heating profile and a vapor heat-transfer coefficient of 22.7 W/m^2 K (4 BTU/ft^2-hr-°R), the pressurant requirements for Table 3 were also reduced by 10 percent.

The insulation system around the pressure vessel delayed the effects of the heat input to the liquid cryogen. During the drain simulations, the effects of the applied heating rates on the pressure vessel were delayed up to 0.5 hr. This thermal delay was affected by the insulation conductivity, density, and thickness. Variations in these parameters changed how quickly the effects of the applied heat load reached the cryogen. For transatmospheric vehicle performance, the insulation thermal delay may impact pressurization and fuel tank heating rates. Pressurization requirements were too large to be met by self-pressurization in all of the drain simulations. Subcooling the liquid cryogen due to pressure increases and the insulation thermal delay did not allow external heating to produce boiloff gas for self-pressurization during draining.

CONCLUDING REMARKS

Two-dimensional finite-difference fill and drain models were developed to simulate the thermal–fluid behavior of the Generic Research Cryogenic Tank under anticipated test conditions to be conducted at the NASA Dryden Flight Research Facility. The results of the fill and drain models provided insight into defining future Generic Research Cryogenic Tank subsystems and test requirements. The fill model predicted fill times and profiles, boiloff rates, and temperature gradients in the pressure vessel and insulation. Based on the fill model, the Generic Research Cryogenic Tank will require from 2 to 5.3 hr and 5815 kg (12,820 lbm) of liquid nitrogen to cool down and fill to 75-percent capacity once liquid has reached the pressure vessel. Wall cooling for the fill process was significantly influenced by the degree of vapor heat transfer, with higher vapor heat transfer lowering the wall-to-vapor temperature difference and therefore reducing the cooldown time and liquid cryogen requirements. As an unexpected result, the NONEQFIL model showed that vapor-free convection and boiling heat transfer were the primary mechanisms for cooling the pressure vessel during the fill process. Circumferential conduction played a minor role in cooling the pressure-vessel wall. The drain model predicted pressurization rates, wall and insulation temperatures, and drain profiles. From the drain model predictions, the Generic Research Cryogenic Tank will require from 0.23 to 0.76 hr to pressurize before draining and require from 188 kg/hr (414 lbm/hr) to 23 kg/hr (51 lbm/hr) flow rates to meet drain times of 10 to 60 min. The degree of vapor heat transfer and the applied heating profile had only a slight effect on the pressurant requirements.

Dryden Flight Research Facility
National Aeronautics and Space Administration
Edwards, California, December, 1993

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Table 1. Calculated liquid nitrogen fill rates for the GRCT cooldown–fill operations.

	Minimum	Maximum
Liquid nitrogen fill rate, kg/hr (lbm/hr)	1099 (2422)	3629 (8000)
Liquid nitrogen fill rate, m^3/min (gpm)	0.022 (5.9)	0.076 (20.0)

Table 2. Calculated nitrogen boiloff and venting parameters for the GRCT cooldown–fill operations.

	Minimum	Maximum
Boiloff rate, kg/hr (lbm/hr)	211 (466)	952 (2100)
Boiloff rate, m3/min at 273 K and 101.3 kPa (ft^3/min at 492 °R, 1 atm)	2.8 (100)	12.7 (450)
Vent velocity in m/sec at 273 K and 101.3 kPa (ft/sec at 492 °R and 1 atm) assuming one 101.6 mm (4 in.) vent line	5.8 (19)	25.9 (85)

Table 3. Calculated gaseous nitrogen pressurant requirements for the GRCT drain operation.

	Minimum	Maximum
Pressurization time, hr, for 137.9 kPa abs to 179.3 kPa abs (20 psia to 26 psia)	0.23	0.76
Pressurization rate, kg/hr (lbm/hr), for draining	23 (51)	188 (414)
Pressurization rate, m^3/min at 273 K and 101.3 kPa abs (ft^3/min at 492 °R and 1 atm)	0.31 (11)	2.49 (88)

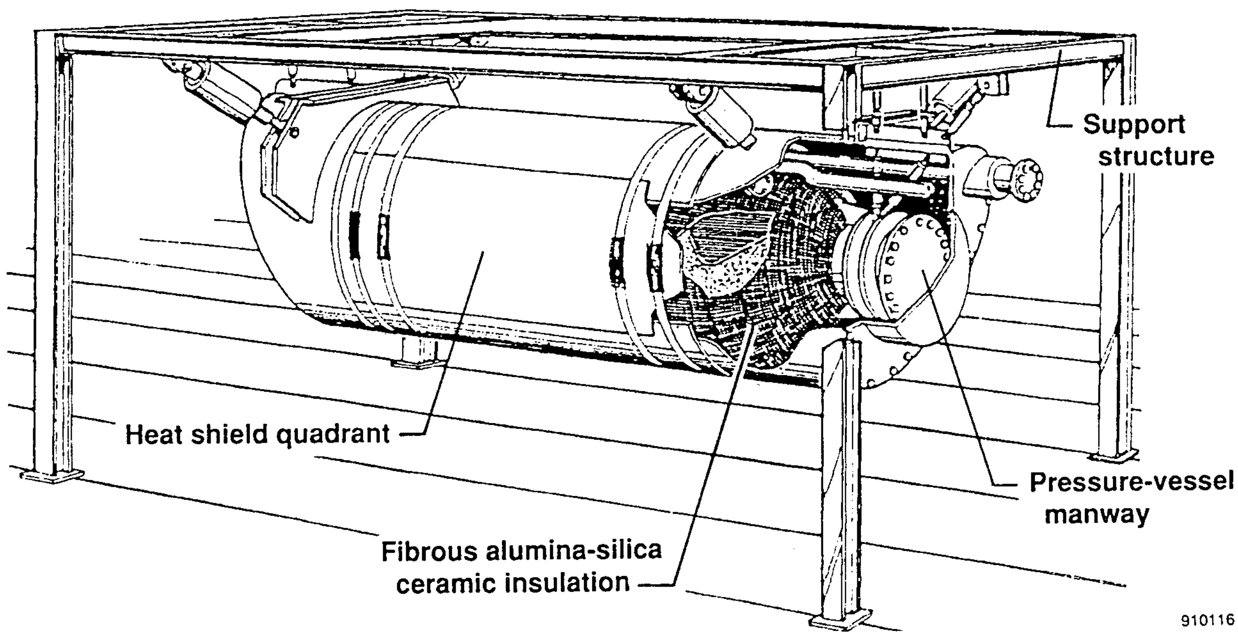

Figure 1. Perspective of the Generic Research Cryogenic Tank (GRCT).

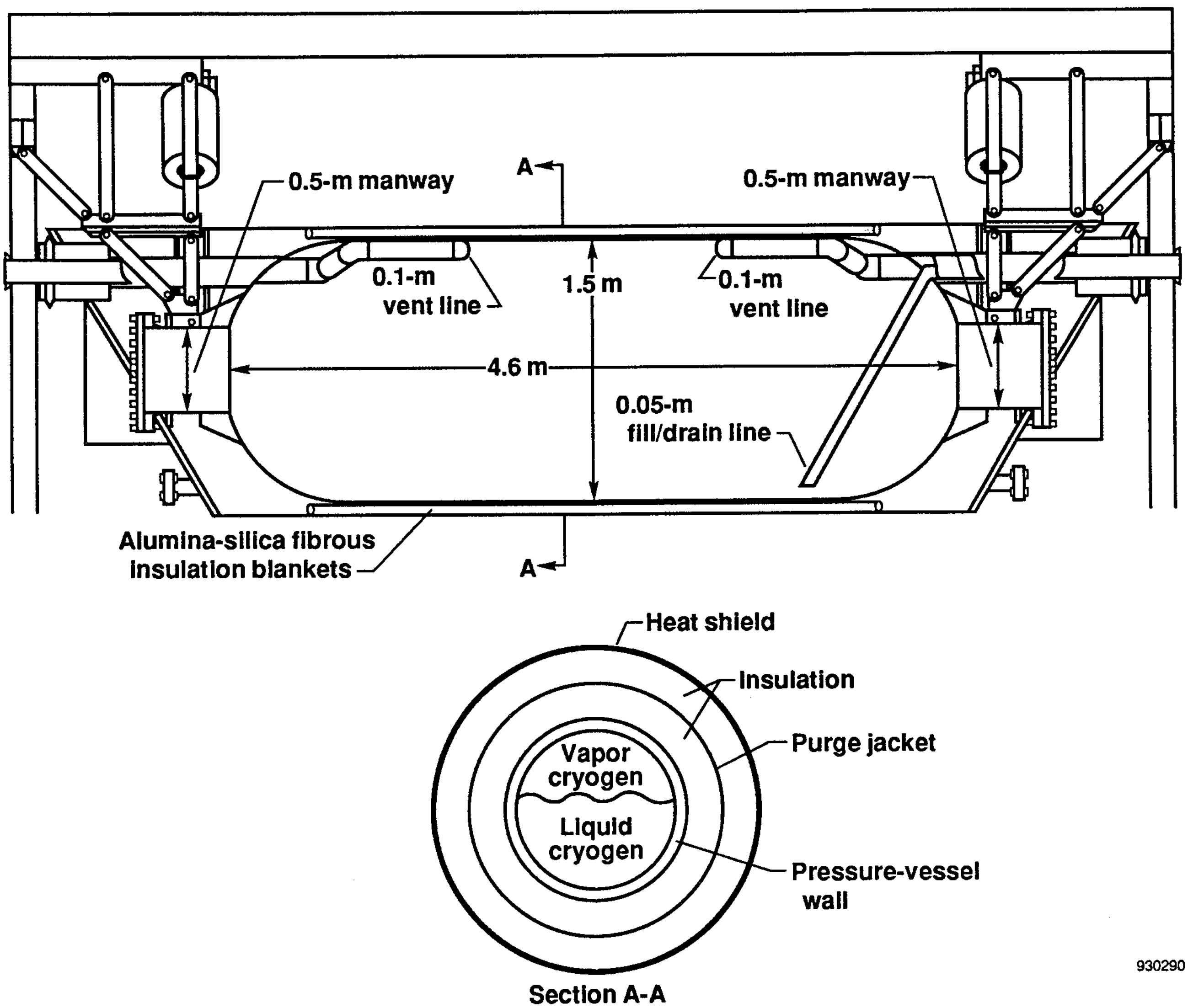

Figure 2. Cut-away and section view of the GRCT

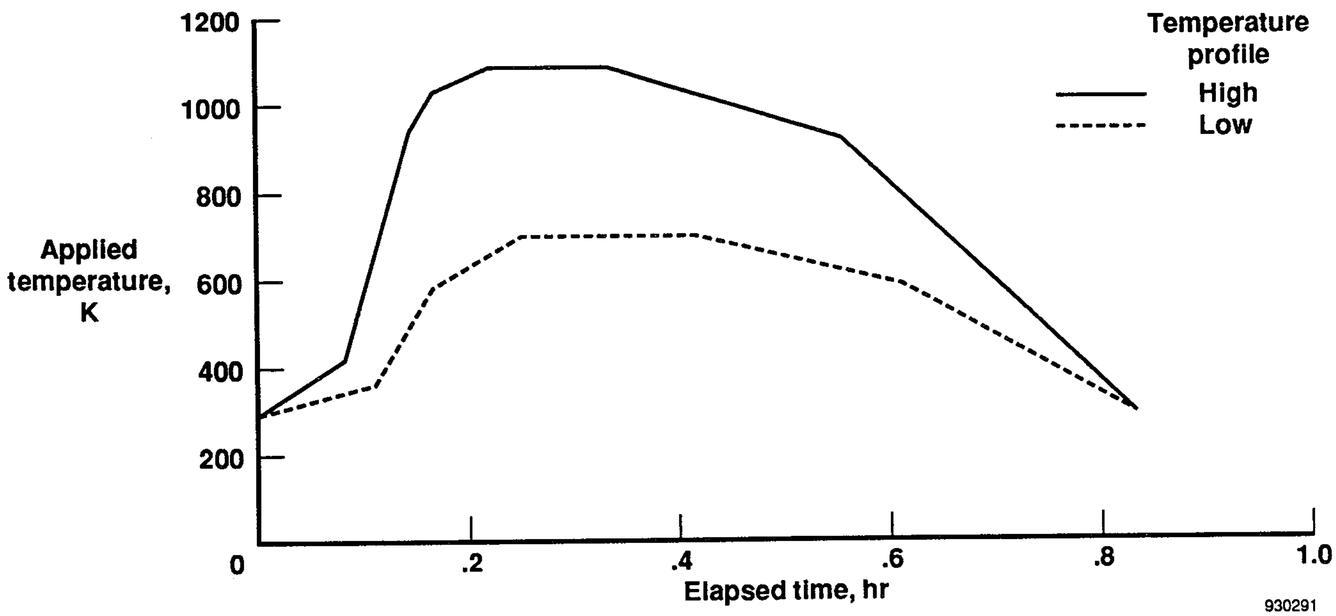

Figure 3. Proposed heating profiles as a function of time to be applied to the GRCT heat shields.

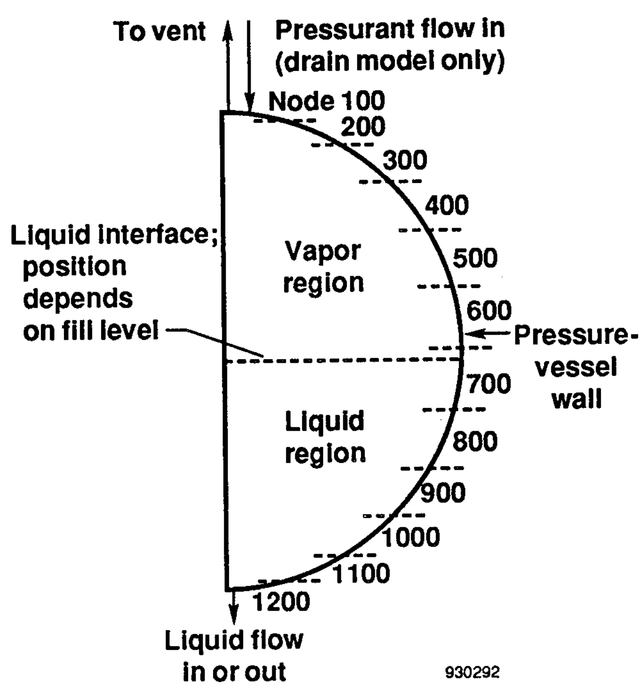

Figure 4. The pressure vessel node and lump layout for the NONEQFIL and NONEQDRN models. The insulation and heat shields are not shown.

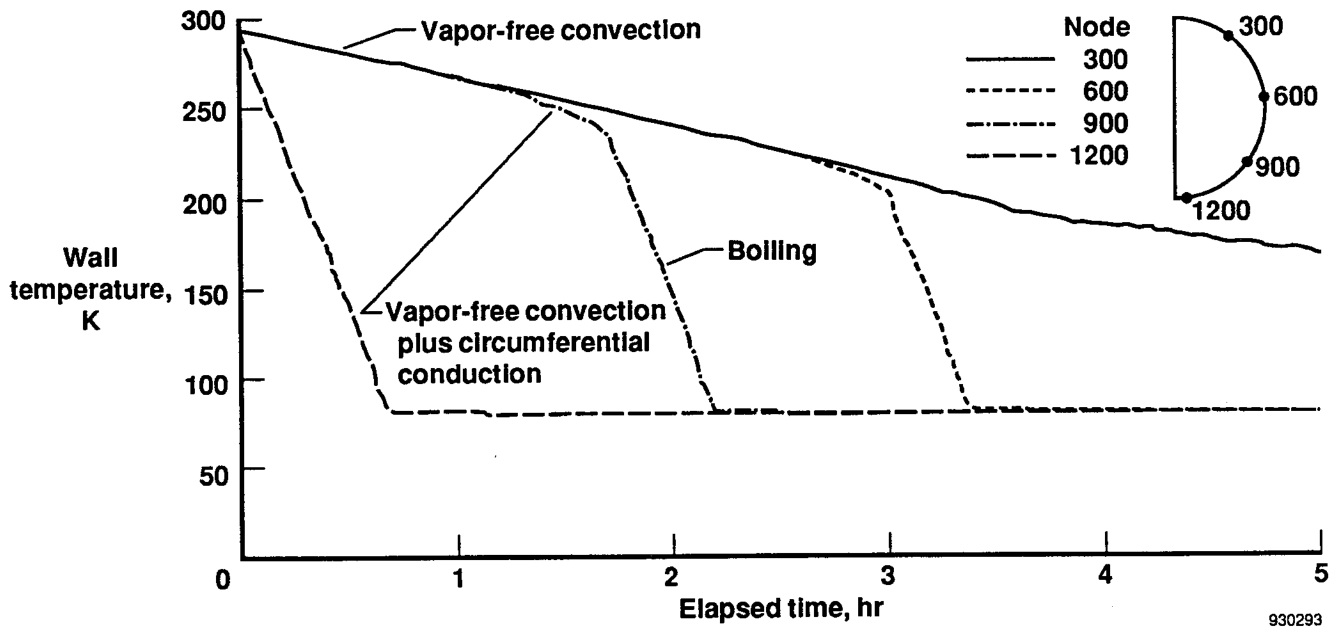

Figure 5. Wall temperature profiles as a function of time for a 75-percent fill simulation using NON-EQFIL.

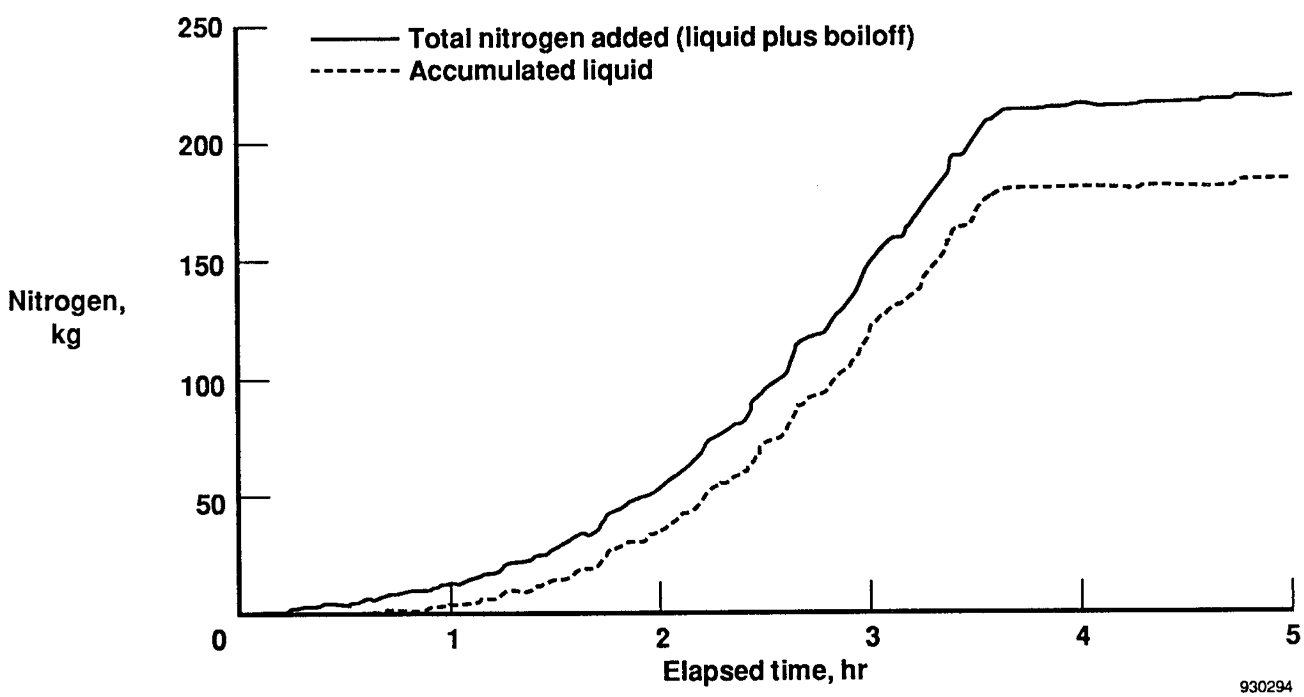

Figure 6. Total nitrogen added and the amount of accumulated liquid as a function of time for a 75-percent fill simulation using NONEQFIL.

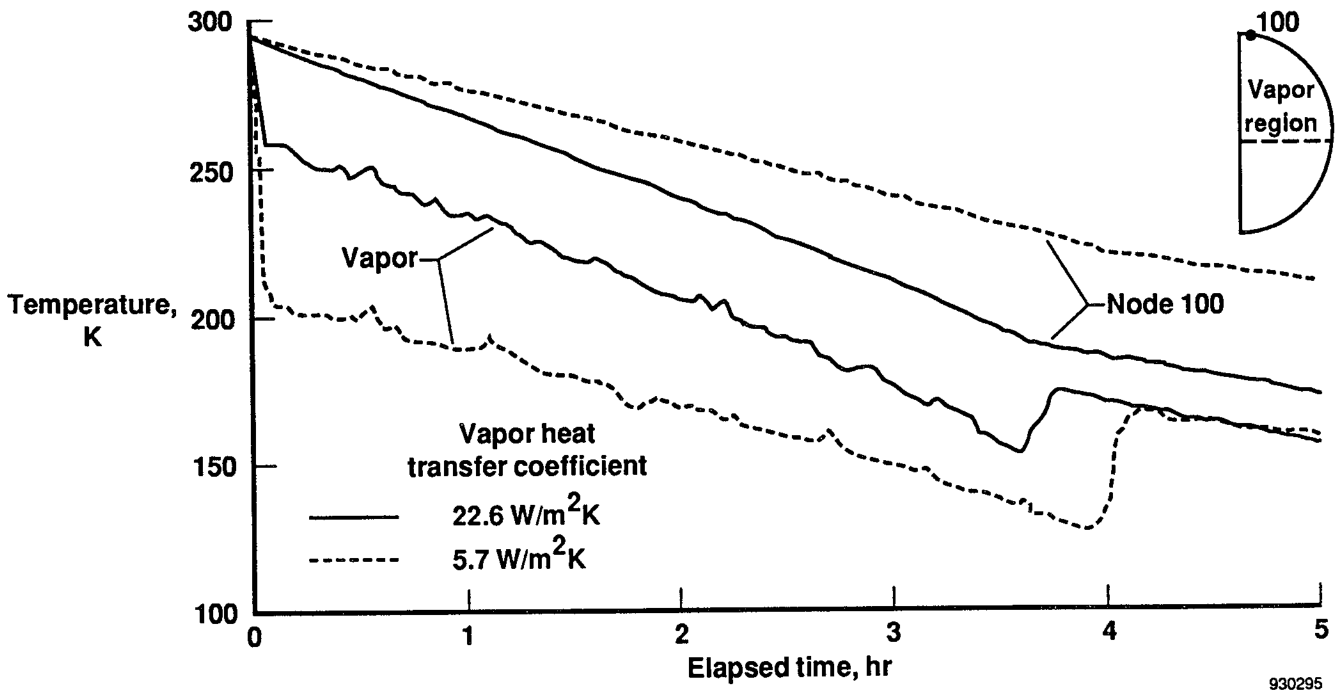

Figure 7. The vapor heat-transfer coefficient effects on the wall-to-vapor temperature difference as a function of time for a 75-percent fill simulation using NONEQFIL.

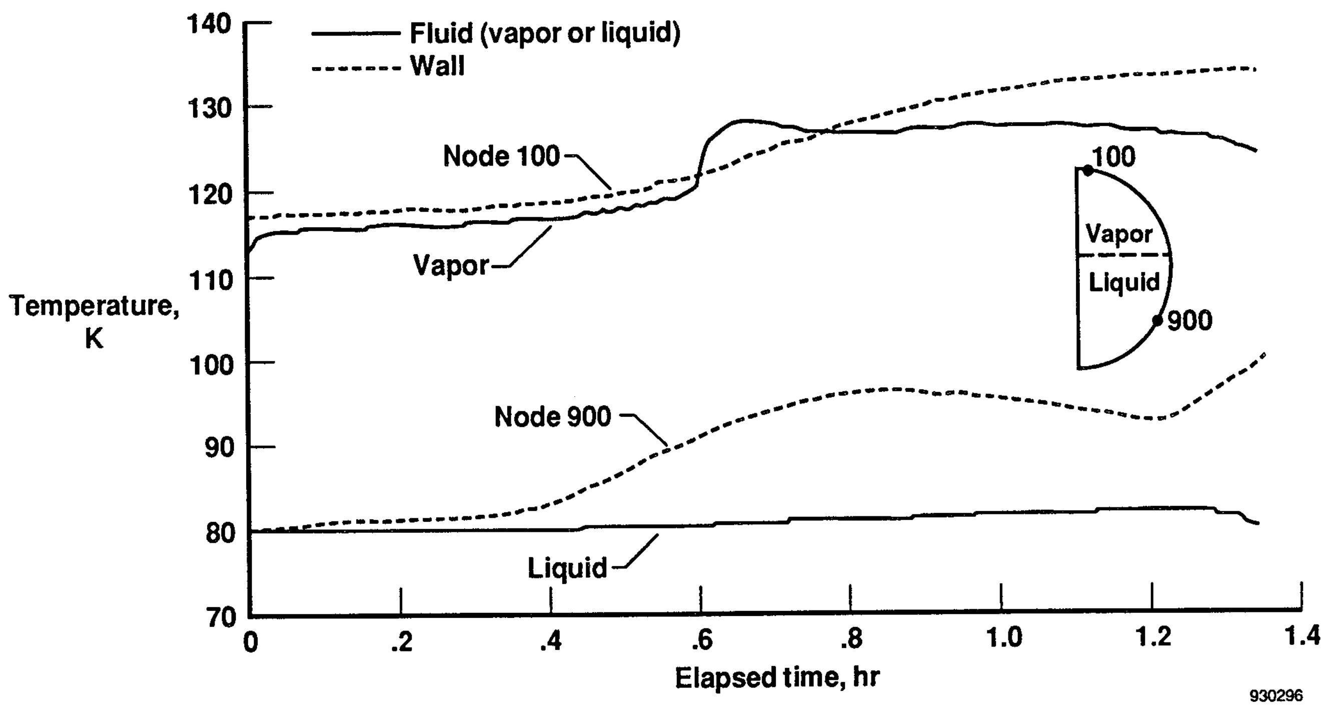

Figure 8. Wall, vapor, and liquid temperatures as a function of time during a 75-percent fill – 45-min drain simulation using NONEQDRN.

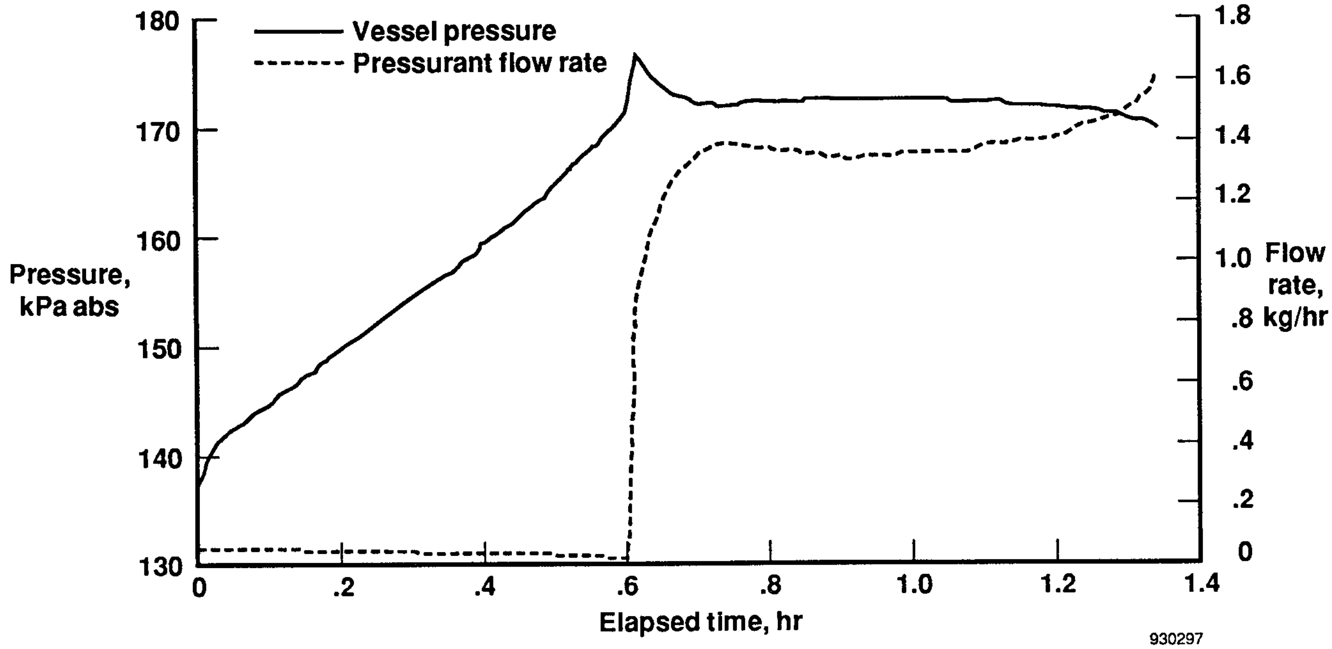

Figure 9. Vessel pressure and pressurant flow rate as a function of time during a 75-percent fill – 45-min drain simulation using NONEQDRN

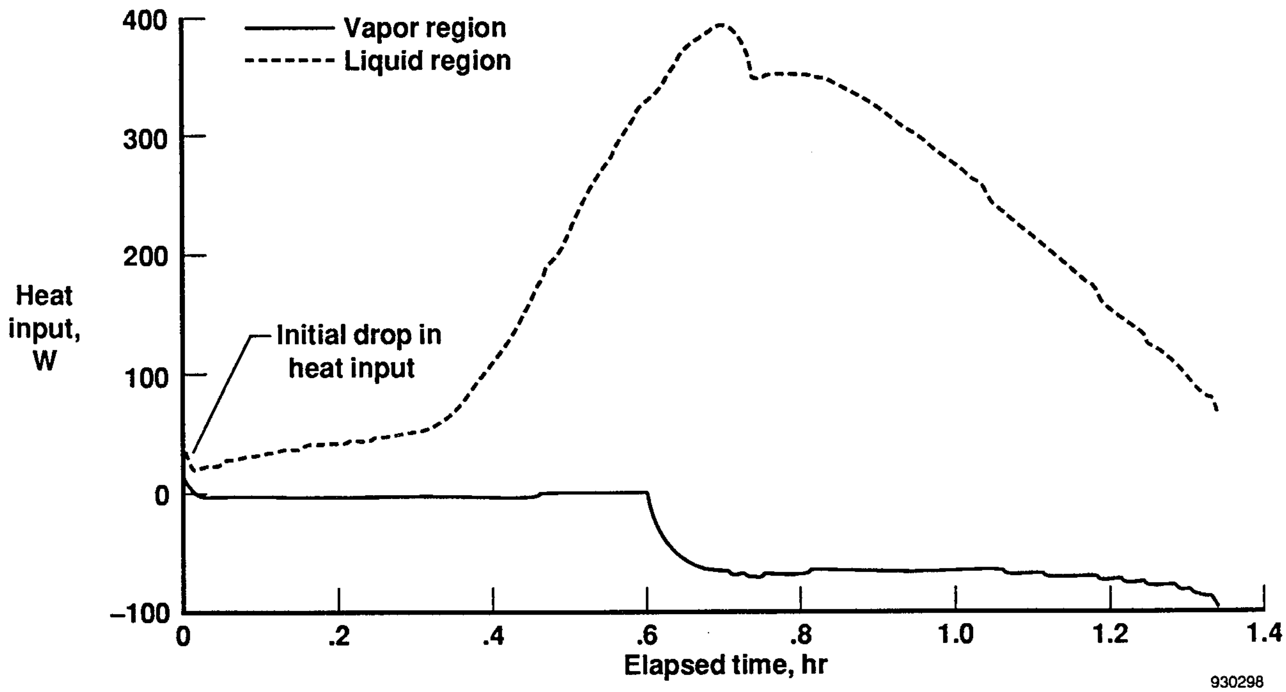

Figure 10. Heat input to the vapor and liquid regions as a function of time during a 75-percent fill – 45-min drain simulation using NONEQDRN.

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13. ABSTRACT (Maximum 200 words)
The Generic Research Cryogenic Tank was designed to establish techniques for testing and analyzing the behavior of reusable fuel tank structures subjected to cryogenic fuels and aerodynamic heating. The Generic Research Cryogenic Tank tests will consist of filling a pressure vessel to a prescribed fill level, waiting for steady-state conditions, then draining the liquid while heating the external surface to simulate the thermal environment associated with hypersonic flight. Initial tests of the Generic Research Cryogenic Tank will use liquid nitrogen with future tests requiring liquid hydrogen. Two-dimensional finite-difference thermal–fluid models were developed for analyzing the behavior of the Generic Research Cryogenic Tank during fill and drain operations. The development and results of the two-dimensional fill and drain models, using liquid nitrogen, are provided, along with results and discussion on extrapolating the model results to the operation of the full-size Generic Research Cryogenic Tank. These numerical models provided a means to predict the behavior of the Generic Research Cryogenic Tank during testing and to define the requirements for the Generic Research Cryogenic Tank support systems such as vent, drain, pressurization, and instrumentation systems. In addition, the fill model provided insight into the unexpected role of circumferential conduction in cooling the Generic Research Cryogenic Tank pressure vessel during fill operations.

14. SUBJECT TERMS
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