T H E U N I V E R S I T Y O F M I C H I G A N

COLLEGE OF ENGINEERING
Department of Mechanical Engineering
Heat Transfer and Thermodynamics Laboratory

Progress Report No. 1
For the Period January through March, 1960

PRESSURIZATION OF LIQUID OXYGEN CONTAINERS

J.A. Clark
D.F. Jankowski
H. Merte, Jr.
W.O. Winer
V.S. Arpaci

UMRI Project 03583-1-P

under contract with:

DEPARTMENT OF THE ARMY
DETROIT ORDNANCE DISTRICT
CONTRACT NO. DA-20-018-506-ORD-254
DETROIT, MICHIGAN

administered by

THE UNIVERSITY OF MICHIGAN RESEARCH INSTITUTE   ANN ARBOR

May 1960

ABSTRACT

The report covers research conducted under this contract during the period January 1, 1960, through March 31, 1960. Research is underway on three principal topics:

A. Optimization of pressurized-discharge processes in cryogenic containers.

B. Boiling of a cryogenic fluid under reduced gravity.

C. Heat transfer to a cryogenic fluid in an accelerating system.

A refined experimental system is described which will improve the precision of gas-temperature measurements in the vicinity of the liquid interface. Preliminary correlation with theoretical predictions of gas- and wall-temperature transients are discussed and the need for improvement is indicated. Methods for accomplishing this are given. Analytical procedure is being revised.

The initial design of research apparatus to study heat transfer with cryogenic fluids in free and partial gravity is given. Apparatus to study heat transfer at high gravity (1-21 g's) is also described.

I. OPTIMIZATION OF PRESSURIZED-DISCHARGE PROCESSES IN CRYOGENIC CONTAINERS

A. EXPERIMENTAL PROGRAM

During the last period the existing experimental system was dismantled and the design of a new system was started. The features which will be incorporated in the new experimental system are, for the most part, a result of the combined efforts in the experimental and analytical directions to understand more fully the pressurized-discharge process of a cryogenic container.

The Consolidated Recording Oscillograph, on loan from the Detroit Ordnance District, had to be returned, making it necessary to synchronize the Sanborn recorder to the Visicorder directly. Since each recorder has a built-in timing system, it is necessary only to establish zero time simultaneously on the two recorders to synchronize the records of the experimental runs. This was accomplished by a suitable switching arrangement whereby the initial timing signals from the Sanborn are impressed on one of the Visicorder galvanometers and thereby recorded to give the simultaneous zero time on each instrument. After the first few seconds are recorded, the Visicorder channel is reconnected to a thermocouple in the experimental section to record its behavior throughout the remainder of the run.

The experimental system was dismantled and the new designs were started. The next system will incorporate a styrofoam top on the inside of the container, a floating thermocouple column, an annular float, electrical ribbon heaters, and guard-heater type of insulation.

The styrofoam top on the inside of the container is being installed to reduce the cooling effects on the inlet gas which were previously present with the cold aluminum top. In the previous system the 1/2-in.-thick aluminum top was cooled to -320°F at the beginning of a run, and when the pressurizing gas, at as high as 98°F, was forced into the small void at the top of the tank, an excessive amount of heat transfer took place between the cold top plate and the relatively hot gas. It is believed that the installation of the styrofoam layer at the top will reduce the heat-transfer interaction between the top and the pressurizing gas and therefore reduce an "end effect" in the system. This will enable a closer control of variables in the experimental operation.

The reasons for installing the floating thermocouple column were discussed in Progress Report No. 19. Briefly, this will improve the accuracy of the gas-temperature measurements in the region of the interface, a particularly difficult place to make such measurements.

An annular-shaped piston made of HD2 type styrofoam will be installed to support the level indicator and the floating thermocouple column. The annular piston will be slightly smaller than the inside diameter of the discharge container. The members supporting the level indicator and the floating thermocouple column will be attached to the float below the liquid level. In this manner the temperatures measured just above the surface will more closely approximate the temperatures in the vicinity of the bare interface in an uninstrumented discharge container.

New heaters are being installed, using flat, chromel, heater ribbon instead of wire. The new heaters will operate on a 220-v line and will be able to produce a maximum heat flux of 9500 Btu/hr sq ft.

B. ANALYSIS OF GAS- AND WALL-TEMPERATURE RESPONSE DURING THE DISCHARGE OF A CRYOGENIC LIQUID FROM A CONTAINER

In attempting a preliminary correlation of the experimental data with the analysis presented in Progress Report No. 18, certain problems have been encountered. Examples of the type of correlation are given in Figs. 1-4. Figures 1 and 2 show the gas and wall temperatures, respectively, corresponding to a gas-wall convection heat-transfer coefficient assumed to be 10 Btu/hr sq ft °F. Figures 3 and 4 show the gas and wall temperatures, respectively, for a gas-wall convection heat-transfer coefficient of 2 Btu/hr sq ft °F. In most cases the measured temperatures are considerably higher than what the analysis predicts.

Although the analytical model and the experimental system correspond to each other in many respects, there is one very basic condition in which the two presently do not correspond: The boundary condition of no heat flux between the system and the ambient which has been imposed on the analytical model. The physical system is quite well insulated for a steady-state heat transfer from the ambient. That is, the present type of insulation reduces the steady-state heat flux into the system to a minimum which would be quite adequate for a steady-state experiment. But since the process under study is a transient phenomenon, the heat capacity as well as the conduction characteristics of the insulating system play an important role. Because of the unsteady nature of the process, a thermal transient is introduced in the insulation which makes it difficult to specify a definite condition on the heat-flux exchange between the wall and the insulation. Since the character of this heat-flux must be specified for the analysis, the analytical model and the experimental system are rendered incompatible in this respect. For this reason a correlation of data from the present experimental system and the analytical model under discussion should not be expected.

It will be observed from Figs. 1-4 that the experimental data fall above the corresponding theoretical curve. This would be expected if the actual boundary condition with the ambient were not adiabatic as assumed in the analytical model.

A new analysis is underway which will predict the response of the gas and wall temperatures to a moving heat flux on the outer container wall. The heat flux moves with the interface and acts only on the container walls exposed to the pressurizing gas. This model will correspond more closely to the physical system.

In the new experimental system under construction, discussed in Part A, steps are being taken to reduce the heat flux at the exterior of the discharge container to the adiabatic condition imposed as a boundary condition on the analytical model. This will be accomplished by employing an annular-shaped container enclosing the main discharge container. Equivalent heaters will be installed on the container's inside walls, opposing the heaters on the main tank. The annular volume between the two containers will be filled with a noncondensible gas such as helium. The two containers will be discharged simultaneously and the opposing wall temperatures of each wall will be monitored. It is expected that in this system both the walls will experience nearly the same transients. If so, the temperature drop across the separating volume filled with helium will be essentially zero and the exterior boundary condition of zero heat flux to the main interior container will be satisfied within the experimental capabilities.

Such a design will still permit a controllable and metered heat flux up to about 9500 Btu/hr-ft^2 to be applied to the outside of the cryogenic test container.

II. BOILING OF A CRYOGENIC FLUID UNDER REDUCED GRAVITY

Mr. Matthew Starr, who has recently become associated with the project, will concentrate on the study of boiling of cryogenic liquids in force fields less than standard gravity.

Zero gravity will be obtained by the free fall of a test assembly. With suitable counterweights attached to the test assembly, it will be possible to attain values of acceleration between zero and standard gravity.

A free fall height of 42 feet is available in the Heat Transfer and Thermodynamics Laboratory in the Fluids Engineering Building with a clear area of 18 by 44 inches. Wires will be provided to guide the vessel during the drop. Figure 5 shows the over-all experimental facility. At the end of the drop, the test assembly must be smoothly brought to a stop to prevent damage to the vessel and instrumentation. A number of means of accomplishing this were considered, and a hydraulic buffer shown in Fig. 6 was selected as the most suitable from the standpoint of simplicity and reliability.

With a free fall of 42 feet, the duration of the test will be approximately 1.5 seconds. Using the conventional experimental method for obtaining boiling data by the steady-state measurements of temperature and heat flux, such a short test period would require the heater system to have a very low thermal inertia so that the new "steady-state" condition under a zero gravity field may be attained. The term "steady-state" with boiling in a zero gravity field will itself require clarification as to its physical significance. This is one objective of this research.

For the first series of tests, a transient technique will be employed to measure the boiling characteristics. A solid metal sphere with a thermocouple in its center serves as the heated surface. Upon heating the sphere and inserting it in liquid nitrogen, the transient change in temperature can be recorded, permitting computation of an instantaneous rate of heat transfer and suface temperature. Should a lumped parameter system for evaluation of surface temperature prove inadaquate, a numerical method similar to that presented by Stolz[1] can then be used.

The data so obtained in a standard gravity field will be compared with that obtained during free fall.

Provision will be made on the test platform for mounting a high-speed motion picture camera; photographic data may prove desirable later. Acceleration of the test platform will be measured with an accelerometer. All experimental measurements will be recorded on a high-speed oscillograph using a Minneapolis-Honeywell Model 1012 "Visicorder." This is available in the Laboratory.

III. HEAT TRANSFER TO A CRYOGENIC FLUID IN AN ACCELERATING SYSTEM

As an extension of the study of the influence of vehicle acceleration on the boiling of a saturated water,[2] a study of the influence of vehicle acceleration on heat transfer (nonboiling and boiling) to liquid nitrogen is now being undertaken. The initial phase will consider an orientation such that the acceleration vector will be normal to the heating surface, covering a range of 1-20 g's. The heat-flux range will be varied up to approximately 50,000 Btu/hr-ft^2, and the heat flux, heater suface temperatures, and fluid temperature will be measured.

The same basic apparatus described in Ref. 2 will be utilized with the exception of the rotating test vessel. The stainless-steel heater skirt in the original test vessel was assembled to the copper heating disc by means of a shrink fit using liquid nitrogen. It is now necessary to solder a skirt to the heater surface, using the same material as the heater to avoid differential contractions. Further, it will no longer be possible to condense the vapor generated, and the feeding of liquid nitrogen to the rotating member appears to be impractical with the present system. As a consequence, a larger liquid capacity will be provided on the rotating test vessel and the liquid level allowed to decrease during the test run. It is expected that the rate of decrease can be calibrated for the various test conditions. With the above procedure, only a single condition of heat flux and acceleration can be obtained for each charge of the test vessel.

Figure 7 is a sketch of the proposed test vessel. The heating surface system is designed to have as low a mass as is practical so that any transients set up by the acceleration may be dissipated without an undesirable loss of time. This requires the elimination of guard-heater systems on the underside, but it is estimated that the resulting heat loss will be less than 5% of the total heat flux.

The design of the test vessel is virtually complete, and it is expected that construction can begin during the coming period.

Upon completion of this phase of the program, consideration will be given to the orientation wherein the force field will be parallel to the heating surface.

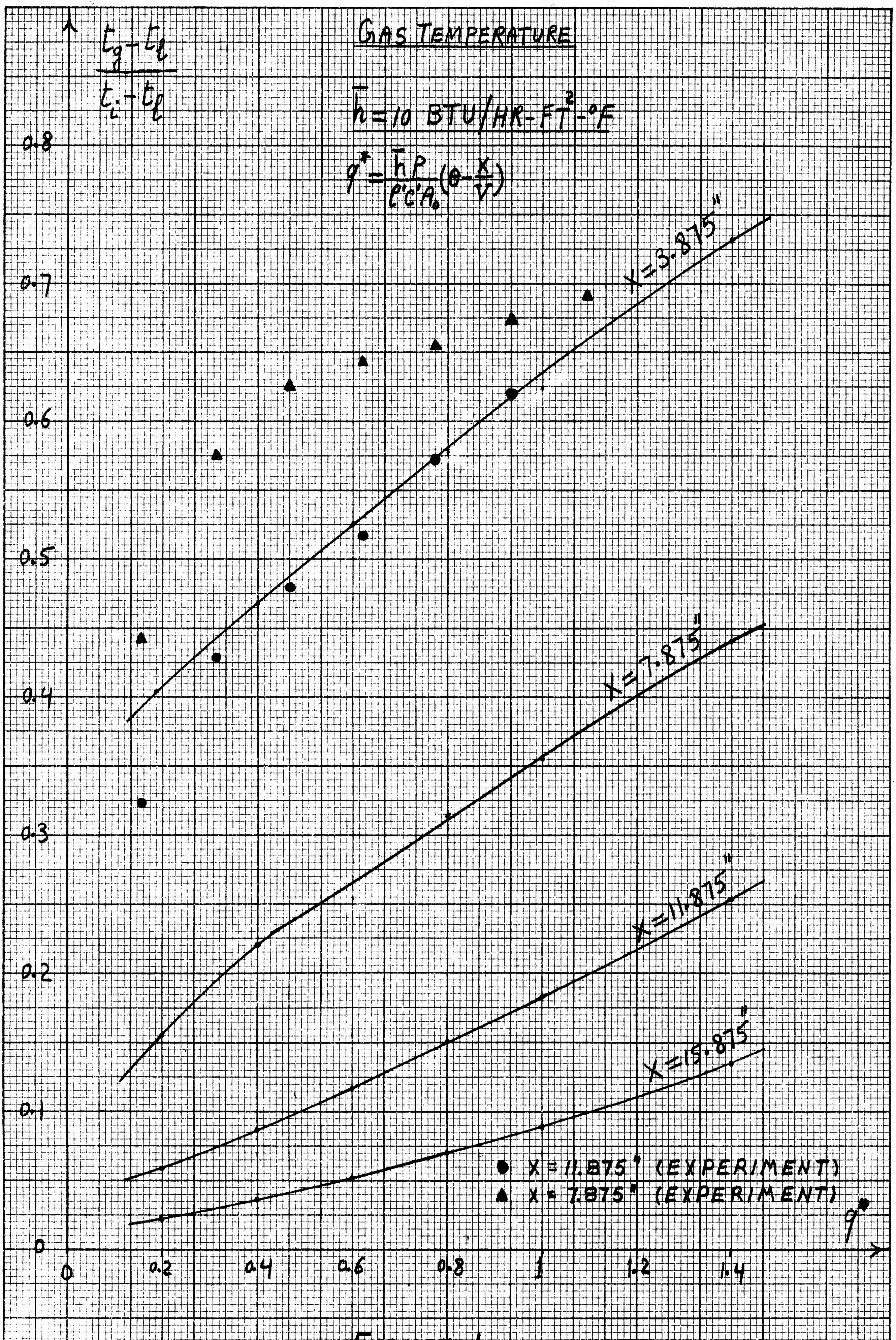
IV. LABORATORY VISITS

A visit to the Lewis Propulsion Research Facility of the NASA was made on March 25, 1960, by Professor John A. Clark, Mr. Herman Merte, and Mr. Matthew Starr to discuss research on boiling heat transfer in the presence of force fields different from that due to normal gravity. Discussions were held with Dr. Robert Siegel, Mr. Robert Hendricks, and Dr. Robert Graham.

REFERENCES

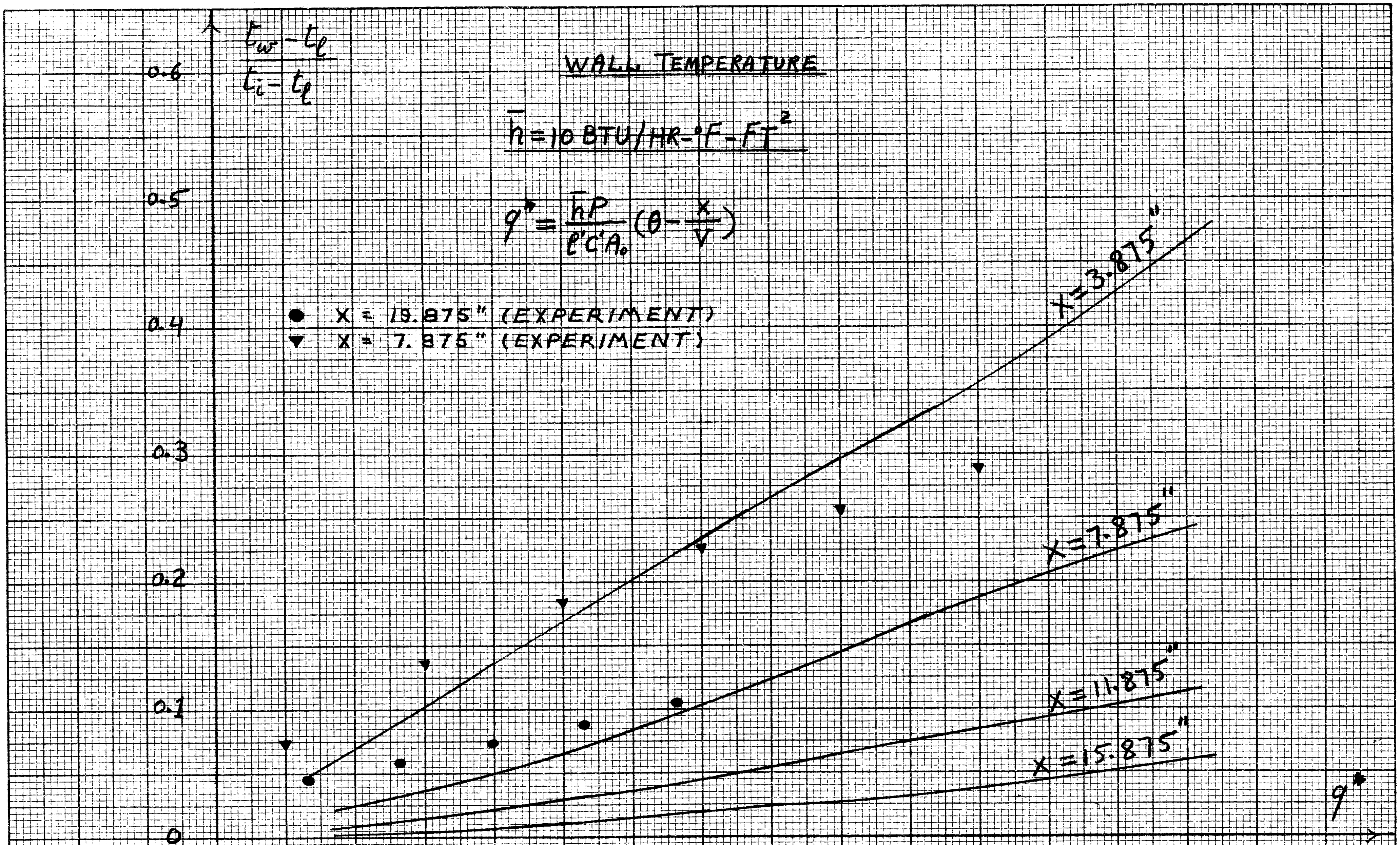
1. Stolz, G., Jr., "Numerical Solutions to an Inverse Problem of Heat Conduction," ASME Journal of Heat Transfer, 82, 20-26 (1960).

2. Merte, H., Jr., and Clark, J. A., A study of Pool Boiling in an Accelerating System, Technical Report No. 3, November, 1959. Dept. of the Army, Detroit Ord. Dist., Contract. No. DA-20-018-ORD-15316.



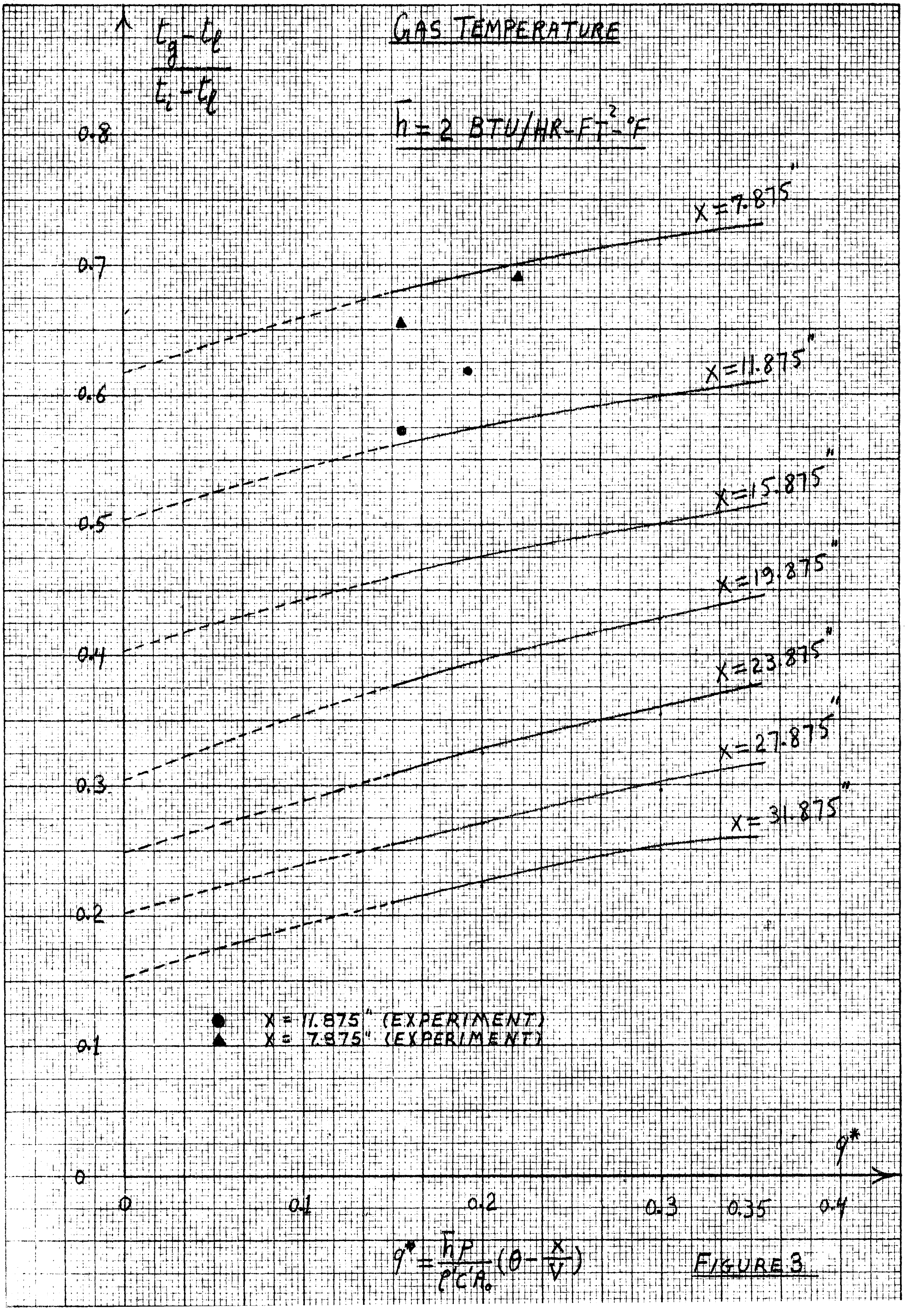
GAS TEMPERATURE
$\bar{h} = 10$ BTU/HR-FT²-°F
$q^* = \frac{\bar{h} P}{\rho' c' A_0}\left(\theta - \frac{X}{V}\right)$
$\frac{t_g - t_l}{t_i - t_l}$
X = 3.875"
X = 7.875"
X = 11.875"
X = 15.875"
● X = 11.875" (EXPERIMENT)
▲ X = 7.875" (EXPERIMENT)
q^*
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.2
0.4
0.6
0.8
1
1.2
1.4

FIGURE 1



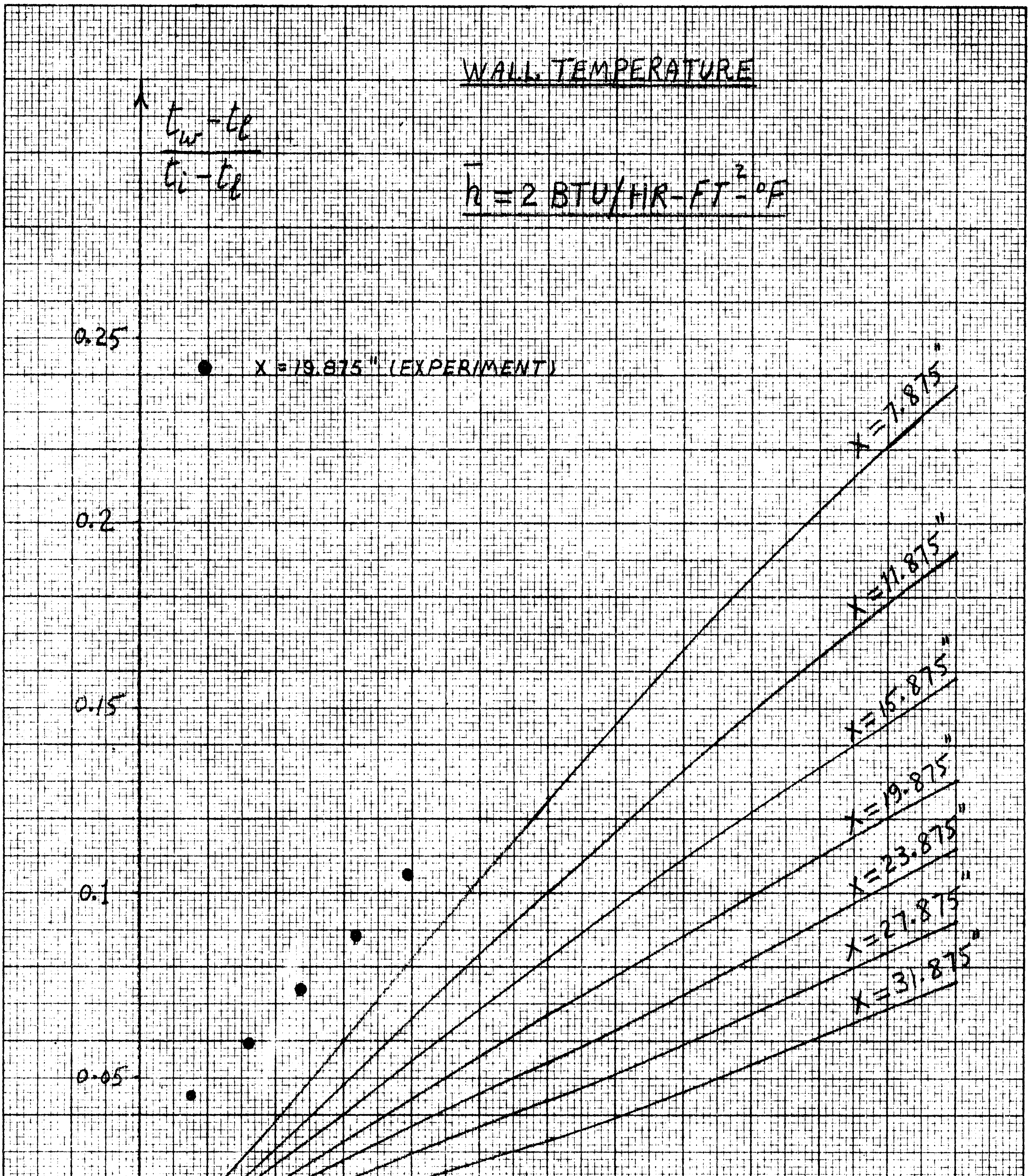
WALL TEMPERATURE
$\bar{h} = 10$ BTU/HR-°F-FT^2
$q^* = \frac{\bar{h}P}{\rho' C' A_0}\left(\theta - \frac{X}{V}\right)$
● X = 19.875" (EXPERIMENT)
▼ X = 7.875" (EXPERIMENT)
$\frac{t_w - t_\ell}{t_i - t_\ell}$
q^*
X = 3.875"
X = 7.875"
X = 11.875"
X = 15.875"
0
0.1
0.2
0.3
0.4
0.5
0.6
0.2
0.4
0.6
0.8
1
1.2
1.4

FIGURE 2



GAS TEMPERATURE
$\frac{t_g - t_\ell}{t_i - t_\ell}$
$\bar{h} = 2$ BTU/HR-FT^2-°F
X = 7.875"
X = 11.875"
X = 15.875"
X = 19.875"
X = 23.875"
X = 27.875"
X = 31.875"
● X = 11.875" (EXPERIMENT)
▲ X = 7.875" (EXPERIMENT)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.35
0.4
φ^*
$\varphi^* = \frac{\bar{h}P}{\rho' C' A_o}\left(\theta - \frac{x}{V}\right)$

FIGURE 3



WALL TEMPERATURE
$\frac{t_w - t_\ell}{t_i - t_\ell}$
$\bar{h} = 2$ BTU/HR-FT^2-°F
0.25
X = 19.875" (EXPERIMENT)
0.2
0.15
0.1
0.05
0
X = 7.875"
X = 11.875"
X = 15.875"
X = 19.875"
X = 23.875"
X = 27.875"
X = 31.875"
q^*
0
0.1
0.15
0.2
0.3
0.35
0.4
$q^* = \frac{\bar{h} P}{\rho' c' A_o}\left(\theta - \frac{X}{V}\right)$

FIGURE 4

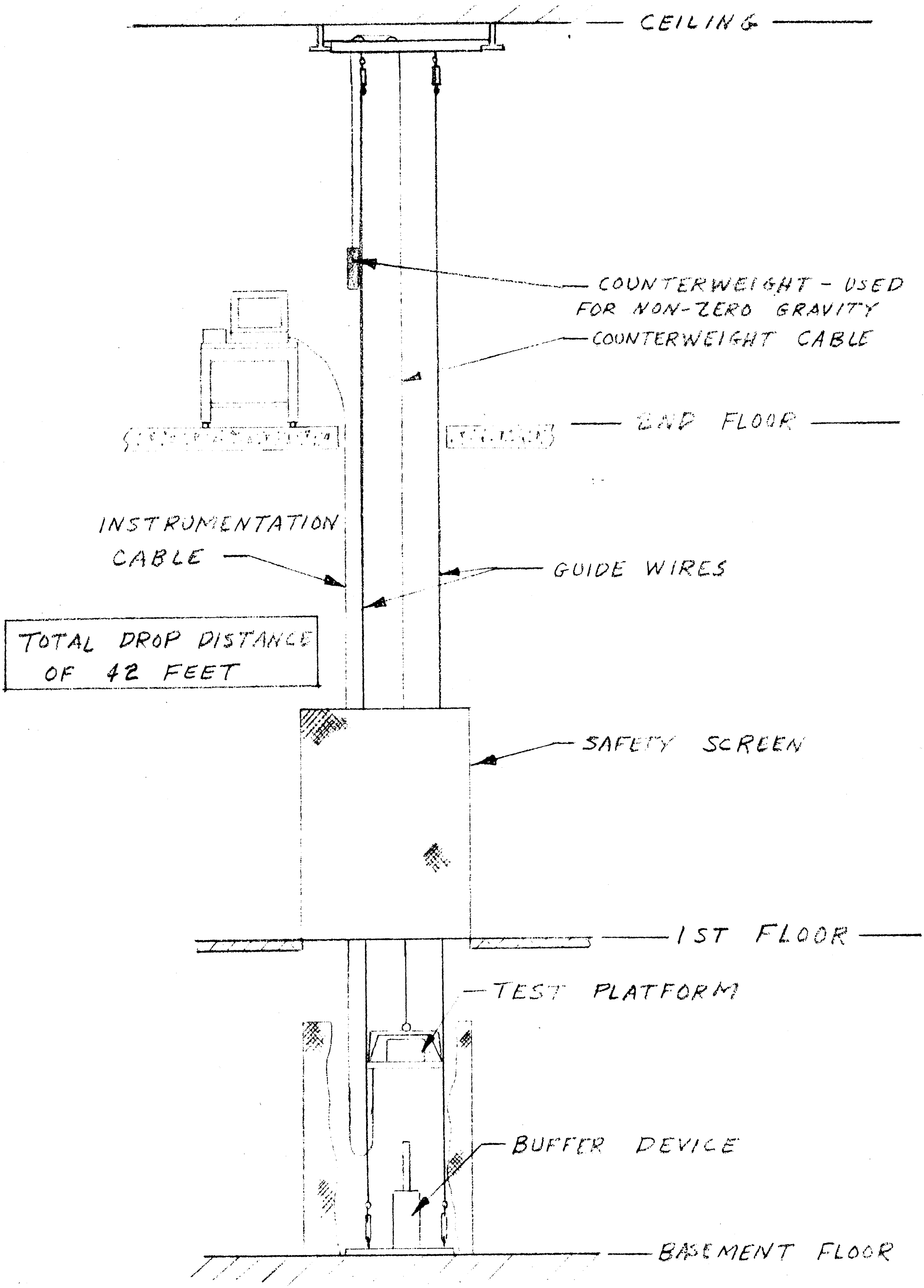


FIGURE 5. ELEVATION VIEW OF ZERO GRAVITY BOILING TEST ASSEMBLY IN FLUIDS ENGINEERING BUILDING.

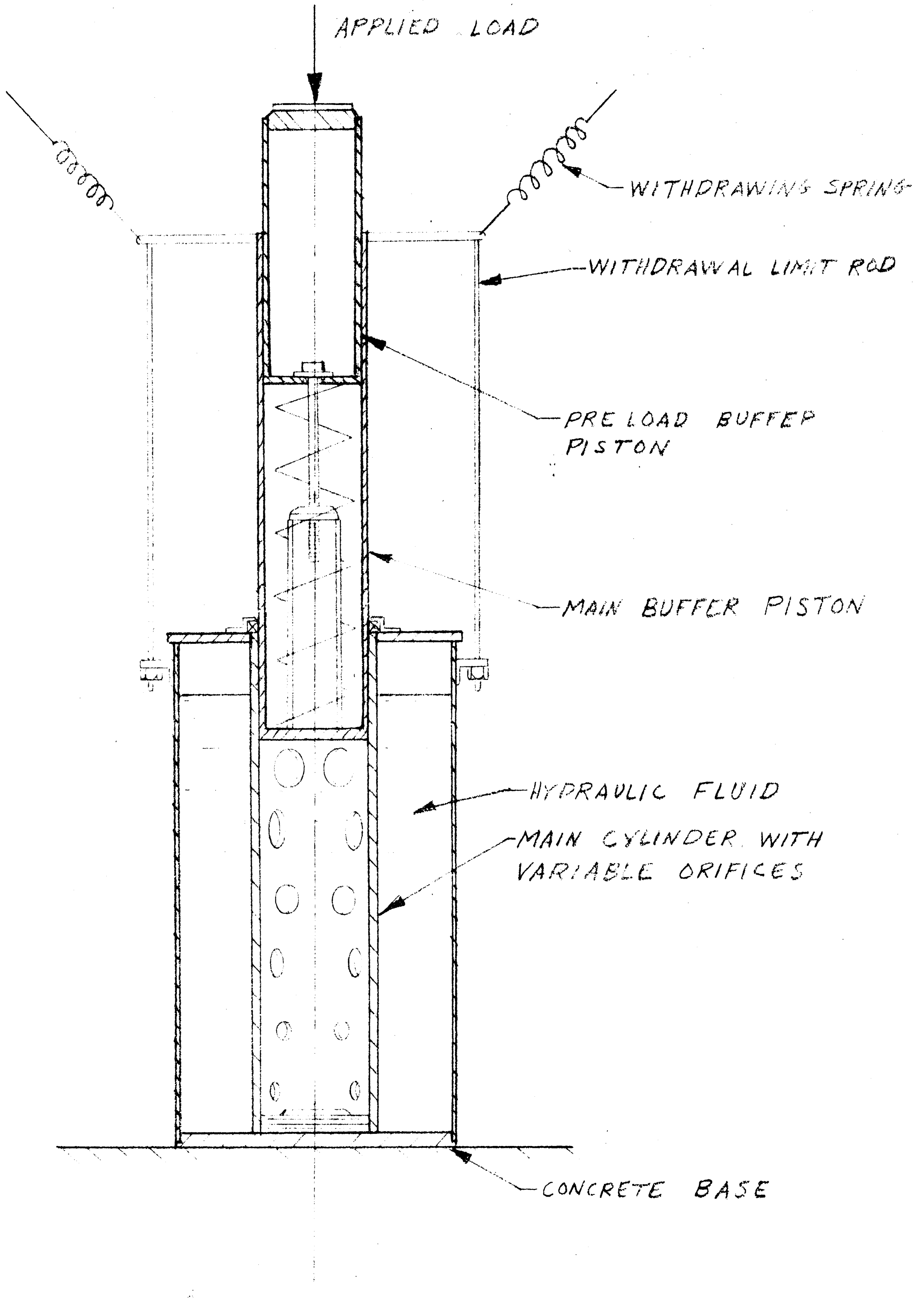


FIGURE 6. HYDRAULIC BUFFER

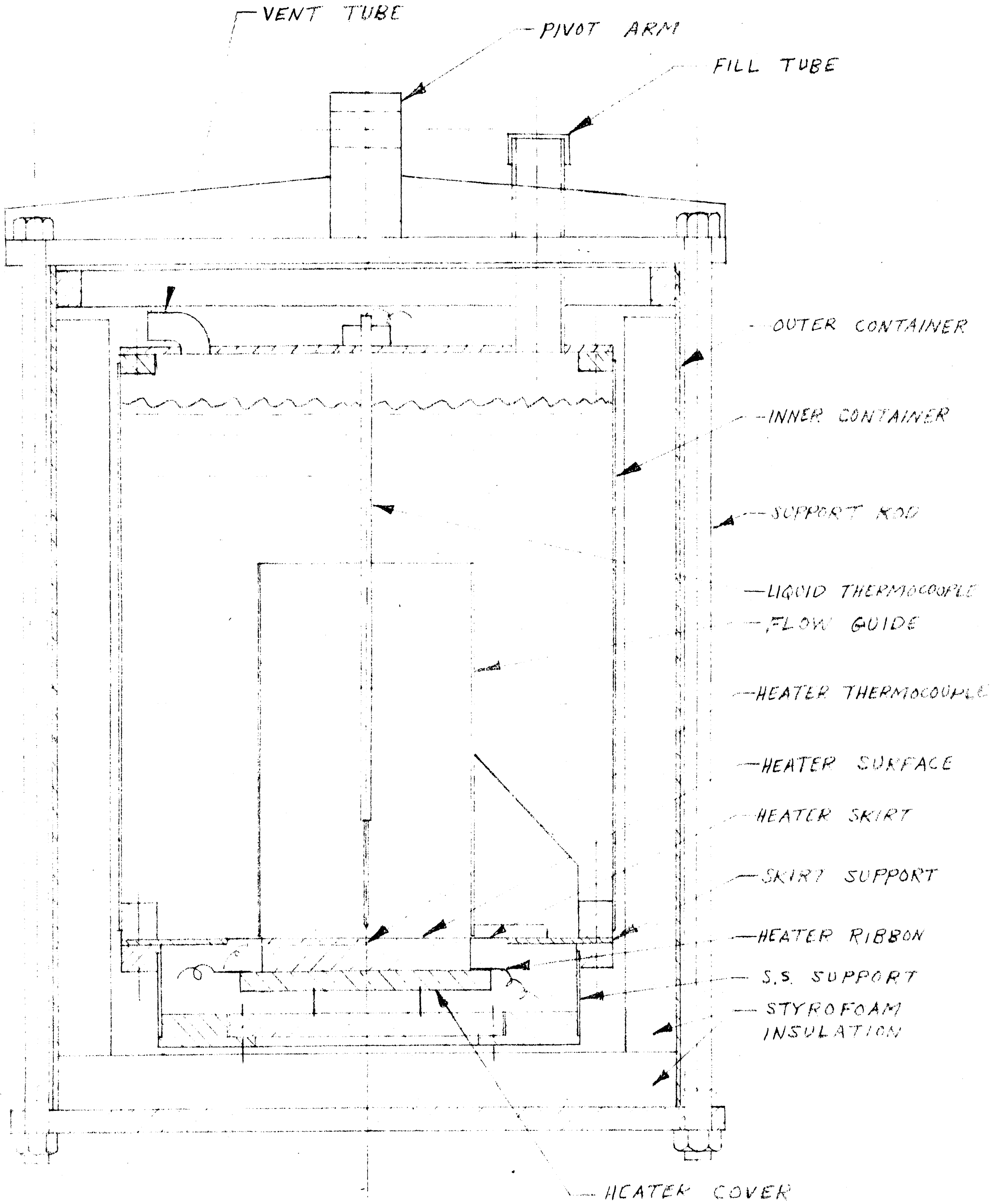


FIGURE 7 . LIQUID NITROGEN BOILING ACCELERATION TEST VESSEL.