THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Department of Chemical and Metallurgical Engineering
Department of Mechanical Engineering

Second Quarterly Progress Report

INVESTIGATION OF LIQUID METAL BOILING HEAT TRANSFER

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FOREWORD

This report summarizes efforts to date on Phase II of Air Force Contract AF 33(616)-8277. A literature survey of liquid metal boiling technology has been released as an ASD report (ASD Tech. Rept. 61-594). Phase II consists of analytical and experimental studies with boiling metal systems. The investigation is being conducted at the University of Michigan in the Liquid Metals Laboratory of the Departments of Chemical and Metallurgical Engineering and in the Heat Transfer and Thermodynamics Laboratory of the Department of Mechanical Engineering. Professors Balzhiser, Hucke and Katz of the Chemical Engineering faculty and Professors Clark and Merte of Mechanical Engineering are participating in the program. Misters Colver, Smith, Barry, McSweeney and Harrington, all graduate students in the College of Engineering, have responsibilities for specific segments of the study.

Lt. Lloyd Hedgepeth and Mr. Kenneth Hopkins are serving as project engineers for ASD.

Comments are solicited by both the authors and ASD.

ABSTRACT

Modification and finalization of equipment design has progressed during the second quarter. Equipment specifications are near completion for each phase of the experimental program. Potassium will be boiled in a forced circulation loop where quality and flow rate effects on the heat transfer coefficient will be studied. Pressure drop and void fraction measurements will be made in a second test section to learn more about two phase flow behavior with metallic fluids.

A pool boiler will be used to study pressure effects and to increase the temperature and flux levels beyond the 1800°F and 10^6 Btu/hr-ft^2 anticipated in the loop. Film boiling of potassium will be studied using condensing sodium or lithium as a heat source. A columbium vessel will be used thus making it possible to increase the range of surface temperatures.

Initial agravic experiments will utilize mercury pool boiling from a stainless surface with normal accelerations up to 20 g's. Fabrication of equipment is expected to begin during the next quarter.

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Forced Circulation Studies - R. E. Barry

Energy conversion cycles employing liquid metals as intermediate heat transfer fluids in the process of generating electricity have been the subject of intense study in recent years. Such an application requires a much improved understanding of the heat transfer process occurring across a solid-liquid interface at high flux levels. High flux operation permits minimization of heat transfer surface for a given power and hence a reduction in size. For applications employing a turbine-like converter driven by metallic vapor it is important that liquid droplets be eliminated to reduce wear problems on the rotor surfaces. Pumping requirements are also minimized if recycle is kept to a minimum by achieving high qualities in a single pass, thus increasing the effective extractable power. Therefore, the study of heat transfer coefficients at high fluxes with varying qualities is of major importance in the loop studies.

Academically a better understanding of the phenomena that lead to variations in flow patterns and heat transfer characteristics are sought. Fragmentary studies with aqueous and other simple systems have produced some insight regarding the two phase heat transfer and burnout problem. Data with metallic fluids permits substantial extensions and variations of certain important physical parameters such as density ratio, interfacial energies and the more common transport properties. These studies should subject existing theories and correlations to more severe tests.

The present design will permit operation in the test section with heat fluxes approaching one million Btu/hr-ft^2 and inlet fluid conditions ranging from subcooled to 100% quality. Condensing sodium will be used as the primary heat transfer fluid thus eliminating dangers otherwise encountered when operating near the "dry wall" condition. Qualities will be determined by heat balance measurements around the preheaters and test section. Heat losses previously determined at various temperature levels will be subtracted from the input power to these heaters. Quality changes across the test section were intentionally kept low so that quality effects might be more precisely determined. Void fraction measurements will be made immediately downstream of the test section as part of the two phase flow study to be discussed later in this report. Thus holdup or slip can be determined as an aid in determining the flow regimes existing within the test section.

Preliminary calculations of the sodium condensing coefficient when heat is transferred to a nonboiling potassium stream will permit the determination of the sodium condensing coefficient. During the boiling studies the overall temperature difference will be obtained by placing thermocouples in the sodium vapor space and the flowing potassium just inside the test section exit. Heat input to the natural convection loop will be determined and the pre-determined losses subtracting thus permitting the calculation of the test section flux. Prior knowledge of the tube wall resistance and the condensing coefficient will permit determination of the boiling coefficient from the determination of the overall resistance.

Flow rate and pressure level are other parameters to be controlled independently. Both velocity and pressure effects on heat transfer in high quality streams will be explored.

Major concern has centered about the pressure drops likely to be encountered in two phase flow and the inevitable problem of instability. The former has led to the adoption of three short parallel preheaters each 4" in diameter after calculations using Martinelli-Lockhart correlations suggested prohibitively large pressure drops in long segments of small tubing. Flow merges from the preheaters into a single 4" pipe prior to being funnelled down to the 1/2" line leading to the test section. Proper design of the inlets and outlets in this region of the loop should lead to negligible pressure drops. However, stability problems could well arise.

A simulation study employing air-water is being conducted to evaluate more reliably the feasibility of such an approach (See Figure 1). It seems that stability problems are inherent in boiling studies and it is virtually impossible to predict in advance the operating characteristics of a given piece of equipment. Consequently, the design has been finalized pending the results of the simulation study and efforts will be made to obtain data over the stable range of operation. Instabilities will not be ignored; appropriate readings will be taken before, during and after such phenomena.

Loop Materials:

A discussion of the loop components follows. Haynes-25 alloy tubing in the preheater and test section with the remainder of the loop will be fabricated from 316 stainless steel tube.

Electromagnetic Pump - MSAR Style II, 0-2 gmp @ 100-80 psi at 1400°F. 316 stainless steel flow tube.

Electromagnetic Flowmeter, MSAR type FM 2, 3/8" stainless steel flow tube 0.1 to 2 gpm @ 1400°F.

Throttling Valve, 1/2" stainless steel.

Preheater, 4" Haynes 25 pipe. This will consist of three 36" sections mounted in parallel and each heated by 10 KW radiant clamshell heaters. The average heat flux over this section will be 9,000 Btu/hr-ft^2. The maximum preheater temperature will be 1800°F.

Test Section - A flux of one million Btu/hr-ft^2 will be transferred through a 2" length of 0.5" diameter Haynes-25 tubing by condensing sodium on the outside of the tube. This concept is based on a maximum allowable sodium temperature of 2000°F affording a 200°F overall temperature drop to the 1800°F test fluid. In order to achieve the desired flux, the temperature drops in the condensing sodium film, the metal wall and the boiling potassium film should be made as low as possible for a given flux. At a flux of one million, it is estimated that there would be a drop of 20°F in the boiling film, about 50°F in the 10 mil Haynes-25 wall and about 80-130°F in the condensing sodium film. The estimate for the condensing coefficient is in doubt since there is only one reference to sodium condensing coefficients (1) and the data were taken

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1. Bonilla, C. F. and Misra, B., NYO-3154 (1954).

at fluxes of 100,000 Btu/hr-ft^2. The test section will be enclosed in a 4" Haynes pipe containing the sodium vapor.

Sodium Heater - This section is a 36" length of 4" Haynes-25 pipe heated by a 10 KW radiant clamshell heater. The maximum sodium heater temperature will be 2000°F and it will supply vapor to the test section.

Pressure Measurement Section - This is discussed in detail elsewhere in this report. It will consist essentially of a two foot section of 5/8" Haynes-25 tubing over which pressure drop and fluid density measurements will be taken.

Condenser - 1 1/2" stainless steel fin tube - The condenser will be air-cooled. The pressure in the loop will be controlled by the heat removed in this section. A louvre on the suction side of the blower will control the air flow.

Hot Well - This is provided to maintain a positive suction head on the pump and insure that no vapor flows to the subcooler. Provision will be made to insert columbium surface to scavenge carbon introduced by Haynes-25 alloy.

Subcooler - 1 1/2" stainless steel fin tube - The subcooler is of substantially the same design as the condenser. Air flow control will be manual, however. This section will provide 1400°F fluid to the pump.

The auxiliary equipment consists of a stainless steel cold trap, a sodium dump tank, a test fluid dump tank and dump valves.

For potassium 100% quality is available at the entrance to the test section at flows up to 0.4 gpm and temperatures ranging from 1400°F to 1800°F. The maximum attainable quality drops to 36% @ 1 gpm and 18% @ 2 gpm.

Pool Boiling Studies - C. P. Colver

Material limitations will prevent loop fluxes and temperatures from extending over the entire range of interest. To supplement the data attainable in the forced circulation studies a pool boiler was conceived which would permit extension of heat fluxes beyond the value of one million anticipated in the loop and temperatures above the 1800°F level. Insufficient funds and time have necessitated several compromises in this study which reduce somewhat the expected performance levels.

Fabrication difficulties and excessive costs prohibited the use of a columbium vessel which is necessary to insure lengthy operations at 2200°F. Uncertainties in feasibility of a composite tube as a heating element have also required certain modifications with respect to the maximum achievable fluxes. The present design still seems capable of yielding nucleate boiling data at temperature levels up to and perhaps exceeding 2000°F. Maximum fluxes of 1 x 10^6 Btu/hr-ft^2 appear possible but recent burnout studies reported by Noyes (2) indicate that such a flux level will not produce burnout at

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2. Noyes, R. C., "An Experimental Study of Sodium Pool Boiling Heat Transfer," NAA-SR-6769, Mar. 30, 1962.

pressures above atmospheric. Consequently, the helium circulation for purposes of preventing tube damage under burnout conditions appears unnecessary and has been eliminated.

The study is intended to provide further insight into nucleate boiling characteristics of potassium as temperatures and fluxes are increased. Pressure effects on coefficients can also be determined over a wide range of temperatures.

Efforts during the last quarter were directed toward a feasible design for accomplishing the above goals. Substantial modifications in the design of the pool boiler were made during the quarter. The primary changes involve the use of an all Haynes-25 vessel with H_2O cooling coils brazed to the outside of the condensing portion, the replacement of the columbium boiling surface with a Haynes-25 surface, the use of a replaceable heating element not bonded to the Haynes boiling tube, and the measurement of surface temperatures by thermocouples attached directly to the surface. A cross sectional drawing of the updated apparatus is shown in Figure 2. Figures 3, 4, and 5 give additional details of some vessel components.

Boiling will take place from a 0.35-in. O.D., 2 inches long Haynes-25 tube welded into the cylindrical Haynes-25 vessel as shown. This tube will be machined from a standard 16 B.W.G., 3/8-in. diameter by 2 3/4 inches long section. Particular details of the composite tube arrangement are shown in Figure 3. Fabrication of the tube is as follows: The Haynes-25 boiling tube is machined to size and welded into the vessel. The tube is then reamed to exactly 0.27-in I.D. A 0.25-in O.D. (0.01-in. wall thickness) by approximately 6 inches long tantalum tube is plasma-sprayed with a 10 mil coating of high purity alumina. The oxide surface will be precision ground to minimize contact thermal resistance between oxide and the inside of the Haynes-25 tube. A tantalum rod, 0.23-in. diameter by approximately 2 inches long, is then inserted in each end of the tantalum tube as shown. These rods shunt the current through the portion of the tantalum tube coinciding with the vessel wall and busbar. With this arrangement undesired heat generation is maintained to less than 6.5%. In addition a groove machined in one of the rods (see Figure 2) permits a thermocouple to be inserted in the adiabatic inner space of the tantalum tube.

Power to the tantalum resistance heater will be transmitted through nickel busbars clamped to the tantalum tube as shown. Figure 4 gives details of each busbar. Silver solder or other similar filler metal will be used to assure good electrical contact between the busbar and tube. Power to the vessel will be measured and the heat flux will be calculated by subtracting all predetermined heat losses from the total power input. Heavy copper leads bolted to each busbar will carry the power from an Udylite Company rectifier to the vessel. These leads pass through ceramic electrode glands welded in the top plate of the outer steel enclosure. The rectifier will supply 12 KW with rated output of 250-2000 amps at 18-6 volts DC respectively.

The cylindrical Haynes-25 boiling vessel is to be machined from two pieces of bar stock, one 3 1/2-in diameter by 14 inches long and the other 2 3/4-in. diameter by 5 inches long. A 2-in. diameter hole will be bored in each piece leaving the ends closed. Other necessary holes (shown in Figure 1) are subsequently drilled. The water cooling coils are 9/16-in. diameter stainless steel tubing. They will be silver brazed to the outside of the Haynes-25 condenser section and arranged in such a way that five parallel cooling systems (3, 3, 3, 5, and 5 coils each counting from the bottom) will be used. This arrangement permits manifolding the cooling water through all, none, or any combination of the parallel cooling systems.

The filling line is a Haynes-25 16 B.W.G. 3/8-in. diameter tube wrapped with a resistance wire heater. This heater will hold the filling tube above the melting point of the test metal while charging or emptying the vessel.

The outer steel vessel is a standard sch. 40 14-in. diameter pipe with a plate welded on the bottom end and a standard flange connection at the top. It will be constructed as shown. The inner space between the two vessels will be filled with insulation and maintained in a helium atmosphere. The helium will be regulated to the same pressure as the boiling system. In addition nichrome or molybdenum resistance wire guard heaters are to be used to minimize undesirable heat losses from the boiling vessel. Power to these heaters will be regulated by variacs connected to a 110 volt AC circuit.

All thermocouples measuring elevated temperatures will be chromel-alumel or platinum-platinum, 10% Rh. Several thermocouple locations are shown in Figure 2. Thermocouples shown inside the boiling vessel will be in metal sheaths of Haynes-25 and will leave the vessel in the 1/2-in. tube at the top of the condenser. It is planned to measure the boiling surface temperature by spot welding a thermocouple directly to the surface. This method of obtaining the surface temperature was chosen over equating it from a thermocouple measurement made in the tube wall for two reasons. First, to determine the surface temperature from a temperature somewhere within the tube wall requires extrapolating this temperature to the surface. Not only must the exact location of the thermocouple be known, but also it must be installed in such a way that it indicates the true wall temperature at that point. This becomes difficult when very steep gradients are produced at high flux levels. Small errors in either of these requirements may give large errors in the true surface temperature. Secondly, temperatures at possible thermocouple locations in the composite wall may be as much as 500°F above the surface temperature even at moderate heat fluxes.

Film Boiling - A. Padilla

The design of experimental apparatus to study liquid metals in the stable film boiling regime has been completed and the equipment is in the process of being procured. The system utilizes a condensing medium as the heat source and is designed to bypass the critical heat flux region. Liquid metals film boiling in the range 1200°F to 1800°F can be studied.

Figure 6 is a schematic diagram of the system. Heat is supplied to boiling potassium by means of condensing sodium. Potassium is condensed by radiation from condensing surface to a water-cooled confining surface.

Figure 7 gives a detail view of the tube assembly. Sodium is contained in the 8-in. section of 1-in. columbium tubing below the boiling plate and is heated by a 3-in. induction coil. A 6-in. length of smaller stainless tubing extends from the bottom to a stainless valve required for charging and discharging purposes. Condensing sodium temperatures will be measured with a thermocouple.

The .090 inch boiling plate will be machined from columbium and welded into place. The flux across the plate will be measured by thermocouples appropriately in the plate. The temperatures of both surfaces of the plate will be obtained by extrapolation.

A 3 foot condensing section of 1-in. columbium tubing should permit dissipation of the necessary energy by radiation to the confining vessel. A scrubber located at the top of the condenser will insure the removal of potassium vapor from the inert gas stream used for pressure control. It consists of a 3-in. packed section of stainless steel wool which is cooled by water coils brazed to the outside of the tube. The temperature of the boiling potassium will be measured by means of a thermocouple.

The entire operating part of the system is contained in a casing which acts both as a water wall for the radiation condenser and as a safety container. Water flows in the annular space between the two standard steel pipes. The top and bottom are closed off by standard pipe flanges. Connections to the induction coil and thermocouples are made through the bottom flange. The scrubber is welded to the top flange cover and will be used for lifting the tube assembly out of the casing.

Operating Procedure

Initially, the tube assembly supported by the top flange cover will be out of the casing. The section below the boiling plate will be evacuated and the charge of sodium added through the bottom valve. The tube assembly will then be inserted into the casing and the top flange secured.

The casing and condenser will be evacuated and the casing filled with an inert gas. Power will then be supplied gradually to the coils until the temperature of the boiling plate is high enough to insure that potassium which comes into contact with the plate surface instantly passed into film boiling. Additional potassium will then be added slowly under a blanket of inert gas. Power input to the sodium will be increased to anticipate the increased energy extraction when potassium is introduced into the upper portion of the system. After steady-state conditions are reached the data will be taken. The power supply will then be adjusted to a new level to give a different boiling plate surface temperature.

Calculations:

The heat flux can be evaluated from the gradient determined by thermocouple readings at known positions in the plate.

The temperatures at both surfaces of the boiling plate will be obtained by extrapolation. A film boiling coefficient is then determined from the relationship:

$$h_b = \frac{q/A}{T_{VS} - T_b}$$

where h_b = boiling coefficient

T_{VS} = temperature of the upper surface of the plate

T_b = temperature of the boiling liquid

Similarly, a condensing coefficient for the sodium can be evaluated from the equation:

$$h_c = \frac{T_{LS} - T_c}{q/A}$$

where h_c = condensing coefficient

T_{LS} = temperature of the lower surface of the plate

T_c = temperature of the condensing fluid

The heat transfer to boiling fluid will be studied at various levels of constant pressure. At each level, the temperature of the boiling plate will be varied and the effect on the flux and heat transfer coefficient studied.

Liquid Metal Boiling in Agravic Fields - J. Clark

The experimental apparatus described in the first quarterly progress report (January 1962) has been revised to permit its operation at pressures in excess of atmospheric. A sketch showing a preliminary design of the high pressure apparatus is shown in Figure 8.

It is desired to operate this revised system at pressures as high as 800 psia. However, certain compromises must be made as the centrifuge from which the capsule will be suspended has certain weight and space limitations. They will influence the ultimate strength of the pressure enclosure, thus controlling the level of pressure at which it will be safe to operate the system. By an optimization of the internal design of the heater and guard heater arrangement, it is expected that an enclosure diameter somewhat less than that shown can be permitted. Initial estimates indicate that it probably will be possible to operate in excess of 400 psia.

Pressure equalization between the liquid mercury space and the inside of the enclosure is to be made. This will be done by a cooled vent line fitted with a mercury trap to collect any mercury carry-over. While it is not shown on the sketch, both the cooled vent line and the trap are planned for external mounting on the pressure enclosure. Such an arrangement will take advantage of efficient air cooling during rotation as well as permit easy inspection of the mercury trap for carry-over. The inside of the pressure enclosure will then be connected to the vapor space over the mercury trap. System pressure level will be established using helium gas from a stationary source communicating with the rotating test apparatus by means of a rotating seal. The pressure level will be controlled by a regulator in the stationary part of the helium circuit.

Consideration has been given to the problem of solid-liquid interface pressure during acceleration for operation at various pressure levels. In order to vary system acceleration only while the interface (solid-liquid and gas-liquid) pressure is held fixed, it has been decided to operate initially at various liquid depths. With such an arrangement the temperature at the gas-liquid interface also would be fixed. This appears to provide a better control of the process than could be obtained were the liquid depth to be fixed and the system pressure to be altered as the acceleration is changed.

The instrumentation circuits on the existing centrifuge have all been inspected, cleaned and tested for operation. To date it has been found necessary to replace some of the thermocouple wiring and remove contamination from some of the mercury commutation channels. At this writing all thermocouple circuits are operating successfully with no extraneous EMF pick-up under rotation.

During the next quarter the test apparatus design will be finalized. The highest, safe level of pressure for operation will be determined and cost of the system will be estimated. Construction also will be started.

Two Phase Flow Studies - L. Smith

Pressure drop and void fraction data will be obtained during the two phase flow of potassium in a specially instrumented section of the test loop. Preliminary proposals for the research were outlined in the first quarterly progress report. Since that time certain aspects of the experimental program have been amended while portions of the program have been more nearly finalized.

The experimental data will be taken from a vertical test section following the high-flux test section. The pressure drops will be measured over a one foot length of tube by diaphragm type pressure gauges. A one foot long calming section will precede the data section. The tube will have an inside diameter of about a half inch.

Void fractions will be measured by the radiation attenuation technique. It was formerly proposed that X-rays be used. Subsequently, however, the inaccessible location of the flow test section in the loop, together with spatial limitations, has prohibited the use of X-rays. A gamma-ray source, which will be of more convenient size, will be employed. A subprogram to evaluate possible gamma sources has revealed that Am^{241} and Tm^{170} are the most suitable isotopes. The former is preferred since its 475-year half-life is more favorable than the 127-day half-life of Tm^{170}. However, the $1500 per gram cost of Am^{241} will probably necessitate using the less costly Tm^{170}. Negotiations are in progress to see if a curie of Am^{241} can be rented. An analysis of Am^{241} requirements is presented in the following section.

It was formerly proposed that a direct-current amplifying system be used in attenuation measurements. It seems now, however, that a Geiger tube may have advantages over a scintillation detector system. The Geiger tube will be simpler to operate in a high temperature environment and would be less costly. The feasibility of using a Geiger tube is being further examined and the final decision is pending.

Most of the recent work in the two phase flow studies has been to begin examination of two phase flow from an analytical viewpoint. The work is still in its early development, but some of the activities and application will be discussed. The ultimate goal, of course, is to describe two phase metallic flow in a manner that is reliable for design and operating purposes.

The independent operating variables of the test loop are preheater heat flux, heat transfer test section heat flux, pressure level and liquid flow rate out of the pump. It was decided to develop a digital computer program whereby the pressure at any point in the loop can be calculated during steady-state operation with any combination of the above variables in the operating range. The computer program, which will be executed on the IBM 709, is still in development. A program for calculating pressure drops in nonboiling (and noncondensing) sections of the loop has been written and is being regularly used to estimate pressure losses in the flow test section.* Potassium is the working fluid. The program utilizes the Lockhart-Martinelli correlation (3), and all fluid properties have been given proper temperature dependence. Figure 9 presents typical results obtained by this program. Horizontal and vertical pressure drops were calculated for flow at 1400°F.

In the first approach to the computer treatment of pressure drops over boiling sections, the Martinelli-Nelson method (4) was employed.

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* Acknowledgement is given to James A. Craig of the Metallurgical Thermodynamics group as writer of this computer program.

3. Lockhart, R. W. and Martinelli, R. C., "Proposed Correlation of Data for Isothermal Two-Phase, Two-Component Flow in Pipes," Chem. Eng. Prog., 45, 39 (1949).

4. Martinelli, R. C. and Nelson, D. B., "Prediction of Pressure Drop during Forced-Circulation Boiling of Water," Trans. A.S.M.E., 70, 695 (1948).

Preliminary calculations soon made it apparent that this method is not as suitable for potassium as it has proven for steam-water. The Harvey-Foust analysis (5) is currently being used as an alternative approach to this problem.

The Harvey-Foust model is a mixed model for pipe flow, the basic assumptions of which are:

(a) No radial variations of velocity, pressure, temperature.

(b) No slip--i.e., liquid and vapor superficial velocities are assumed equal.

(c) Vapor and liquid are in equilibrium.

(d) Pressure drops are given by Martinelli's original method.

(e) The vapor equation of state is known.

(f) Heat transfer is uniform.

(g) Mixture density is the weighted average of the phase densities.

It is evident that this model has serious limitations and at best will only provide reasonable estimates of pressure drop. Three of the above assumptions are particularly subject to criticism. Item (b), the assumption of no slip, could lead to considerable error in mixture density. The homogeneous flow assumption, item (a), is contradictory with item (d), the assumption of Martinelli-predicted pressure drops.

Under the above assumptions, the procedure in the Harvey-Foust analysis is to derive one-dimensional momentum, energy, and continuity equations for the flow. Appropriate terms are eliminated between the equations, and a nonlinear total differential equation in pressure and length is obtained. The original development was done only for the water-steam system. The equations have been rederived for general use in any flow system. The resulting differential equation, written for vertical flow of boiling potassium, is:

$$\begin{aligned}
&-\frac{u_0^2\rho_L}{P\rho(32.17)778}(0.252T\rho_L - P)\left[-(C_{p_L} + x\,\Delta C_p)\frac{T^2}{18{,}100P} + \frac{144}{778\rho}\right]dP \\
&+\lambda\left[\frac{0.252\,u_0^2\rho_L^2\,xT}{\rho P^2(32.17)778}\left(\frac{-T}{18{,}100}+1\right) - \frac{144}{778\rho}\right]dP = \\
&\frac{u_0^2\rho_L}{P\rho(32.17)778}(0.252T\rho_L - P)\left[\frac{Q/L}{u_0\rho_L A} + \frac{2\phi^2 f(1-x)^2u_0^2\rho_L}{32.17(778)D\rho}\right]dz \\
&\qquad + \lambda\left[\frac{2\phi^2 f(1-x)^2u_0^2\hat{\rho}_L}{32.17(778)D\rho} + \frac{1}{778}\right]dz
\end{aligned} \tag{1}$$

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5. Harvey, B. F. and Foust, A. S., "Two-Phase One-Dimensional Flow Equations and Their Application to Flow in Evaporator Tubes," Chem. Eng. Prog. Symposium Series, No. 5, 45, 91 (1953).

where $C_p = C_{pv} - C_{pl}$

C_{pl}, C_{pv} = liquid and vapor specific heats, Btu/16 °F

u_o = inlet liquid velocity, ft/sec

ρ_l = liquid density, lb/ft^3

ρ = mixture density, lb/ft^3

T = absolute temperature, °R

λ = heat of vaporization, Btu/lb

Q/L = linear heat flux, Btu/sec ft

A = cross sectional area, A^2

D = pipe diameter, ft

Z = tube length, ft

ϕ = Martinelli two-phase flow parameter

f = friction factor evaluated from all-liquid flow

X = vapor quality, lb vapor/lb mixture

Although equation (1) is nonlinear and complicated algebraically, it is amenable to numerical solution. A similar equation previously arose out of a Harvey-Foust analysis. In numerically treating the equation, it was found that certain terms were negligible and the equation could be linearized to a very good approximation. It is believed that equation (1) can be linearized in similar fashion. The equation is presently being treated on the computer to ascertain whether such linearization can be accomplished. If so, the final solution will not be difficult and can be made to cover the desired operating range for the loop.

<u>Supplementary Programs</u> - W. Myers and C. Revak

A) Minimum Am^{241} Requirements for Void Fraction Determination

1. In making these calculations the following data have been used:

   a. 1 curie = 3.7×10^{10} disentigrations per second.

   b. 1g Am^{241} = 3.14 curies.

   c. The half thickness of Haynes tubing for 60 KEV gamma radiation is approximately 0.27 g/sq cm.

   d. For each alpha disentigration of Am^{241} there are 0.40 60 KEV gamma radiations produced.

2. The overall counting efficiency of any system (ratio of count rate to source strength) can be expressed as the product of the several factors which influence count rate. The overall efficiency, E, is:

$$E = G\epsilon_{\gamma} f_m f_{\tau} f_W f_B f_S$$

where G is the geometric efficiency of the system.

ϵ_{γ} is the intrinsic efficiency of the system for the particular radiation, i.e., 60 KEV gamma radiation.

f_m is the multiple count factor.

f_{τ} is the dead time correction.

f_W is the correction due to absorption between source and detector.

f_B is the backscatter factor.

f_S is the sample self-absorption factor.

Some of these factors can be computed or estimated, and others can be neglected.

3. If the radioactive material is considered to be a point source at a distance, L, from the detector, with the detector considered to have a circular window of diameter 2d, the geometric efficiency can be calculated as:

$$G = 1/2 \quad 1 - \frac{L}{(L^2 + d^2)^{\frac{1}{2}}}$$

Values of G have been calculated for L ranging from 10 cm to 50 cm, considering d to be 2 cm. This would be a reasonable value of d for a collimated beam since NaI crystals are commonly 3 in. in diameter. These values of G are:

L (cm)	G
10	0.009775
20	0.002363
30	0.00111
40	0.000625
50	0.000395

The distance from the center of the Haynes tube to the surface of the detector will be 0.685L for this particular geometry. Since the NaI crystal and photomultiplier must be maintained at a constant temperature, 25°C or less, there will be a problem of refrigeration as the source to detector distance is decreased. However, we stand to gain a great deal by keeping this distance at the absolute minimum without being forced to interpose thermal insulation between them.

4. The intrinsic counting efficiency for 60 KEV gamma radiation depends

on both the size of the crystal detector and the distance between source and detector, but for any system that we might use it would be very close to unity. If a G-M tube were to be used it would be on the order of 0.01.

5. Values for the backscatter and self-absorption factors can not be accurately predicted. However, their product will be close to unity.

6. The dead time correction will depend both on the type of system and the count rate. For a G-M counter at a rate of 10,000 cpm it might be approximately 1.05. For a NaI detector it can be considered to be unity except at very high counting rates. The multiple count factor is also dependent on the particular counting system, but it is also close to unity.

7. The absorption between source and detector will include the absorption due to: the source container, air, the Haynes tube, any thermal insulation that is used, potassium, and the aluminum casing containing the NaI crystal. Union Carbide Nuclear Company has indicated that the encapsulation required will attenuate approximately 50% of the 60 KEV radiation. The attenuation of the Haynes tube is estimated to be 0.000075. Liquid potassium at 1402°C will transmit approximately 70% of the incident radiation. The attenuation due to air can be neglected. If thermal insulation can be limited to Al foil radiation shields and dead air (or something similar of minimum mass) the absorption due to insulating material can also be neglected. If large amounts of insulation are required it will be necessary to provide a "window" for the gamma radiation beam.

8. For a source strength of one curie, located 50 cm from a NaI detector, we can expect the following count rates: (T = 1402°C)

   a. 100% liquid K; 9150 cpm

   b. 100% vapor; 12,300 cpm

We can expect background radiation of about 200 cpm.

9. This is a count rate that we could live with, but it offers no great safety factor. Since Am^{241} sells for $1500 per gram it would be most expensive to purchase a comfortable safety factor, but there are two places where we might gain a great deal. We should attempt to move the source as close to the detector as is possible without exceeding our ability to cool the crystal. If it were possible to operate with the source 25 cm from the detector, the count rates predicted above would be increased by a factor of four. A second point would be to, subject to AEC and U of M regulations, request that the encapsulation include the thinnest possible window so that we have the minimum possible attenuation in the source container. (This is not too promising, but if we are going to pay $250 to have the source put up we should try to get our money's worth.)

10. I believe that we will be able to work with a one curie source. According to my information from Union Carbide Nuclear Company this would cost us $480 for the Am, plus $250 for encapsulation and $20 handling fee, a total of $750. However, since we could get 1.5 curies

for a total cost of just less than \$1000, I would favor spending the extra \$250 if costs were not a great problem.

11. The possible accuracy that we can expect will, of course, depend eventually on the slope of the void fraction-density curve in the region that we are investigating. However, it is possible to predict, from the statistics of counting processes, some idea as to the expected accuracy of count rate measurements. Since the count rate through the potassium will be inversely proportional to the density, this will give us some idea of the possible accuracy of our density measurements. If the count rates predicted in paragraph 8 are correct, we will collect approximately 10,000 counts over a one minute interval of steady-state flow. The standard deviation for such a count rate is 100 cpm. Since we will be considering the range of count rates between all liquid and all vapor, about 3000 cpm, our standard deviation would be approximately 3%. If we counted over a ten minute interval, it would be possible to reduce the standard deviation of the count rate to approximately 1%.

B) Plasma-Sprayed Test Sections

A molybdenum tube, plasma-sprayed with 10 mils of alumina and three mils of tantalum, was received from the vendor after a second spraying attempt. A direct short was found between the two metallic layers, rendering it useless for resistance heating of the outer layer. Metallographic examination of the tube cross section revealed threads of tantalum extending through the porous alumina to the molybdenum tube.

Others have been more successful with this method. Greater care must be taken in producing a dense refractory layer prior to application of the outer metallic layer. Better control of purity and particle size would likely improve results.

Since we no longer plan to use a resistance-heated test section in the loop, recent efforts have been directed to pool boiling studies. In this application a 5-10 mil alumina layer should be adequate as it will be sprayed with a metallic layer. It will, however, serve to insulate electrically the inner current carrying tube and the Haynes-25 tube in which the heating element will be inserted.

C) End Effects in Test Section

Present design calls for a test section two inches long by 1/2 inch I.D. Heat fluxes of 10^6 Btu/hr-ft^2 will be supplied to the potassium by sodium vapor condensing on the outside of the tube. For such a short test section, the question arises as to whether heat losses at the ends will affect the measurement of these high heat fluxes.

To check on this "end effect," the heat losses and the temperature profile at the top end were determined by a trial-and-error graphical method. As a basis for calculation, the wall of the 10 mil thick test section tubing was considered to be joined to a 1/4 in. plate at the top. Heat flow is from the condensing sodium through the test section and quarter-inch plate to the flowing potassium. Losses through the insulation can be calculated directly by other means, so they are not included here.

The heat flux map and isotherms are shown in Figure 10 and values of Q/A obtained from this map are plotted in Figure 11 which shows the variation of Q/A in the area near the top plate. Integrating the area under the curve gives a loss of 0.14 KW at Q/A = 10^6 Btu/hr-ft^2 in the test section. This has the effect of making the test section 46.5 mils longer than its actual length. Thus, end effects are not large and the calculated correction factor can easily be applied to the measured fluxes.

D) Instrumentation

The University of Michigan will supply all instrumentation for the loop except for the flowmeter and thermocouples. The actual construction and wiring will be done either on campus or by a qualified panel manufacturer. Various aspects of the loop instrumentation problem are considered below.

1. Pressure Measurement - Several different methods of measuring qauge pressure and differential pressure are being evaluated. Gauge pressures can be measured to our requirements (0-100 psia, ±1%) without great difficulty, but no entirely satisfactory method is available for the measurement of differential pressure in the range of 0-200 inches of water. The two most promising routes both employ Taylor pressure sensors. These sensors utilize a flexible diaphragm to transmit the fluid pressure to a NaK filled capillary, which serves as a buffer between the high temperature fluid and the actual pressure measuring device (such as a Bourdon tube). Two sensor pressures can be applied to a differential pressure diaphragm or alternatively, two absolute pressures can be measured and then subtracted electrically.

In the first method the differential pressure diaphragm is transmitted to a force-balance system, and the output can be read as a standard 3-15 psig air signal. The basic system has been in use for several years in the chemical industry, using buffering fluids other than NaK and operating at lower temperatures.

The second method* relies on the fact that linear variable differential transformers (LVDT's) can be mechanically connected to ordinary Bourdon tube movements and the LVDT output varies linearly with the pressure on the Bourdon tube. The D.C. outputs of two LVDT's can be "bucked" to give a differential pressure reading. This method of subtracting two large numbers from each other is not ordinarily attractive; however, the LVDT's have very low hysteresis, and high resolution and sensitivity. We might thus be able to expect good accuracy and reproducibility in a differential pressure measurement.

2. Temperature Measurement - About 30 thermocouples will be used to measure temperatures around the loop. Pt vs Pt-Rh thermocouples will be used at those points requiring high accuracy and good stability, while the remainder will be chromel-alumel.

3. Flow Measurement - An electromagnetic flowmeter supplied by MSA Research will be used to measure flow. This is their style II model, which delivers an output of 6-7 milivolts at 2 gpm. We have received some indication that the calibratinn of this meter is subject to change

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*Most of the ideas for this method were supplied by personnel at the General Electric Corporation in Evendale, Ohio.

with time, the principal reason being variation of the permanent magnet strength. Since the calibration is directly proportional to magnet strength, it is important that this value should not change. For this reason, we will conduct our own measurements of field strength upon receipt of the meter, and later after it has been operating for some time. We also plan to make in situ calibrations, using a heat balance around the preheater along with known heat capacities, to calculate flow rates. This method is not highly accurate, but it will serve as a check and will also indicate any changes in calibration that may occur.

4. **Control Panel** - A drawing of the proposed control panel is shown in Figure 12. It will include instruments for the measurement and/or control of temperature, pressure, differential pressure, flow and power.

There will be five alarms on the panel, which will shut down all power to the loop and air blowers and dump the loop contents into dump tanks. The alarms will be actuated by any of the following conditions:

a) High wall temperature of the Haynes-25 in the preheat section

b) High wall temperature of the sodium boiler

c) High potassium temperature into the pump

d) High air temperature from air-cooled condenser

e) Low potassium flow (with an override provision for startup)

In addition to the above, a scram button will be provided for emergency use.

Most of the temperatures will be measured on a 48-point flight recorder, while a Leeds and Northrup K3 potentiometer will be used for precise measurement of certain critical temperatures. In addition, a continuous recording will be made of one chosen temperature, so that temperature trends during startup, operation and shutdown may be monitored carefully.

Both pressure and differential pressure are to be recorded continuously on a two-pen recorder. Pressure range will be 0-100 psia and differential pressure range will be about 0-200 inches of water.

The only automatic control on the loop will be provided for pressure control. A proportional plus reset pneumatic controller will be used to adjust the damper position on the air-cooled condenser. If instability of two phase flow causes too much noise in the pressure reading, we will resort to control of pressure via the equilibrium temperature in the vapor-liquid hot well.

Manual air-loading stations will be used to supply air to a throttling control valve and also to the servo motor on the subcooler air damper. Switches will be provided for electrically operated solenoids on various filling and drain lines.

Power to the preheater will be supplied by a 35 KVA, three phase variac and to the test section boiler by an 18 KVA, single phase variac. The power to the preheater and to the test section will be measured separately as well as voltage and current on each phase.

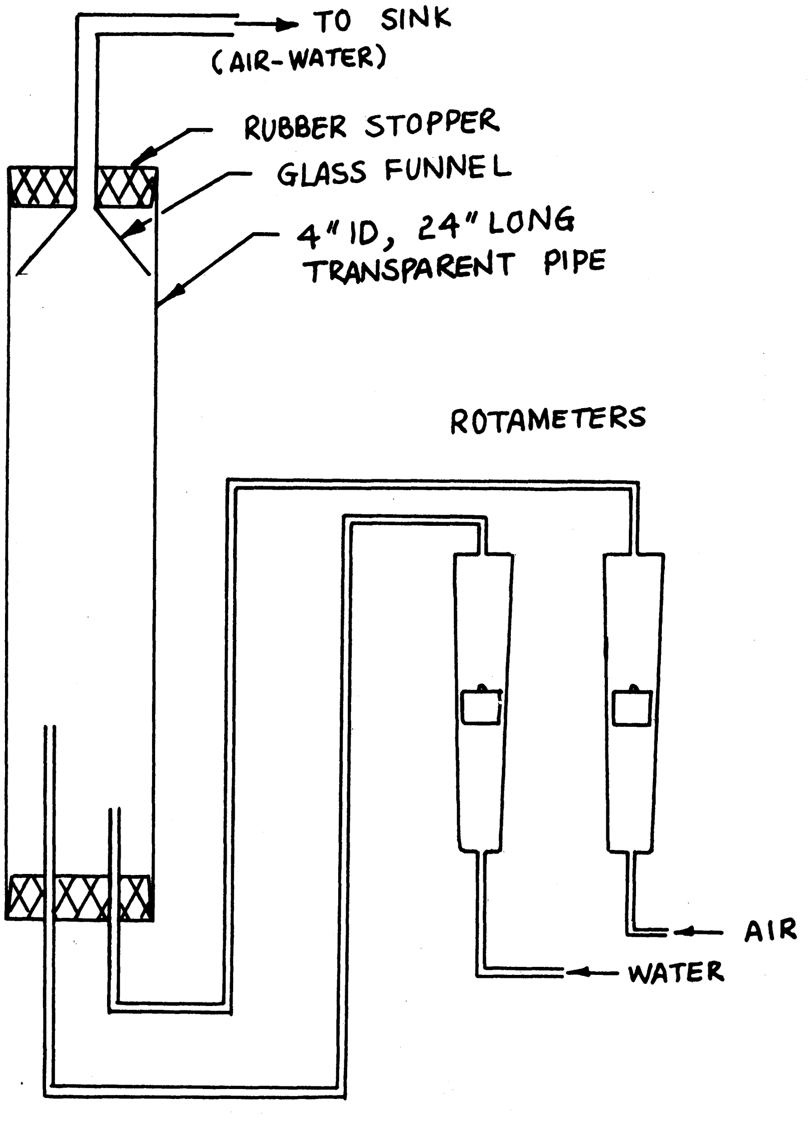


FIG. 1 TWO-PHASE FLOW STABILITY MODEL

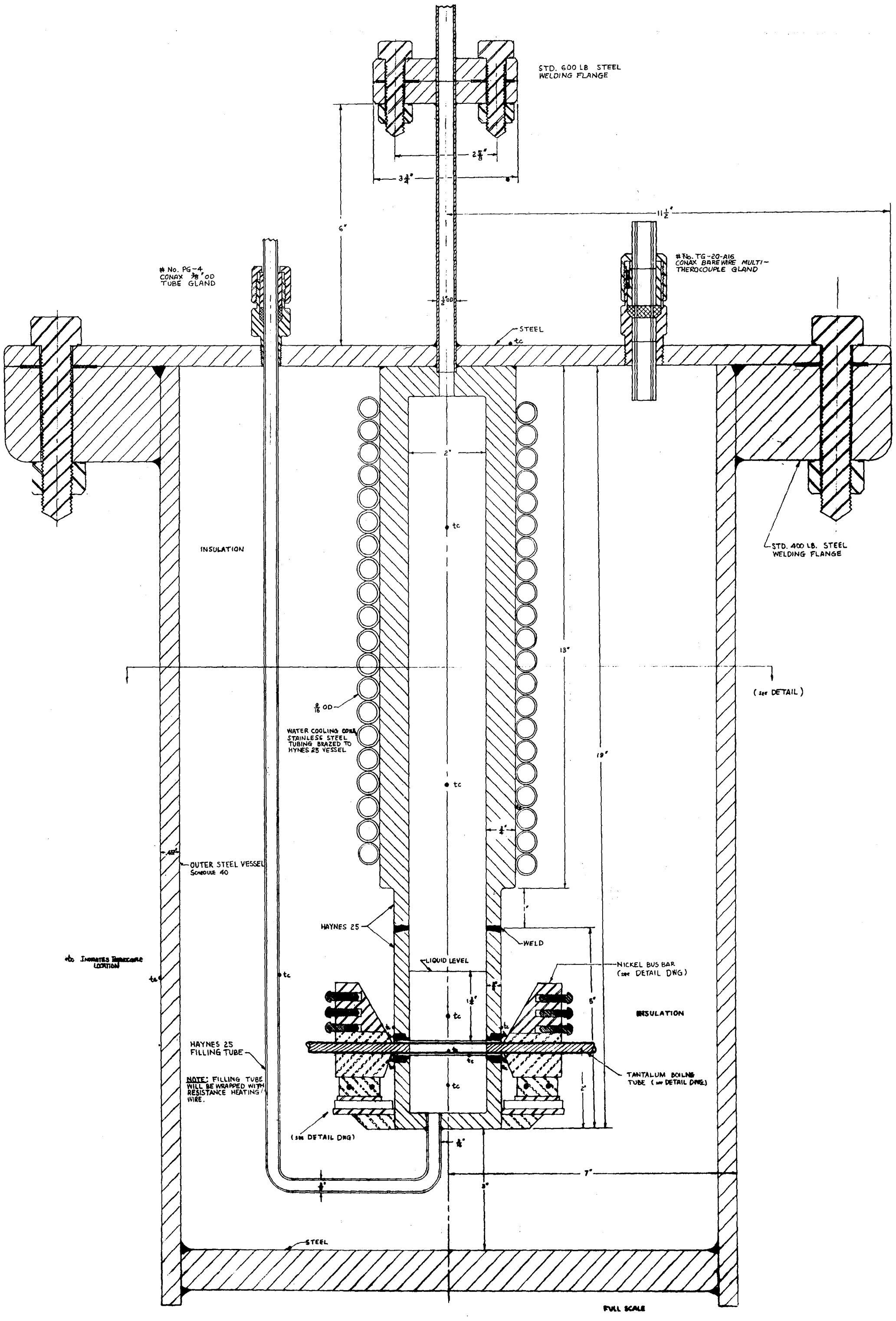
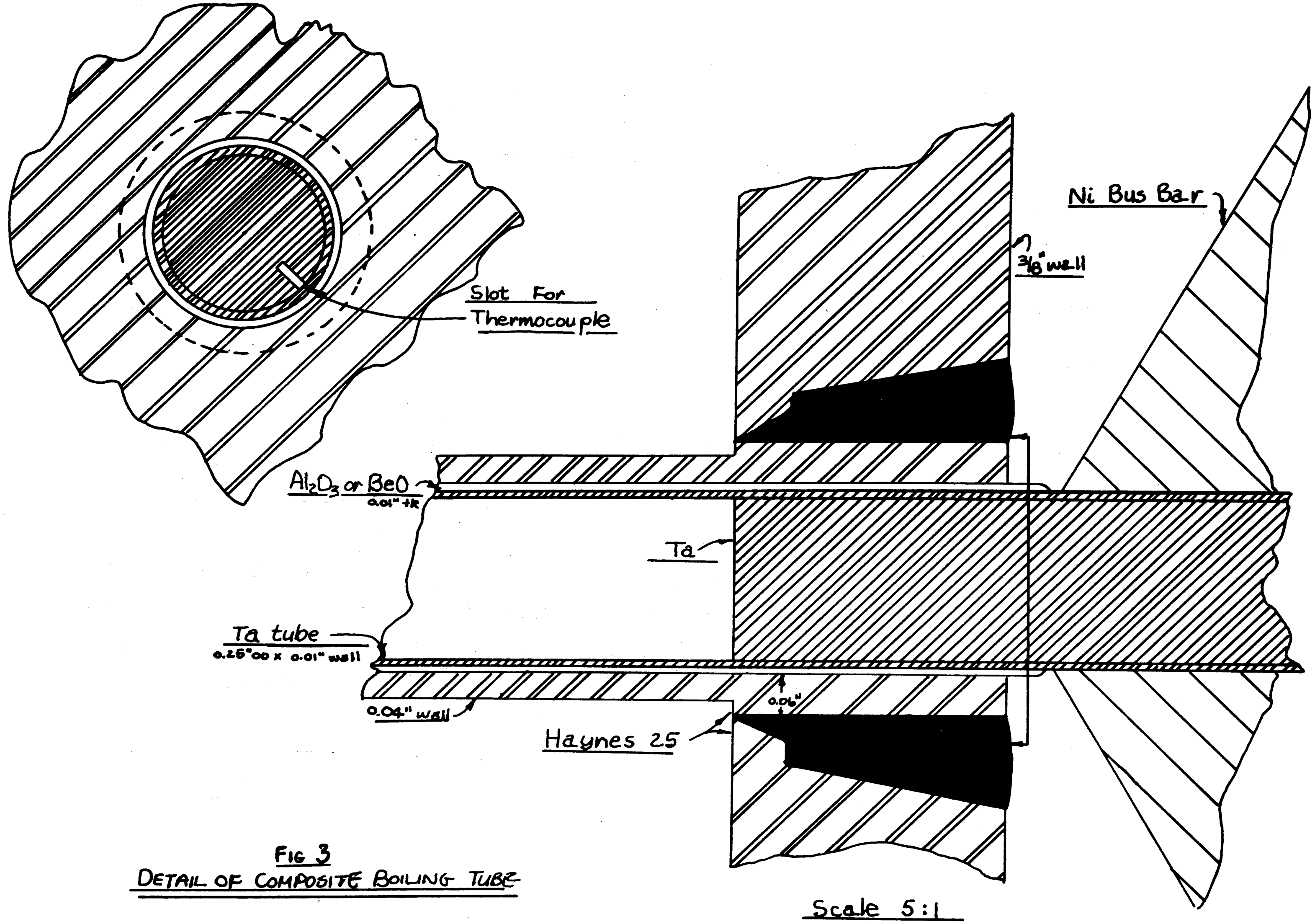


Fig. 2 Cross Section of Boiling Vessel and Outer Enclosure



Scale 5:1

FIG 3
DETAIL OF COMPOSITE BOILING TUBE

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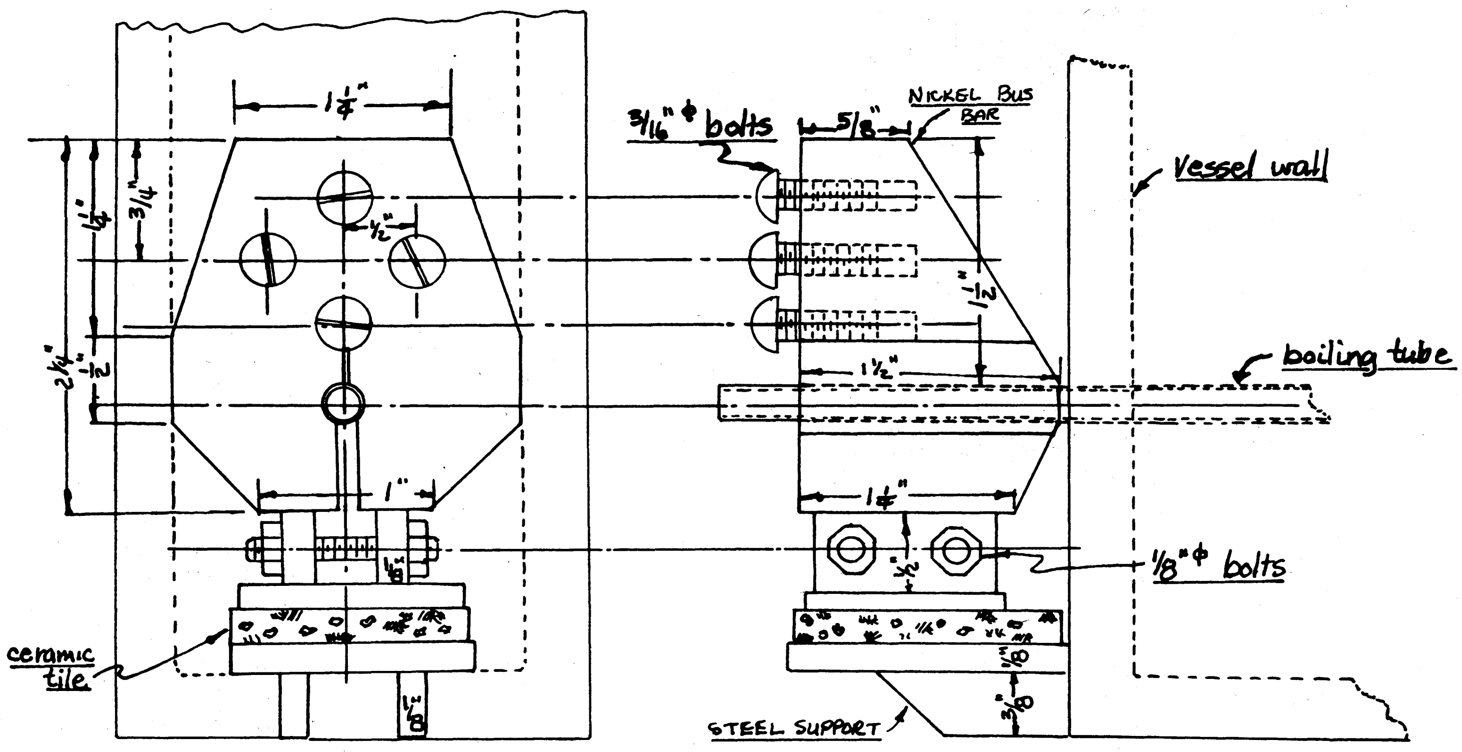

FIG 4
: BUS BAR:

Full Scale

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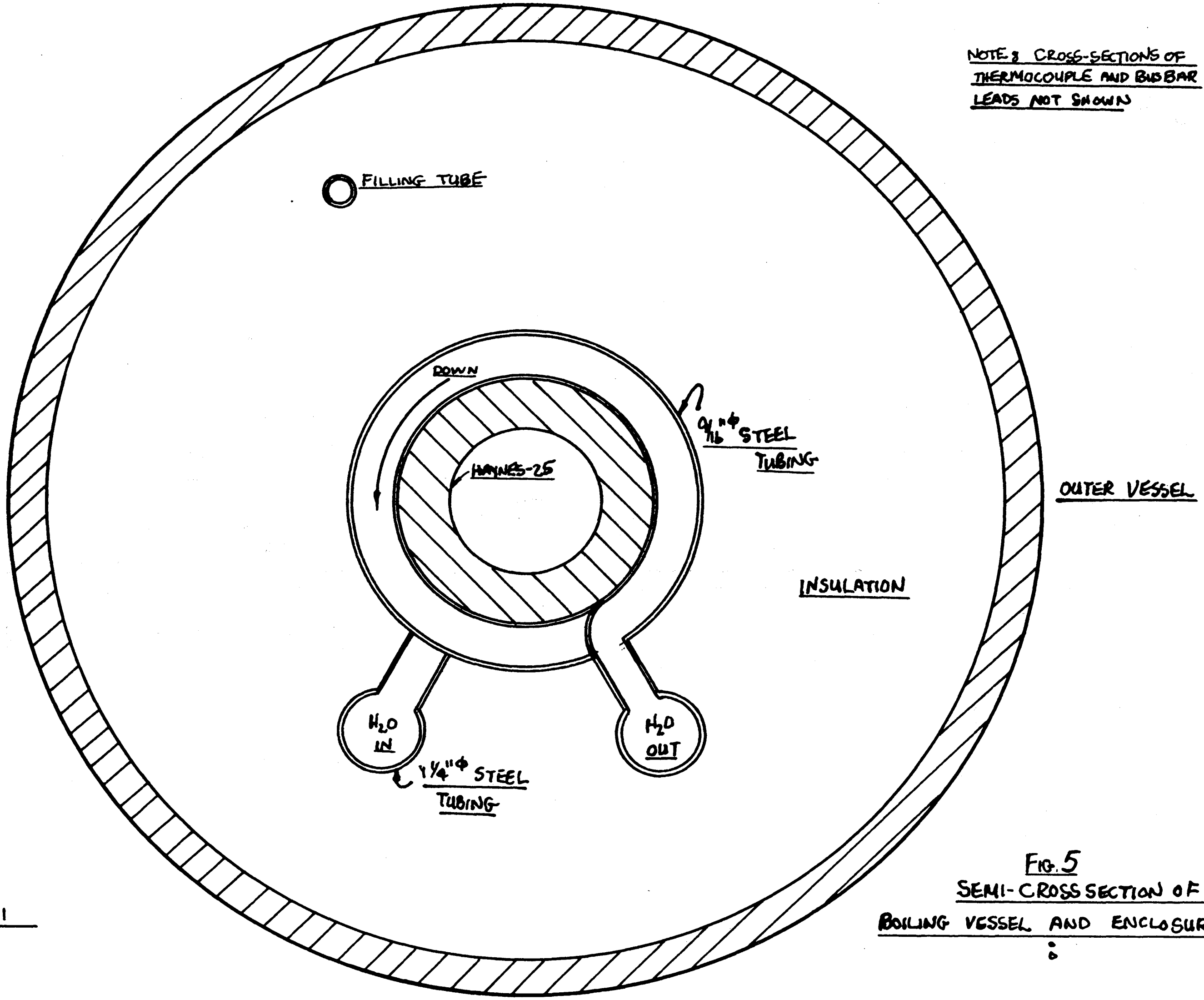
NOTE: CROSS-SECTIONS OF THERMOCOUPLE AND BUSBAR LEADS NOT SHOWN



SCALE 2:1

FIG. 5
SEMI-CROSS SECTION OF
BOILING VESSEL AND ENCLOSURE

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FIGURE 6
FILM BOILING APPARATUS

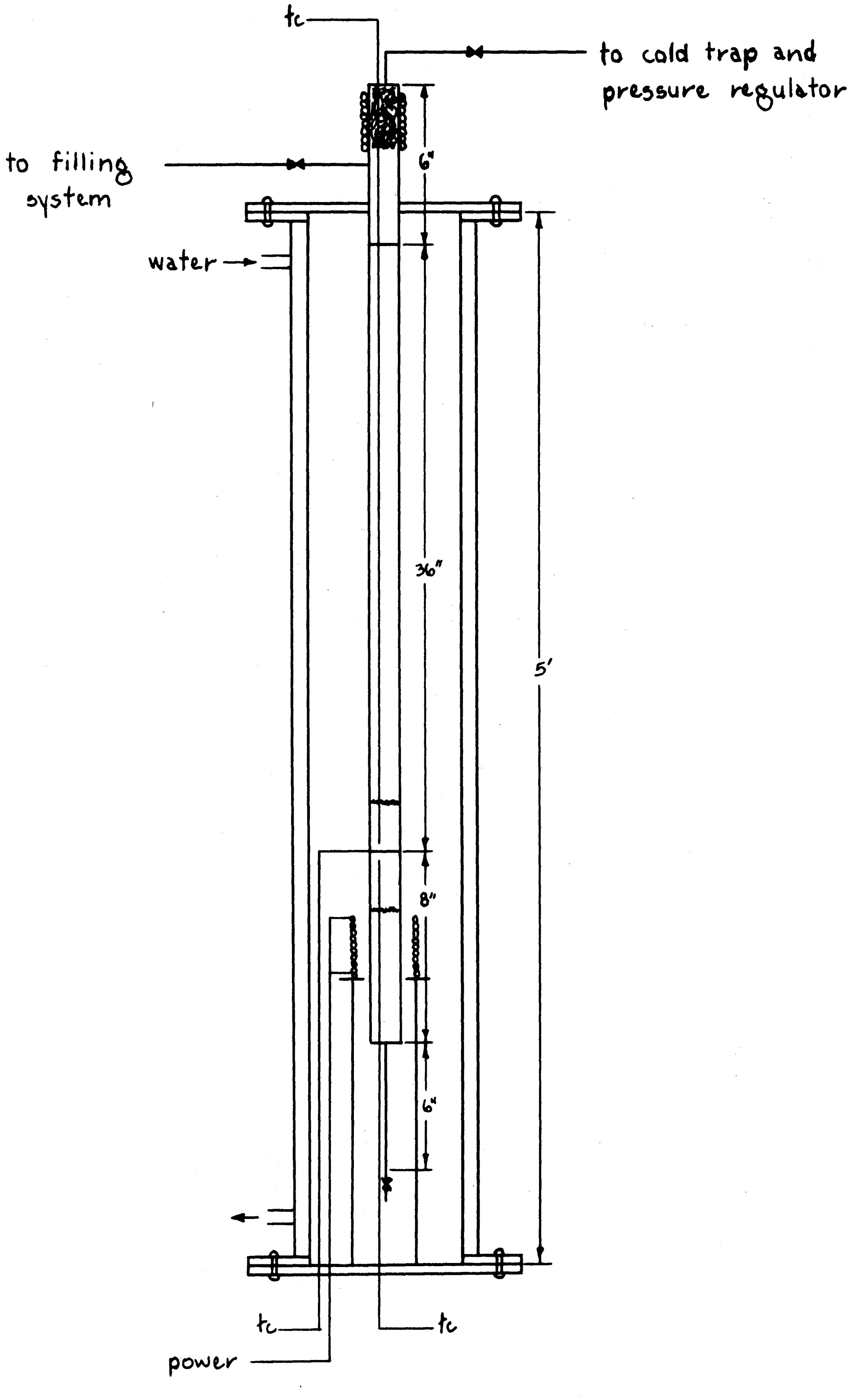
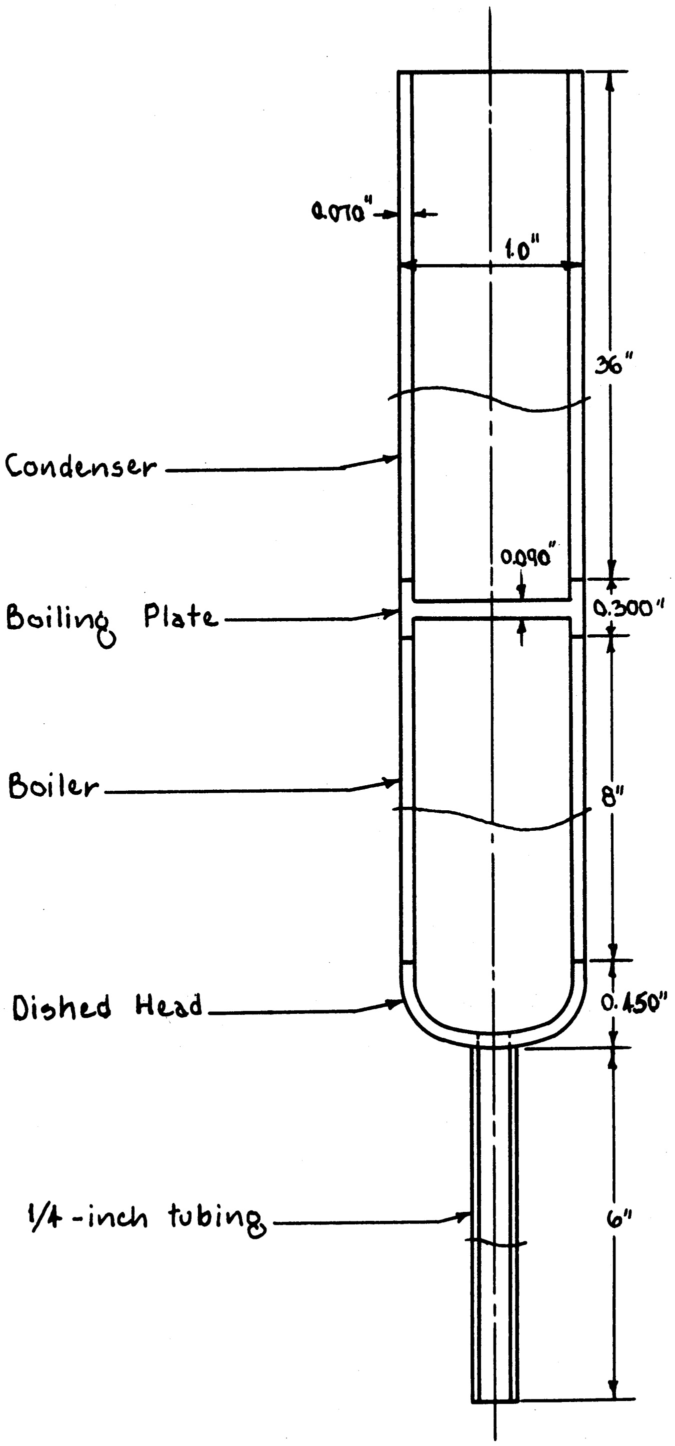


FIGURE 7
TUBE ASSEMBLY



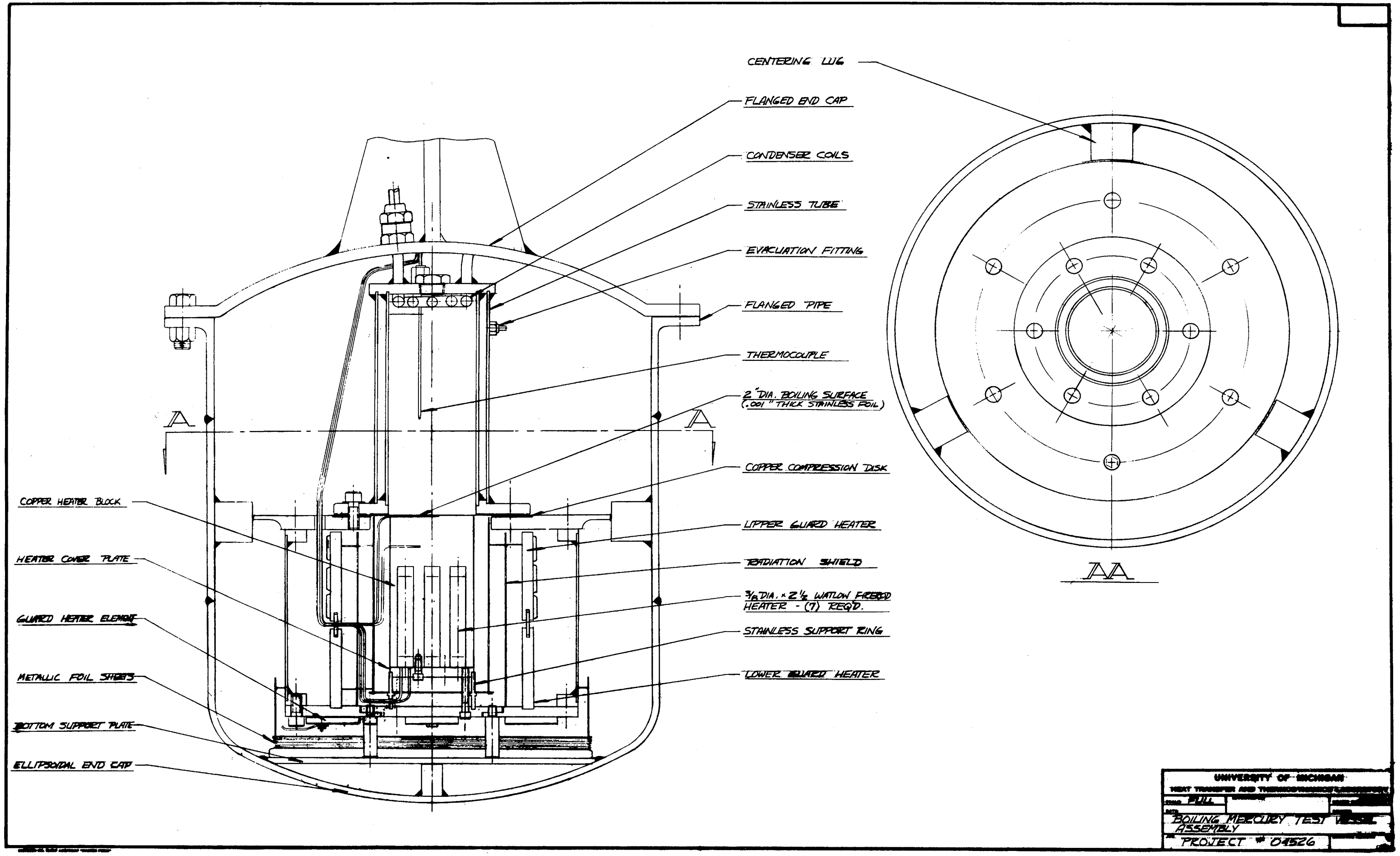


Fig. 8 Boiling Mercury Test Vessel Assembly

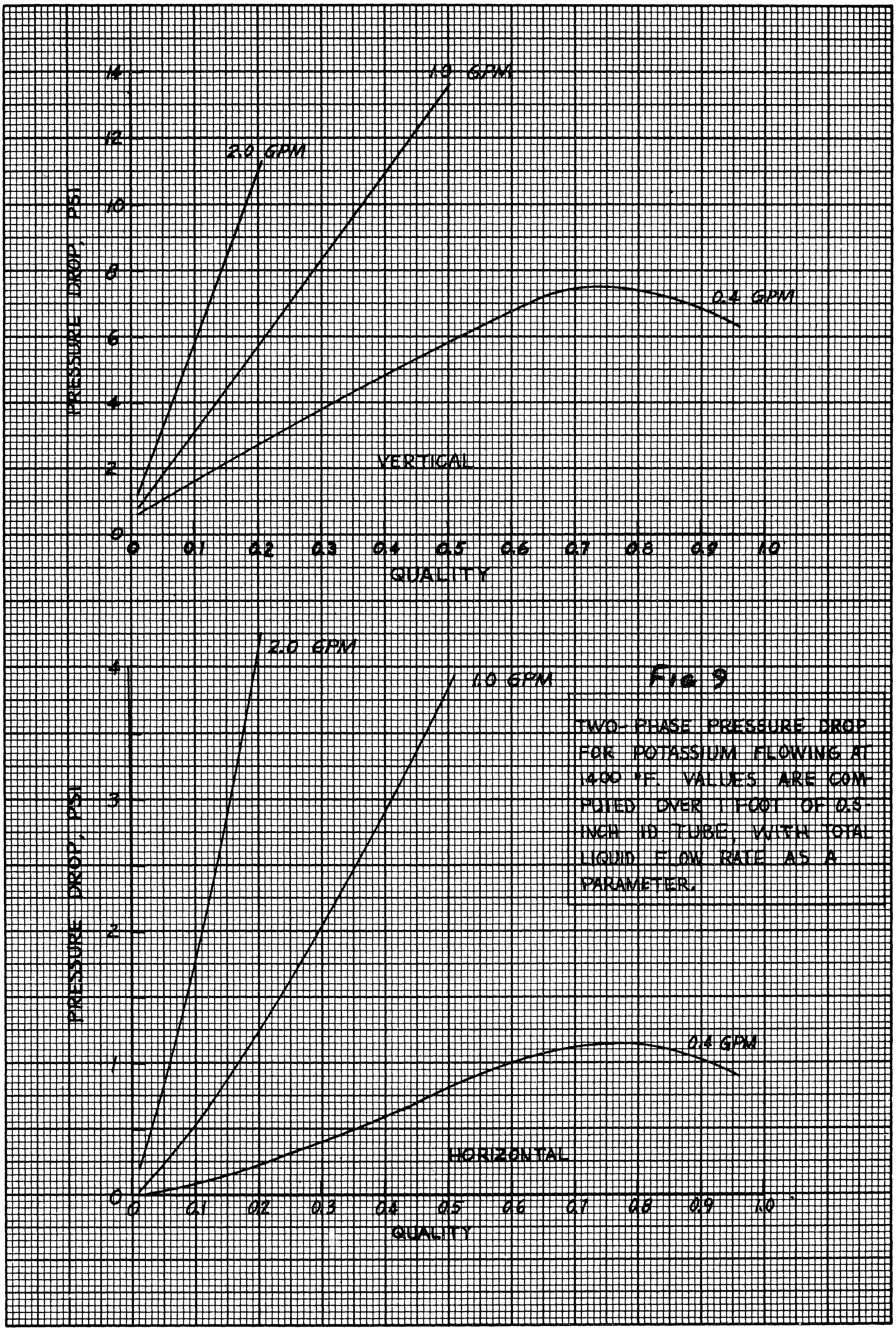
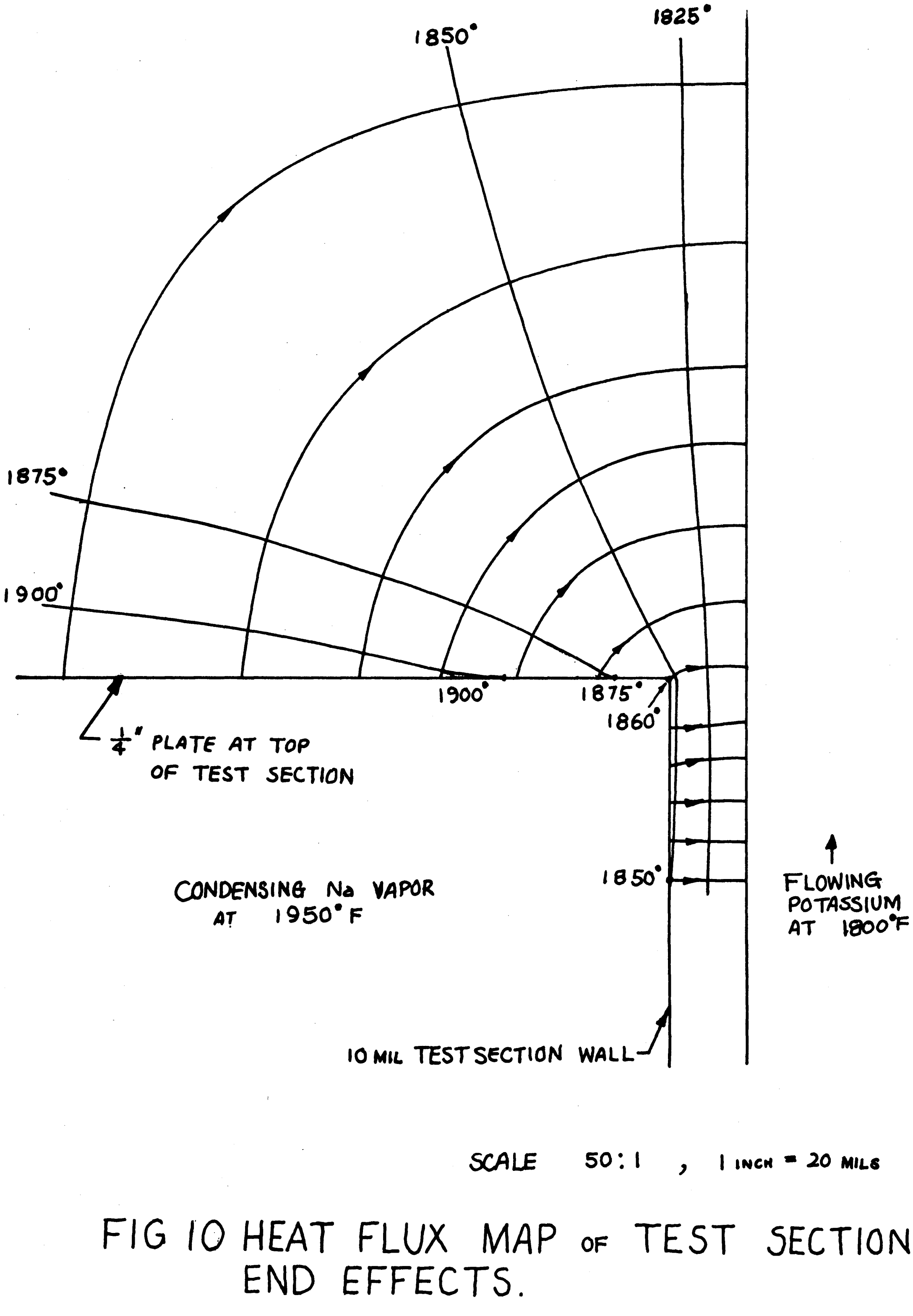


Fig 9

TWO-PHASE PRESSURE DROP FOR POTASSIUM FLOWING AT 1400 °F. VALUES ARE COMPUTED OVER 1 FOOT OF 0.5-INCH ID TUBE, WITH TOTAL LIQUID FLOW RATE AS A PARAMETER.



SCALE 50:1 , 1 INCH = 20 MILS

FIG 10 HEAT FLUX MAP OF TEST SECTION END EFFECTS.

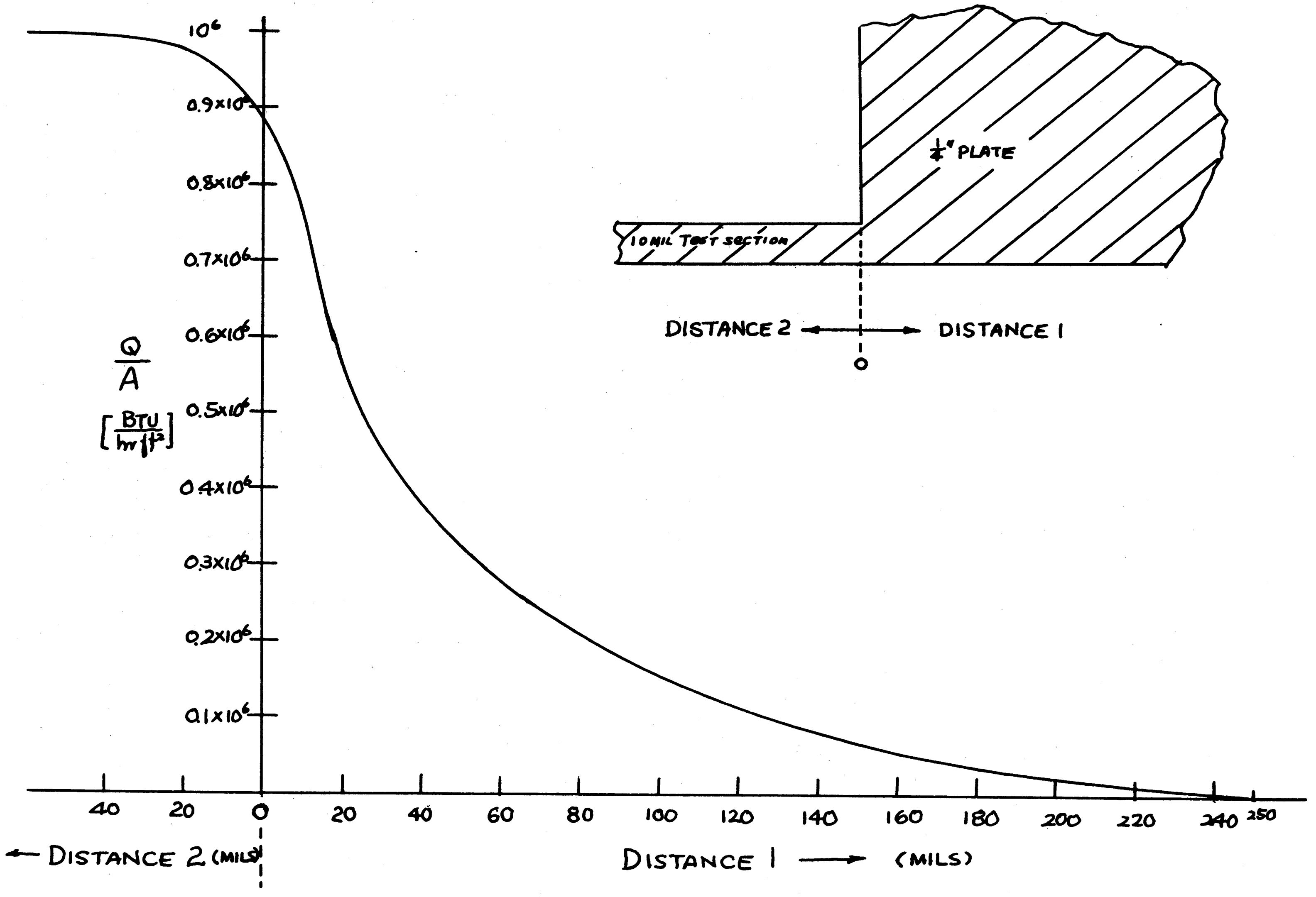


FIG 11 HEAT FLUX AT TOP OF TEST SECTION

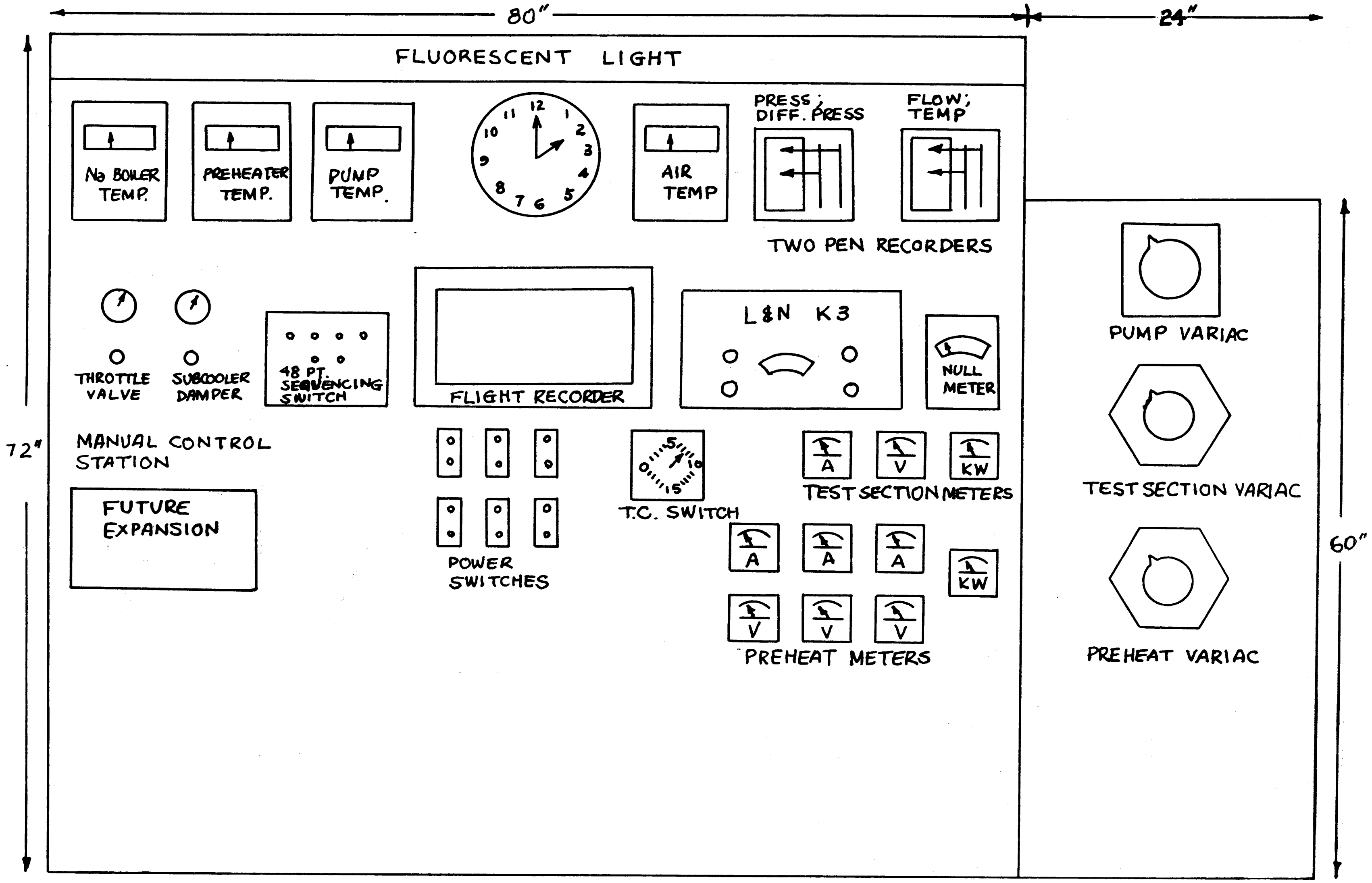


FIG 12 CONTROL PANEL FOR BOILING LIQUID METAL TEST LOOP