THE UNIVERSITY OF MICHIGAN RESEARCH INSTITUTE
ANN ARBOR, MICHIGAN

Progress Report No. 10

PRESSURIZATION OF LIQUID OXYGEN CONTAINERS

J. A. Clark
S. K. Fenster
H. Merte, Jr.
W. A. Warren

UMRI Project 2646

DEPARTMENT OF THE ARMY
DETROIT ORDNANCE DISTRICT
CONTRACT NO. DA-20-018-ORD-15316
DETROIT, MICHIGAN

July 1958

ABSTRACT

This report includes a summary of project activities for the six-month period January 1, 1958, to June 30, 1958, as well as a report of progress for the period May 15, 1958, to June 30, 1958.

Revisions in the experimental apparatus have been made necessary for the measurement of the mass of residual gas in a pressurizing discharge system. Both nitrogen and helium pressurizing gas have been used.

In addition, theoretical analysis has been completed on the prediction of wall-temperature transients, gas and liquid-side heat-transfer coefficients, and the condensation process at the gas-liquid interface. Reasonable agreement is obtained between theory and measurement.

The Ph.D. thesis work of Mr. H. Merte, Jr., and Mr. S. K. Fenster has continued.

During the six-month period (1/1/58 - 6/30/58) approximately 1460 payroll man-hours and 1960 nonpayroll man-hours were devoted to the project. Also during this same period, project supervision was assumed by Professor J. A. Clark in the absence of Professor G. J. Van Wylen, who was on sabbatical leave. As of July 1, 1958, Professor Van Wylen will rejoin the project as Project Supervisor.

I. SUMMARY OF PROJECT ACTIVITIES DURING THE PERIOD JANUARY 1, 1958, TO JUNE 30, 1958

EXPERIMENTAL APPARATUS

It was observed that, owing to environmental heat-transfer and heat-capacity effects, the inlet gas temperature was not constant and considerably lower than desired. A range of heat-exchanger temperatures of 212°F to -320°F did not give anywhere nearly that spread in the pressurizing gas temperatures at the inlet to the pressurizing tank.

To overcome this condition, the inlet gas line between the tank and the heat exchanger was further insulated and a quick-acting valve was attached to the line at the tank inlet. This valve allowed the pressurizing gas to be bled through the inlet prior to pressurization, thus bringing the line to the temperature of the gas and greatly reducing the heat capacity of this portion of the system from influencing the temperature of the inlet gas. In addition, a small annular jacket was placed around the line between the quick-acting valve and the top of the tank. This jacket contained the same fluid as was in the heat exchanger and in this way brought the line immediately adjacent to the tank to a temperature closely approximating that of the gas leaving the heat exchanger.

A small aluminum deflection plate of negligible heat capacity was mounted directly below the inlet gas line inside the pressurizing tank. This plate deflected the inlet gas so that it flowed parallel with the roof of the tank, thus simulating missile operating conditions. A thermocouple was mounted on this plate as one junction of a difference thermocouple, the other junction of which was mounted in the gas line just upstream of the quick-acting valve. This temperature difference was continuously monitored as was the level of temperature of the gas upstream of the quick-acting valve.

For the collection of data with a programmed heat flux, the pressurizing tank was wound with resistance heater ribbon. This heater was controlled by a variac. Operation was carried out with a heat flux of 1140 and 300 Btu/hr-ft^2.

During the last six-week period, design and construction has been completed on a pressurizing tank with a built-in styrofoam piston. This required the construction of a new tank with a flanged top and without ribs in in the bottom. This piston thermally insulates the pressurizing gas from the liquid nitrogen. It is arranged that vertically oriented thermocouple wires will pierce the piston in several places, allowing both movement of the piston and measurement of the liquid and gas-space temperatures. This system has not yet been operated.

On Friday, June 27, the entire project was moved into completely new space in the Heat Transfer and Thermodynamics Laboratory of the Department of Mechanical Engineering located in the new Fluids Engineering Building on the University's North Campus. This will provide the project with considerably more space and enlarged facilities as well as integration of effort. The cost of the move was assumed by the University. An estimated two weeks will be required to reassemble the equipment and start operations.

EXPERIMENTAL DATA

Data have been collected for pressurizing discharge runs for the following conditions:

a. Nitrogen pressurizing gas - uninsulated tank

inlet gas temperature	Residual gas mass
111°F	1.077 lb lbm
63	1.126
-30	1.171
-299	1.352

b. Helium pressurizing gas - uninsulated tank

inlet gas temperature	Total quantity of pressurizing gas required
56°F	0.282
7	0.298
-23	0.333

c. Programmed heat-flux - insulated tank

$$q/A = 300 \text{ Btu/hr-ft}^2$$

inlet gas temperature	Residual gas mass
Approximately 10°F	not reduced

$q/A = 1140$ Btu/hr-ft^2

inlet gas temperature	Residual gas mass
63°F*	1.323
54°F**	1.139

It will be noted the 63°F inlet gas temperature in part (c) results in a considerably larger residual gas mass than the corresponding run for the non-programmed heat flux run in part (a), while the 54°F inlet gas temperature in part (c) agrees favorably with its corresponding run in part (a). The explanation of this appears to rest in the manner in which the heat flux is established. As noted, the 63°F run in part (c) was taken with the heat flux established 4 minutes prior to the 2-minute discharge process, but the 54°F run in (c) was taken with discharge and establishment of heat flux occurring simultaneously. In the former case it is expected that considerable quantities of saturated vapor are present in the form of resident bubbles in the liquid which mixing with the incoming gas produces a more dense gas phase. This effect is probably not a general one, and should, for example, the discharge process be greater in time, it is reasonable to expect the reversed effect, due to the heat transfer to the gas phase.

Gas, liquid, and tank wall temperatures have all been measured and recorded as functions of time for the above runs. It was observed that a considerable lag in response of the liquid thermocouples occurs when the thermocouple element passes through the liquid interface and enters the gas space. This is attributed to the evaporation of resident liquid clinging to the thermocouple. It makes it difficult to measure gas temperatures in the vicinity of the interface. The thermocouples indicate the existence of a very steep gradient in temperature in the liquid in the region of the interface. The general shape of this temperature profile resembles that in a semi-infinite solid whose surface temperature is suddenly increased. This suggested an analytical approach to the heat conduction in the liquid as that corresponding to transient heat conduction in a semi-infinite solid with the interface being increased suddenly to the saturation temperature corresponding to the pressurizing pressure. Furthermore, it bears out the mechanism of condensation at this interface.

ANALYTICAL RESULTS

Analytical work has been directed towards the following:

---

*Heat flux established 4 minutes prior to pressurization and discharge.

**Heat flux established simultaneously with discharge.

a. wall temperature transient analysis,
b. gas-space and ambient heat-transfer coefficients,
c. liquid-gas interfacial condensation.

The temperature-time (or position) relationship of the wall has been obtained by theoretical analysis. The results of this for the pressurization-discharge runs (including programmed heat-flux) are shown in Figs. 1, 2, 4, 5, and 6 of this report. Reasonable agreement is observed with the experimental measurements.

Using the wall as a calorimeter, it has been shown that the wall-temperature transient measurements can be used to obtain gas-space and ambient heat-transfer coefficients. This technique has not proved to be particularly fruitful on the data so far collected owing to the uncertainty in the gas temperatures.

Analysis of the amount of gas condensed on the liquid interface, assuming the liquid to be essentially a semi-infinite solid, has been made. This indicates a negligibly small amount of condensation during the discharge period. Temperature measurements in the liquid indicate a liquid transient closely approximating that of a semi-infinite solid subjected to a step-change in its surface temperature.

Summary Report on H. Merte's Thesis

For the Period January 1, 1958, to June 30, 1958

"A Study of Pool Boiling in an Accelerating System"

The purpose of the thesis is to study the effect of acceleration upon a boiling system, and particularly as it affects the relationships between temperature difference and heat-transfer rate. Since it is impractical to achieve a linear acceleration for a necessary length of time, a centrifuge is utilized, which will provide the same effect. A container in which boiling is taking place is rotated about an axis external to the system, and the heating surface is so oriented that the acceleration is perpendicular to the surface in the direction of the liquid surface.

The flat surface heated indirectly electrically is used to study the nucleate boiling region, but due to the characteristics of electric heating, it cannot be used for determining the peak heat flux. For the peak-heat-flux and film-boiling regions, a platinum wire heated directly with d-c will be used as the heating surface. For details of the apparatus, see the assembly drawings in Progress Report No. 8.

The design of the apparatus was completed on March 15, 1958, and fabrication of the parts was completed by the sub-contractor on June 1, 1958. The total cost of the basic apparatus was approximately $2,500.00. During the fabrication period an investigation of the theoretical aspects of the problem was begun, and the instrumentation and auxilary components of the experimental apparatus were procured and constructed. The cost of the instrumentation and other components furnished by the University was also about $2,500.00.

The apparatus is 90% assembled, and it is expected that test work will begin within a two-week period.

Summary Report on S. Fenster's Thesis

For the Period January 1, 1958, to June 30, 1958

"Transient Thermal Response of a Step Pressurized Boiling Liquid Nitrogen System"

The major part of the work consisted of designing and ordering, and construction and assembly of test equipment and apparatus. In addition, a literature search has been made.

Theoretical analyses, related to the thesis work, but more specifically tied to the work of the project have been completed and included in this and previous progress reports.

II. PROGRESS REPORT FOR THE PERIOD MAY 15 TO JUNE 30, 1958

During the period May 15 to June 30 approximately 400 payroll man-hours and 450 nonpayroll man-hours were spent on the project.

EXPERIMENTAL APPARATUS

The tank used for the previous runs has proven to be unsatisfactory for use with a floating piston for two reasons: (1) The thermocouples would interfere with the piston as it moved the length of the tank; (2) it would have been exceedingly difficult to insert a 12-in.-diameter piston through the small opening in the top of the tank.

To resolve these problems, a flanged top was added to the tank and a new method of locating the thermocouples is being used.

The thermocouples are attached to a frame and are strung longitudinally in the tank. Small holes punched into the piston will allow the unimpeded passage of the thermocouples through the piston.

At present the new tank is being assembled and readied for test runs.

The piping setup has been revised to accommodate the thesis program of S. K. Fenster; this revision will allow (see Fig. 7) both programs to utilize the same equipment.

RELOCATION OF THE EXPERIMENTAL APPARATUS

As of June 27, the project and associated Ph.D. thesis apparatus was moved from the Automotive Building to the Heat Transfer and Thermodynamics Laboratory of the Department of Mechanical Engineering located in the Fluids Building. Approximately one week was required to complete the move. In approximately 2 to 3 weeks, preliminary runs should be in progress on the new apparatus setup.

The cost of this move was assumed by the University.

EXPERIMENTAL DATA

Programmed Heat-Flux Runs

The runs completed under a programmed heat-flux operation have been completely reduced. This includes plots of (1) liquid and gas temperatures vs. time, (2) wall-temperature transients, and (3) residual mass of gas vs. inlet gas temperature. The residual-mass-of-gas-vs.-inlet-gas-temperature results have been compared to the runs done under ambient conditions.

The residual gas mass (see Fig. 3) will vary with any one of three variables: (a) level of heat flux, (b) inlet gas temperature, and (c) time at a given heat flux.

It can be seen that points A and B (Fig. 3) represent differing quantities of residual gas mass even though the heat flux has remained constant at 1140 Btu/hr-ft^2. This marked change in residual gas (1.13 lbm for B, 1.34 for A) is a result of the fact that in run A the heater was turned on 4 minutes before discharge was initiated, whereas in run B, the heater was turned on at the moment that discharge began. If there was to be a longer discharge period, this effect might be reversed due to the heat transfer to the gas phase.

This effect, of increased residual gas mass, can be explained by the fact that, because of the 4-minute period associated with run A, more violent boiling takes place, with the result that the considerably saturated nitrogen vapor enters the gas space. The heat flux to the gas space is not sufficient to superheat this vapor significantly, and the result is a lower temperature vapor above the liquid. However, when heating is initiated at the same time as the discharge (run B), smaller amounts of saturated vapor enter the gas space, and thus a higher superheat can be obtained with a given heat flux. The result is a higher gas-space temperature, and a corresponding lower mass.

As the level of heat flux is increased, point A would probably move to the same level as point B for the reason that, for a sufficiently high heat flux, the increased vapor formed could be significantly superheated. In this case the results obtained as far as residual gas mass is involved would be similar to the runs done with ambient heat flux.

In these heat-flux runs a cross check was made on the level of heat flux maintained by measuring the power input into the system as well as measuring the decrease in weight of the insulated tank with respect to time, and assuming that all the heat introduced into the system caused nitrogen to evaporate. This latter method should give a value of the low side relative to the electrical measurement, because not all the heat input is used to cause evaporation. This was found to be the case. Calculation of the heat flux from the power input to the system gave the value of 1140 Btu/hr-ft^2, whereas using the boil-off under steady-state conditions yielded the value of 1120 Btu/hr-ft^2.

By comparing Figs. 1 and 2 it can be seen that the wall-temperature transients vary with the time that a particular heat flux is maintained. The level of the wall temperature is much higher on the run at the longest time at the heat flux (35A) as compared to the run in which the heat flux was initiated simultaneously with discharge (35B). This temperature difference would indicate the presence of a relatively lower liquid heat-transfer coefficient for the longer time periods.

Discharge Using Nitrogen Gas

Figures 4, 5, and 6 show the experimental temperatures of three different wall thermocouples (Tc-19, Tc-18, Tc-17) during discharge, using a pressurizing gas temperature of 111°F, 63°F, -30°F, and -299°F. Superimposed on each of these graphs are solid lines which were arrived at by the theoretical wall-temperature transient analysis referred to as Model III in Progress Report No. 9 (Eq. 10). These curves illustrate the effect of varying inlet gas temperature as well as lowering the gas side heat-transfer coefficient (hg). The experimental points and theoretical analysis diverge as X increases. This divergence is attributed to the decrease in hg as the tank is emptied.

Discharge of Liquid Nitrogen Using Helium Gas

Figure 3 illustrates the mass of helium gas required to discharge the liquid nitrogen. Due to the original purpose of our system, the instrumentation in operation would not permit an accurate computation of the residual helium-nitrogen gas mixture. However, the total quantity of helium required to discharge the system has been determined and plotted as a function of inlet gas temperature. These values may then be compared to the mass of residual gas for the nitrogen runs, which is approximately equal to the mass of nitrogen required to discharge the system.

ANALYTICAL WORK

The analysis of the wall-temperature transient for the case of a specified wall heat flux has been completed. This follows along the same lines as the wall-temperature transient analysis reported last month (Progress Report No. 9). The model used for analysis is shown in the sketch.

Adopting identical notation as given in Progress Report No. 9, the following results are obtained:

a. $\underline{-\infty \leqq x \leqq 0}$

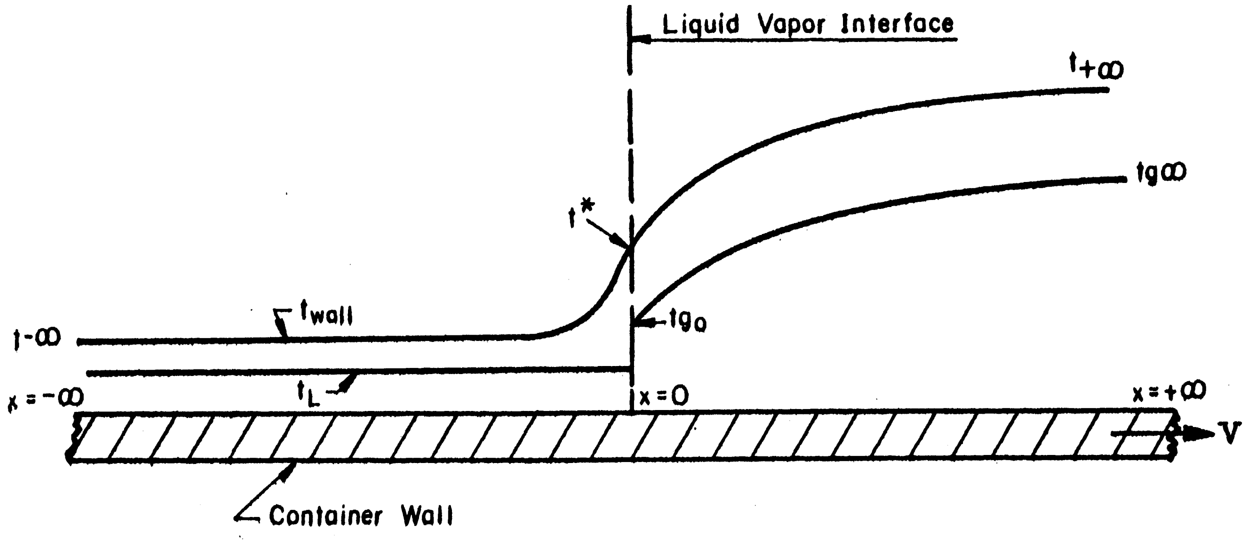
$$t = (t^* - t_{-\infty})e^{a_{1L}x} + t_{-\infty} \tag{1}$$

b. $\underline{0 \leqq x \leqq +\infty}$

$$t = \left(t^* - t_\infty - \frac{\mathcal{L}}{\gamma^2 + m\gamma - \pi g}\right) e^{-a_{2g}x} + t_\infty$$

$$+ \frac{\mathcal{L}}{\gamma^2 + m\gamma - \pi g} e^{-\gamma x} , \qquad (2)$$

Constant Heat-Flux Analysis



$$t_g = t_{g\infty} - \theta_g{}^* e^{-\gamma x} \qquad \theta_g \equiv t_{g\infty} - t_g$$

$$\theta_g{}^* \equiv t_{g\infty} - t_{g0} \qquad \theta_g/\theta_g{}^* = e^{-\gamma x}$$

where

$$t^* = \frac{1}{a_{1L} + a_{2g}} \left\{ a_{1L}\, t_{-\infty} + a_{2g}\, t_\infty + \frac{\mathcal{L}(a_{2g} - \gamma)}{\gamma^2 + m\gamma - \pi g} \right\} \qquad (3)$$

$$\pi_L = \frac{h_L C}{k A} \qquad a_{2g} = 1/2\left(\sqrt{m^2 + 4\pi_g} - m\right)$$

$$\pi_g = \frac{h_g C}{k A} \qquad t_{-\infty} = \frac{(q/A)}{h_L} + t_L$$

$$a_{1L} = 1/2\left(m + \sqrt{m^2 + 4\pi_L}\right) \qquad t_\infty = \frac{(q/A)}{h_g} + t_{g\infty}$$

Results taken from Eqs. (1) and (2) for h_L = 60 Btu/hr-ft^2-F and h_g= 24 Btu/hr-ft^2-F are shown in Figs. 1 and 2. Agreement is reasonable for the case in which the heat flux was established simultaneously with pressurization and discharge but not good for the other run. Better agreement can be obtained in this latter case if h_L is changed to about 35-40 Btu/hr-ft^2-F, a value which the experimental data suggest.

Progress Report for Period May 15 to June 30, 1958 on H. Merte's Thesis

"A Study of Pool Boiling in an Accelerating System"

A. CURRENT STATUS OF WORK

Experimental Apparatus

Fabrication of all parts for the experimental apparatus has been completed by the sub-contractor and the apparatus is 90% assembled. A modification in the design of the flat heating surface was required due to difficulty encountered in soldering a thin stainless-steel skirt to one end of the copper cylinder. This skirt provides a continuous surface from the heater to the walls of the tank. The problem was solved by shrinking the skirt onto the copper cylinder.

The a-c power supply is complete and is capable of furnishing controlled power up to 7.2 kw at 220 v to the flat-plate heater. In addition, a d-c power supply has been constructed for the platinum wire heater which is capable of furnishing up to 50 amp with voltages from 2 to 12.

Tests have shown that the speed of rotation of the main shaft of the centrifuge is constant within ± 1 rpm up to 400 rpm, and the rotating seal for providing cooling water to the rotating assembly performs satisfactorily.

Construction of the platinum-wire holders and a condenser-discharge welding apparatus for welding the platinum wires has been completed. The welding apparatus has been found to be extremely useful in making the thermocouple probes for the flat-plate heater. The thermocouples are presently under construction.

B. EXPECTED STATUS AS OF AUGUST 15, 1958

Upon completion of the calibration of the thermocouples and installation of the heater ribbon in the copper cylinder, test work will be ready to begin. It is anticipated that this period will be devoted primarily to test runs.

Progress Report for Period May 15, 1958 to June 30, 1958
on S. Fenster's Thesis

"Transient Thermal Response of a Step Pressurized Boiling Liquid Nitrogen System"

During the period just passed, the final stages of preparation for experimental work have been essentially completed. Included in this work was the calibration of copper-constantan thermocouples, setup of primary and guard electrical heating apparatus, installation of difference thermocouples for guard-heater control, installation of liquid and wall thermocouples, final piping for pressurization, filling, metering and control of liquid nitrogen and gaseous nitrogen boiloff, preliminary checks of operation of liquid filling system, and installation of styrofoam and glass wool insulation.

The Mechanical Engineering Department has made available a Cenco Megavac vacuum pump and a McLeod vacuum gauge for attaining and measuring high vacua. These will be used in connection with the insulating guard wall between the primary boiloff cylinder and the constant temperature bath.

Connections are being made to an Adjustable Zero Adjustable Range (AZAR) twenty-channel recording potentiometer for temperature measurement and recording.

A four-channel Sanborn recorder is being used to measure and record boiloff rate.

It is anticipated that the first experimental runs will be made shortly.

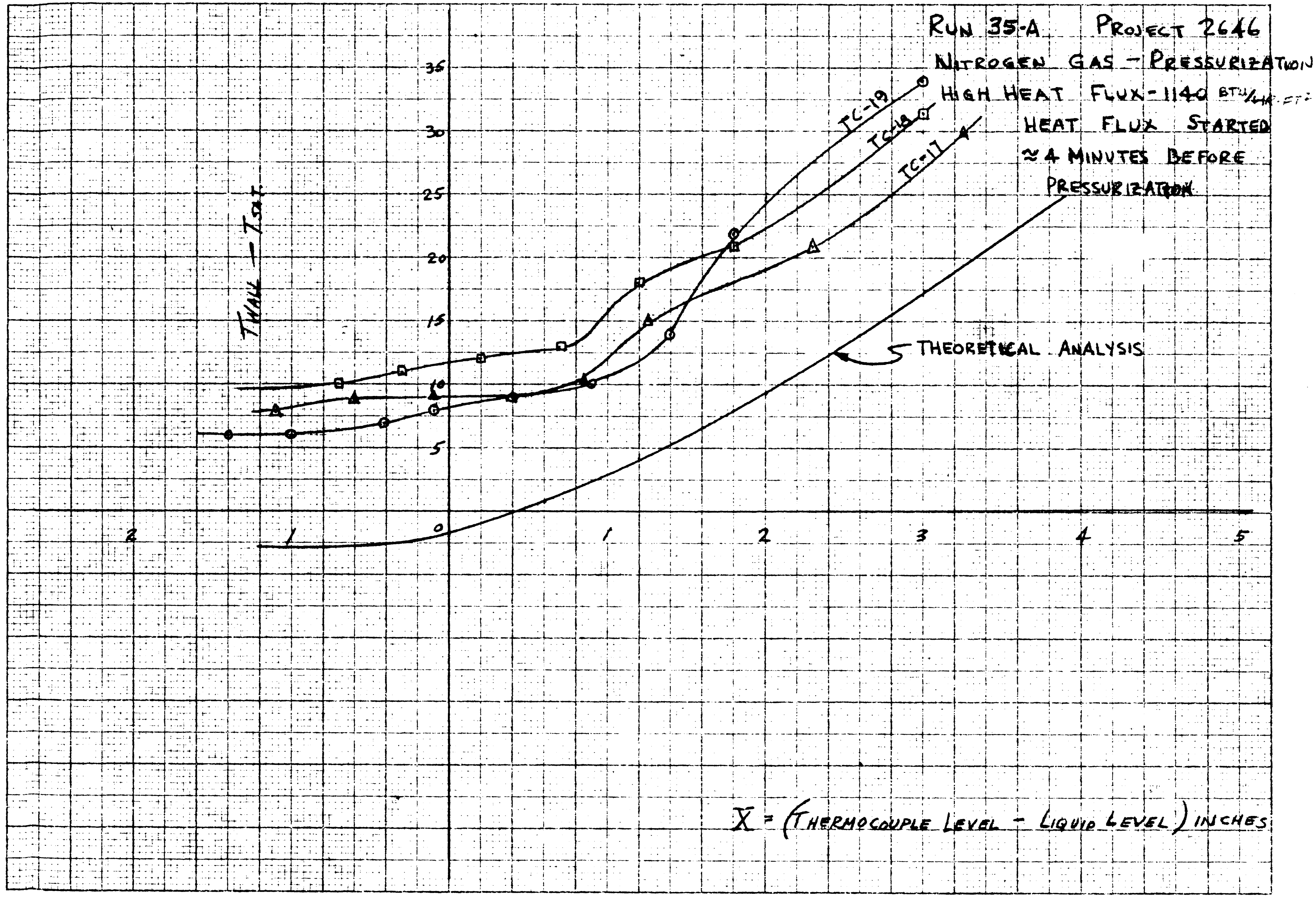

RUN 35-A PROJECT 2646
NITROGEN GAS - PRESSURIZATION
HIGH HEAT FLUX-1140 BTU/HR·FT²
HEAT FLUX STARTED
≈ 4 MINUTES BEFORE
PRESSURIZATION
TC-19
TC-18
TC-17
THEORETICAL ANALYSIS
T WALL - T SAT
35
30
25
20
15
10
5
2
1
0
1
2
3
4
5
X = (THERMOCOUPLE LEVEL - LIQUID LEVEL) INCHES

Fig. 1

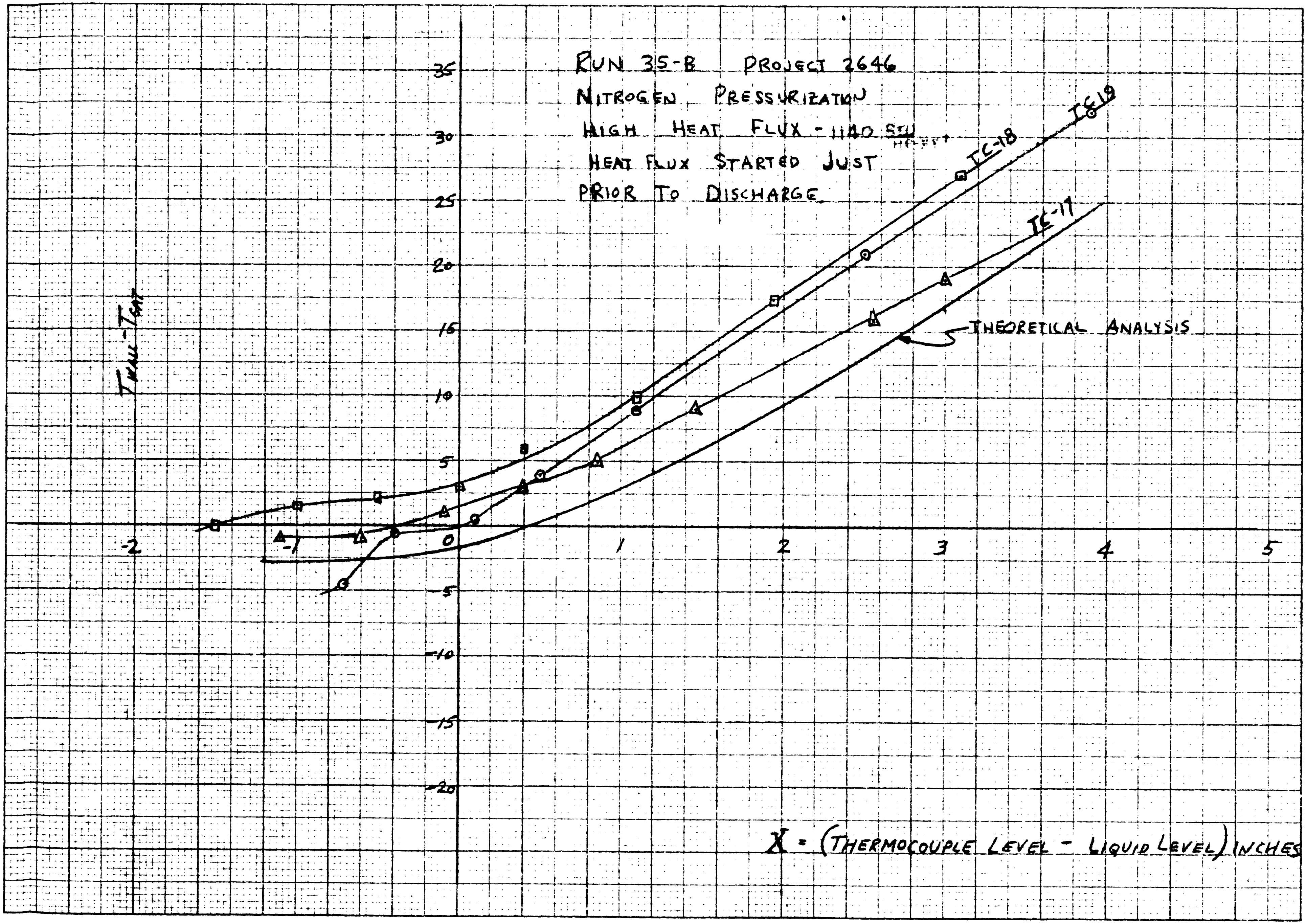

RUN 35-B PROJECT 2646
NITROGEN PRESSURIZATION
HIGH HEAT FLUX - 1140 BTU HR-FT²
HEAT FLUX STARTED JUST
PRIOR TO DISCHARGE
T_WALL - T_SAT
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-2
-1
1
2
3
4
5
TC-19
TC-18
TC-11
THEORETICAL ANALYSIS
X = (THERMOCOUPLE LEVEL - LIQUID LEVEL) INCHES

Fig. 2

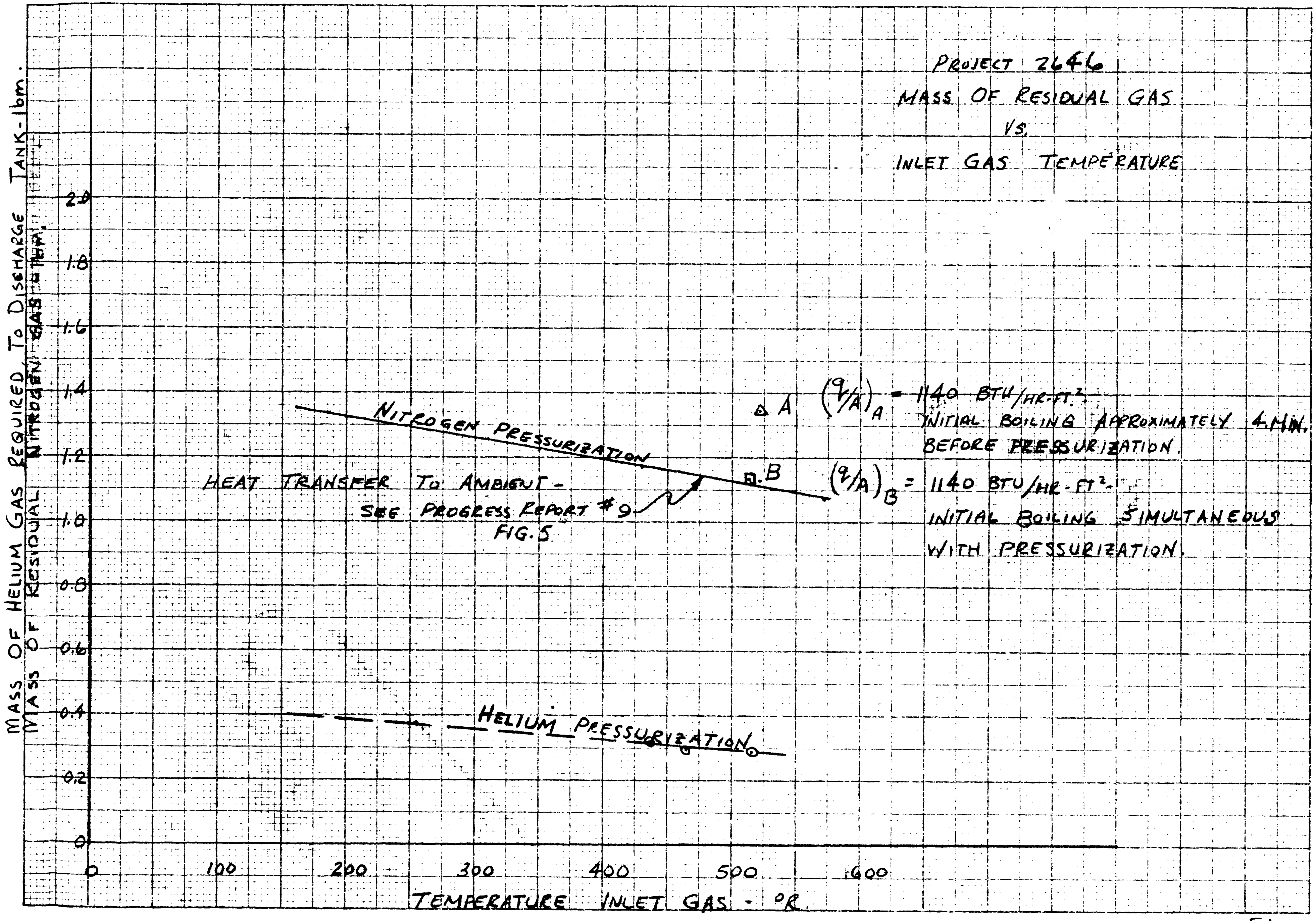

PROJECT 2646
MASS OF RESIDUAL GAS
VS.
INLET GAS TEMPERATURE
MASS OF HELIUM GAS REQUIRED TO DISCHARGE TANK-lbm.
MASS OF RESIDUAL NITROGEN GAS-lbm.
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
100
200
300
400
500
600
TEMPERATURE INLET GAS - °R
NITROGEN PRESSURIZATION
HELIUM PRESSURIZATION
HEAT TRANSFER TO AMBIENT - SEE PROGRESS REPORT #9 FIG. 5
A
B
$(q/A)_A$ = 1140 BTU/HR-FT². INITIAL BOILING APPROXIMATELY 4 MIN. BEFORE PRESSURIZATION.
$(q/A)_B$ = 1140 BTU/HR-FT². INITIAL BOILING SIMULTANEOUS WITH PRESSURIZATION.

Fig. 3

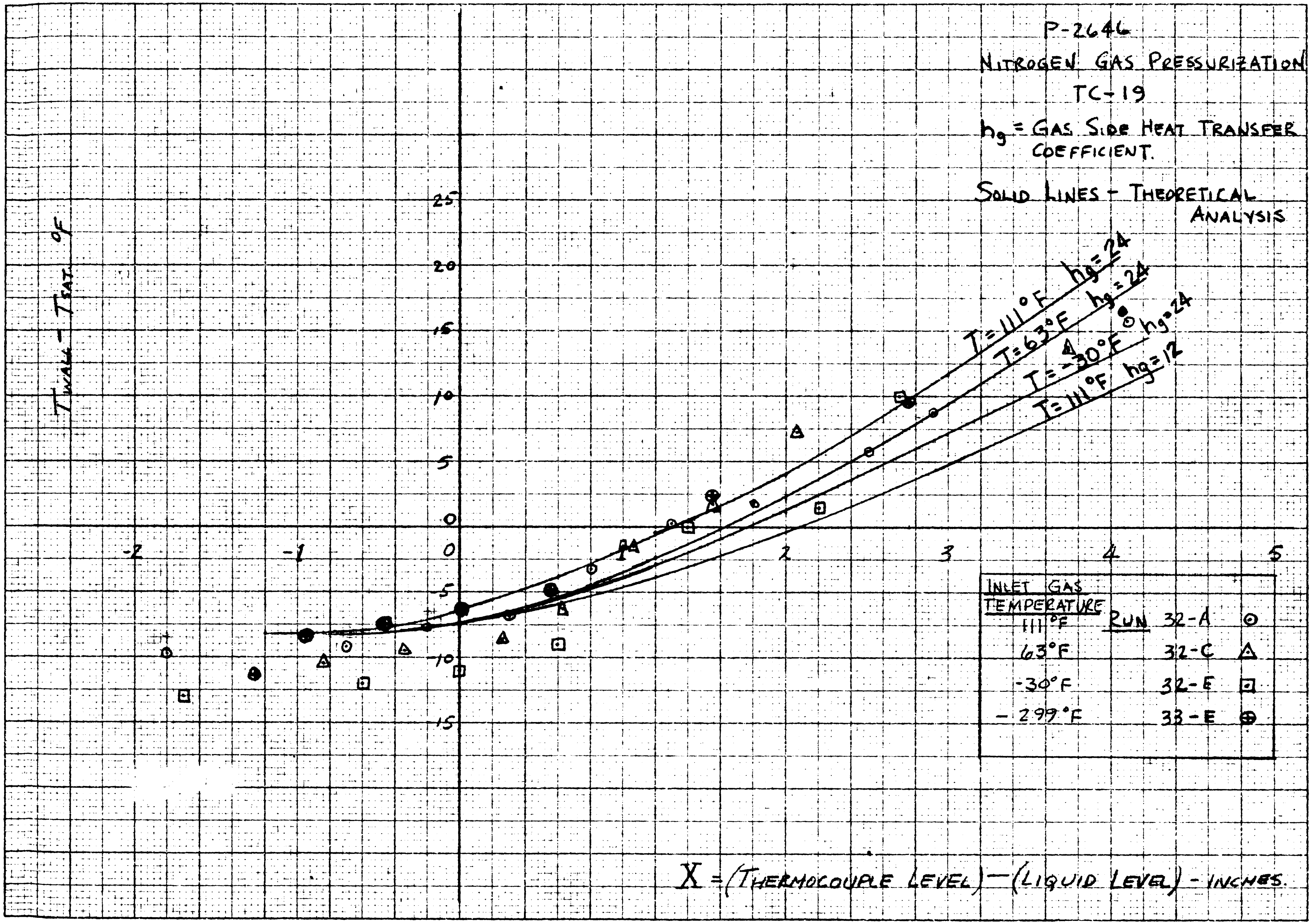

P-2646
NITROGEN GAS PRESSURIZATION
TC-19
hg = GAS SIDE HEAT TRANSFER COEFFICIENT.
SOLID LINES - THEORETICAL ANALYSIS
T = 111°F hg = 24
T = 63°F hg = 24
T = -30°F hg = 24
T = 111°F hg = 12
INLET GAS TEMPERATURE
RUN
111°F 32-A ⊙
63°F 32-C △
-30°F 32-E ⊡
-299°F 33-E ⊕
T WALL - T SAT °F
25
20
15
10
5
0
5
-10
-15
-2
-1
0
1
2
3
4
5
X = (THERMOCOUPLE LEVEL) - (LIQUID LEVEL) - INCHES.

Fig. 4

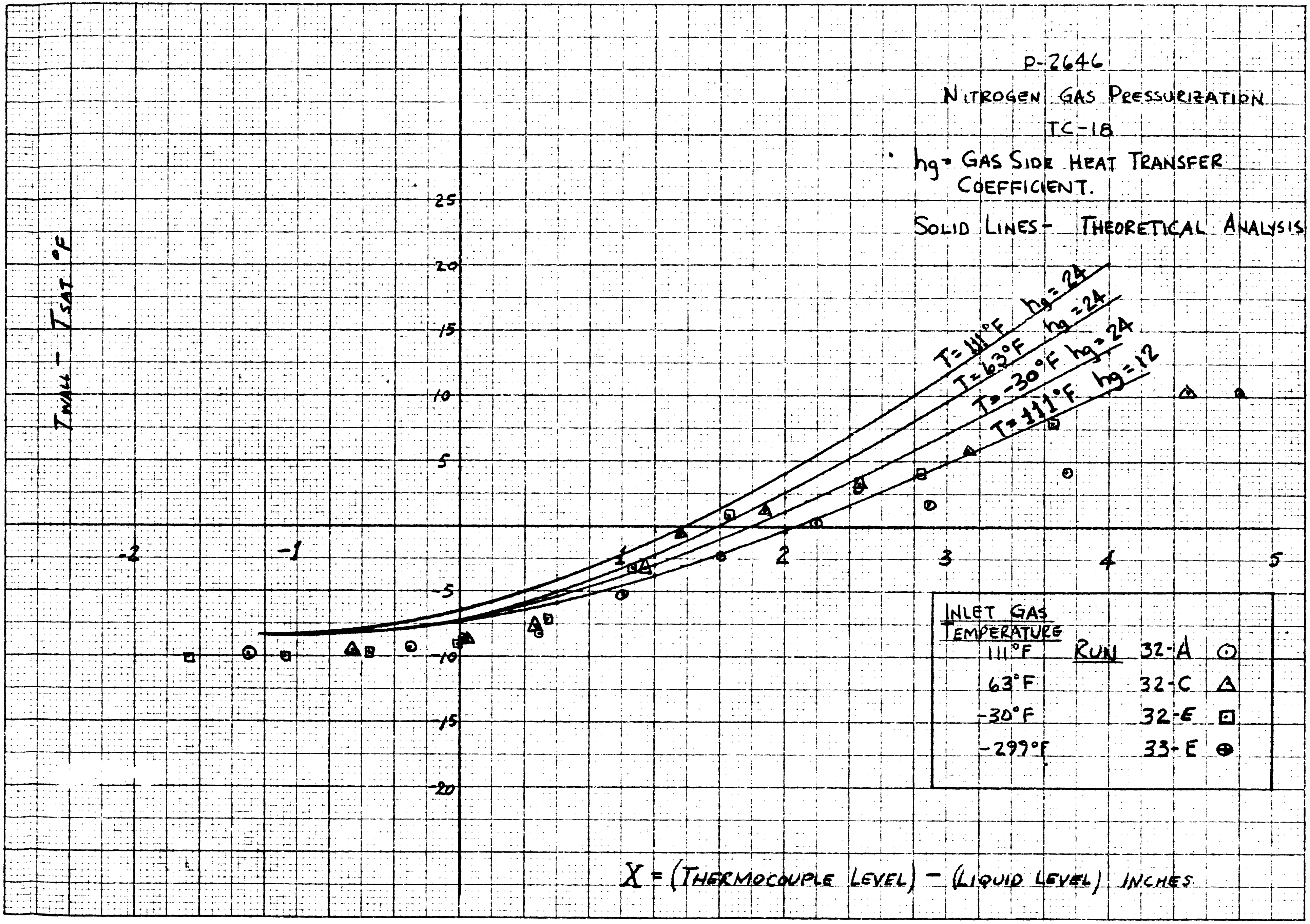

P-2646
NITROGEN GAS PRESSURIZATION
TC-18
• hg = GAS SIDE HEAT TRANSFER COEFFICIENT.
SOLID LINES - THEORETICAL ANALYSIS
T = 111°F hg = 24
T = 63°F hg = 24
T = -30°F hg = 24
T = 111°F hg = 12
TWALL - TSAT °F
25
20
15
10
5
-5
-10
-15
-20
-2
-1
1
2
3
4
5
X = (THERMOCOUPLE LEVEL) - (LIQUID LEVEL) INCHES
INLET GAS TEMPERATURE
RUN
111°F 32-A ⊙
63°F 32-C △
-30°F 32-E ⊡
-299°F 33-E ⊕

Fig. 5

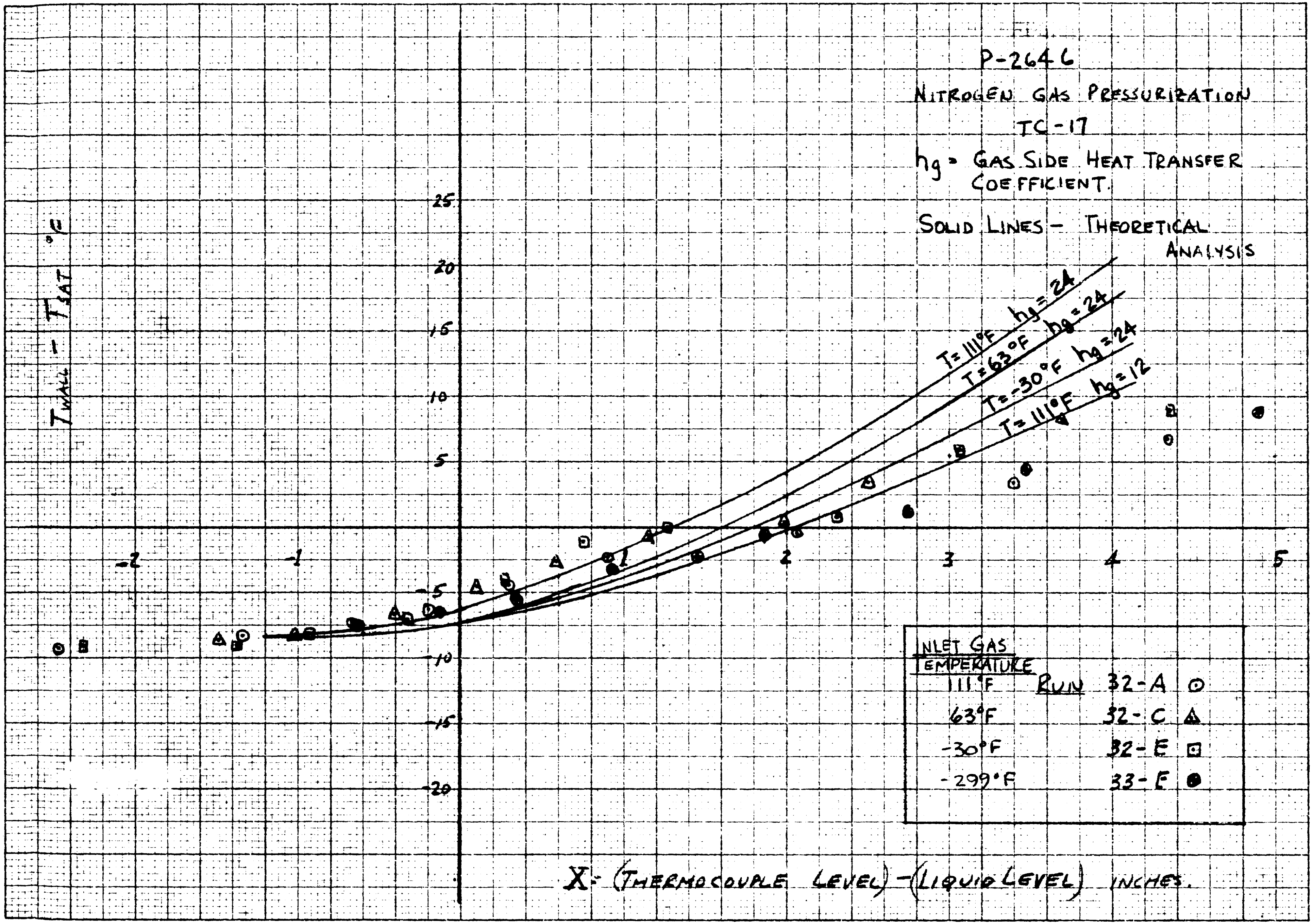

P-264 C
Nitrogen Gas Pressurization
TC-17
hg = Gas Side Heat Transfer Coefficient.
Solid Lines – Theoretical Analysis
T = 111°F hg = 24
T = 63°F hg = 24
T = -30°F hg = 24
T = 111°F hg = 12
Inlet Gas Temperature
Run
111°F 32-A ⊙
63°F 32-C △
-30°F 32-E ⊡
-299°F 33-E ●
T_WALL – T_SAT °F
25
20
15
10
5
-5
-10
-15
-20
-2
-1
1
2
3
4
5
X = (Thermocouple Level) – (Liquid Level) inches.

Fig. 6

DWG. NO. A

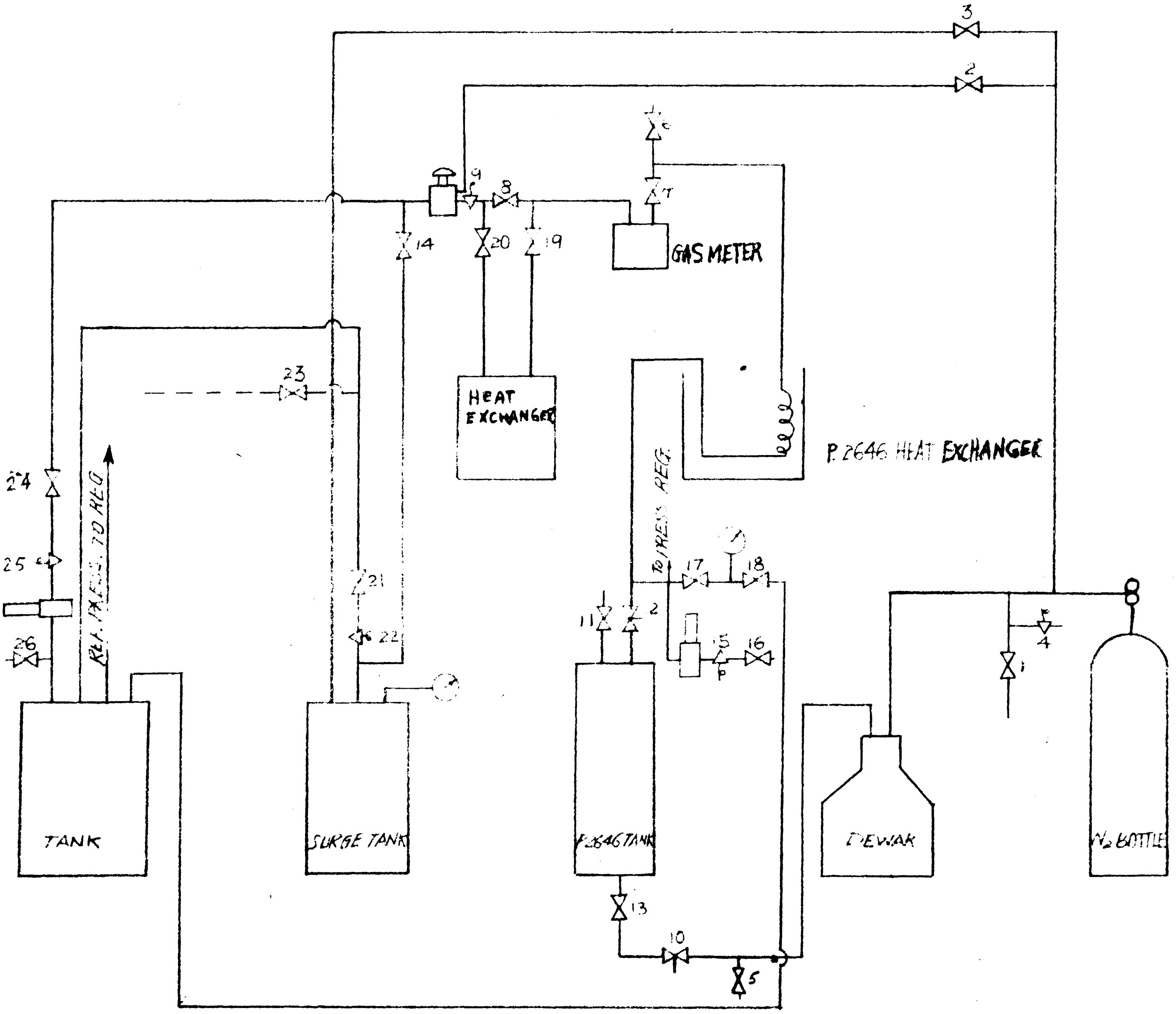


FIG. 7

ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR MICHIGAN

PROJECT 2646

CLASSIFICATION

SUE | DATE

DESIGNED BY
DRAWN BY W.J.Y
CHECKED BY
APPROVED BY
SCALE NOT TO SCALE
DATE July 1, 1958

TITLE TEST APPARATUS FOR PRESSURIZING TANK & MAINTAINING PRESSURE

DWG. NO. A-