

THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
Department of Chemical and Metallurgical Engineering
Department of Mechanical Engineering

First Quarterly Progress Report

INVESTIGATION OF LIQUID METAL
BOILING HEAT TRANSFER

Richard E. Balzhiser, Project Director
John A. Clark
C. Phillip Colver
Edward E. Hucke
Thomas McSweeney
Herman Merte, Jr.
Lowell R. Smith

ORA Project 04526

under contract with:

FLIGHT ACCESSORIES LABORATORY
AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO
CONTRACT NO. AF 33(616)-8277-ITEM IIa

administered through:

OFFICE OF RESEARCH ADMINISTRATION ANN ARBOR

January 1962

"To expedite dissemination of information, this report is being forwarded for your information prior to review and approval by the ASD project officer and is, therefore, subject to change. Any comments which you may have should be forwarded to ASD (Lt. Lloyd Hedgepeth), Wright-Patterson AFB, Ohio, within 15 days of receipt to insure correction of errors before final approval is given."

enon

UMR0522

[v.1]

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

An analytical and experimental study relating to the boiling of liquid metals has been initiated at the University of Michigan under contract with ASD. The program will include pool boiling studies of potassium, sodium and rubidium at temperatures up to 2200°F. Mercury will be pool boiled at temperatures near its normal boiling point as a preliminary step in studying the effect of radial accelerations up to 20 times normal gravity on the boiling process.

A forced circulation loop is being designed to determine the effect of velocity and quality on the heat transfer process. Two-phase flow studies will also be made with this equipment.

T A B L E O F C O N T E N T S

	<u>Page</u>
INTRODUCTION	1
POOL BOILING STUDIES	4
FILM BOILING STUDIES	11
FORCED CIRCULATION STUDIES	12
INTERFACIAL EFFECTS IN LIQUID METAL BOILING	15
LIQUID METAL BOILING IN AGRAVIC FIELDS	17
TWO-PHASE PRESSURE DROP AND VOID FRACTION	21
REFERENCES	25

INTRODUCTION

The literature survey on liquid metal boiling heat transfer conducted as Phase I of this contract confirmed the need for reliable experimental studies in this area. The proposed use of liquid metals as working fluids in space turbines has raised numerous questions with regard to the effect of pressure, velocity, subcooling, quality and acceleration on the maximum obtainable heat flux from a surface to the metallic fluid. The effect of many of these variables have yet to be substantiated for relatively simple systems such as the water-steam system.

With few exceptions experimental programs to date have been confined to heat fluxes below $500,000 \text{ Btu}/(\text{hr})(\text{sq ft})$. Suggested correlations for the critical heat flux for liquid metals estimate these fluxes to be in the neighborhood of $500,000 \text{ Btu}/(\text{hr})(\text{sq ft})$. However, several investigators in preliminary experiments have measured fluxes substantially above those suggested by these theoretical predictions. As reported in our literature survey, the highest flux reported in the literature to date was $600,000 \text{ Btu}/(\text{hr})(\text{sq ft})$ for mercury boiling from an electrically heated surface. No effort was made to electrically insulate the fluid from the surface. Consequently, a substantial portion of the electrical energy was dissipated directly in the mercury. This made it difficult to estimate accurately the heat flux across the mercury solid interface. It is important to note that at this estimated flux the investigators concluded that they had not yet reached the critical flux for their particular system.

Other studies including those of Lyon and Bonilla in this country and those summarized by Kutateladze (1) in the Soviet Union have investigated the pool boiling of liquid metal media. Although the effect of pressure

on the heat transfer process has been investigated by several of these investigators, none of the investigations have achieved fluxes approaching that of burnout. Likewise, none of these investigations have shed any light on the effect of the other significant parameters.

This program has among its goals an experimental study of boiling phenomena at fluxes in the neighborhood of $1,000,000 \text{ Btu}/(\text{hr})(\text{sq ft})$. Considerations have been given to the possibilities of attaining fluxes up to $10,000,000 \text{ Btu}/(\text{hr})(\text{sq ft})$ in the event that the critical flux is found to be above a million. Both pool boiling and forced convection studies have been proposed in an effort to isolate the effects of the important parameters in liquid metal boiling heat transfer.

Another objective of this program is to explore the behavior of metallic fluids in the stable film boiling regime. Some evidence seems to exist that coefficients considerably in excess of those predicted by Bromley-type correlations might be experienced. A possible explanation for such behavior is presently under consideration. It is hoped that experimental studies can be carried out in this regime. A discussion of apparatus capable of operating with highly reactive fluids at the temperatures necessary to sustain film boiling is included in this report.

Considerable time has been spent on analyzing the effect of interfacial energies on the boiling process. Uncertainty exists among investigators in this field as to the significance of surface effects on the critical heat flux. It has been demonstrated that the addition of certain elements to mercury systems improves remarkably the ability of mercury to transfer heat from a surface. In the case of alkali metals which wet most surfaces extremely well, it is questionable as to whether additional improvement might be affected by altering the interfacial energies. Certainly from an

academic point studies in this area would be most worthwhile in providing a clearer picture of the surface phenomena involved in the boiling process. It is hoped that this program might include an experimental study of interfacial effects.

The importance of accelerations normal to the heat transfer surface has been demonstrated by several investigators in the recent literature. For aqueous systems it has been shown that the critical flux is appreciably increased by producing force fields normal to the surface in excess of those ordinarily experienced from gravity. The desirability of such artificially induced accelerations for equipment operating under zero gravity conditions seems obvious from other points of view also. As a phase of the contract a program is being conducted in which mercury will be pool boiled from a surface subjected to radial accelerations up to twenty times that of normal gravity. The details of this program are discussed later in this report.

The two-phase problems associated with the operation of such a cycle require much attention. Existing two-phase flow correlations are highly empirical and have been substantiated only for steam-water, air-water and other similar systems. The literature reviewed indicated a complete absence of two-phase flow studies pertaining to metallic media. The experimental difficulties in this field are complicated by the temperatures at which one must operate and the fact that direct observation of these systems is frequently impossible. Consequently, the determination of flow regimes and the transitions between various flow regimes remains a most challenging task. It is hoped, however, that this study will produce some reliable two-phase pressure drop data which might be used to test the

reliability of existing correlations.

These experimental studies are being conducted by graduate student researchers under the supervision of faculty members in the Departments of Chemical and Metallurgical Engineering and Mechanical Engineering. Several of the more challenging topics are serving as doctoral theses problems for some of these students.

POOL BOILING STUDIES

Heat transfer systems utilizing boiling liquid metals provide one method for efficiently exchanging large quantities of heat at relatively high temperature levels. In order to determine useful design information for such systems, it is necessary to simulate the actual conditions with a relatively simple and yet similar experiment. One might hope ultimately to generate an analytical or semi-empirical relationship substantiated for experimentally selected metallic (possibly aqueous) systems which would provide reliable engineering design information. Unfortunately, to date no relationship exists which reliably predicts the heat transfer coefficient or the critical heat flux for liquid metals.

Some experimental data for pool boiling mercury, sodium, NaK and cadmium and for mercury in a natural convection loop have been reported in the literature. For the most part, the data have not correlated well, and the highest heat flux reached in each case gave no indication of having reached the critical heat flux. Analytical expressions for predicting critical fluxes such as the Zuber-Tribus equation have not been verified for liquid metals. Conversations with persons actively engaged in boiling liquid metals at high heat fluxes indicate considerable uncertainty among

the existing data.

It thus seems desirable to study further liquid metals at higher heat fluxes with the hope of reaching the critical flux. In order to operate a boiling system at these desired heat flux levels without fear of burnout, safeguards must be incorporated which prevent surface temperature excursions when the critical flux is reached.

In accordance with requests from the Aeronautical Systems Division, potassium will be studied initially at temperatures up to 2200°F. Sodium and rubidium will be investigated in subsequent runs.

Proposed Experimental Design

The present experimental design consists primarily of a small columbium boiling vessel containing an electrically heated tube, a water-cooled or air-cooled condenser, an outer protective vessel, auxiliary and guard heaters and necessary instrumentation. Figures (1) and (2) show two alternate designs of the experimental system. Upon inspection of each figure, it is seen that the principal difference in each design is the method and type of heat transfer media used for condensing the liquid metal vapor. The design in Figure (1) uses air as the condensing fluid while the scheme shown in Figure (2) utilizes a conventional-type water condenser. It should be pointed out that water in contact with potassium (particularly at the high temperatures involved here) creates a violent reaction. For this reason, it is imperative that any water used in the apparatus be well confined and far removed from the boiling metal.

In either design, boiling takes place in a columbium vessel 3-in. I.D., 4 inches long with approximately 1/8-in. wall thickness. A small composite tube, extending through the vessel, is to serve as the boiling surface. This tube is shown in Figure (3) and consists of a 0.25-in. O.D.,

0.01-in. thick, and approximately 4.5-in. long tantalum tube, plasma-sprayed with pure aluminum oxide to a layer thickness of 0.005-in. The alumina powder to be used for the layer has a grain size \leq 325 mesh yielding a minimal porosity in the coating. Over the alumina a columbium coating will be plasma-sprayed to a thickness of 0.01 to 0.04 inches along the boiling length. On the region of the tube that coincides with the vessel wall, a build-up of sprayed columbium will be allowed (0.125 to 0.25 in.) such that the composite tube can be welded directly to the boiling vessel. As indicated in the diagram, each end of the composite tube will be welded to type 316 stainless steel tubing. This tube in turn will be directed out of the protective outer vessel and connected to the helium system. The two Pt-Pt, 10% Rh thermocouples (shown on the drawing) will be used to measure temperatures that can be used to determine surface temperatures. These thermocouples are to be fabricated by Motech Company of Kansas City, Missouri, and consist of a core metal and dissimilar annular metal. The metals are electrically insulated from each other by a 0.0005-in. thick layer of oxide. This coaxial assembly will be press-fitted into the inner tube and will protrude from the surface of the tube so that after spraying the oxide coating on the tube the thermocouple may be ground off flush with the surface of the oxide. The response time of such a thermocouple is in the order of 0.3 milli-second for an instantaneous temperature change of 1300°F.

Power to the boiling tube is to be furnished through two bus-bars (type as yet undetermined, but will probably be water-cooled), clamped or welded to the inner tube and set directly against the outside wall of the boiling vessel. Total power to the boiling tube will be determined from voltage and amperage measurements made directly across the tube. The

columbium vessel will be electrically insulated from the bus-bars by a thin layer of plasma-sprayed oxide, sprayed over the vessel. Heavy leads welded to each bus-bar pass through the outer container wall and are connected to a DC power supply. This power source will supply 40 KW with a rated output of 1700 amps at 24 volts DC.

At certain times during the investigation it may be necessary, as a precaution against burnout, to flow a stabilizer gas (helium) through the core of the heater tube. The gas will be furnished by cylinders at 2200 psi and will pass through a purification train to remove essentially all oxygen, flow through the heater tube and exhaust to the atmosphere at high velocity. As much as 300,000 Btu/(hr)(sq ft) (based on the boiling tube O.D.) will be transferred to the gas as it flows through the tube. The cooling effect of this gas will control the temperature of the heater tube and thus prevent burnout at total power inputs above those required to produce the critical heat flux. The inlet and outlet temperatures and the flow rate of helium will be instrumented. From these readings, the amount of heat transferred to the helium can be calculated.

The helium purification train is to be fabricated from stainless steel and designed chiefly to remove oxygen. The gas leaving the storage cylinder will be pressure regulated and then pass through five metal containers (2-in. I.D. by 10 inches long) containing either hot liquid sodium or NaK. Each container in the train is to be heated by nichrome wrapped heaters, variac controlled. Insulation will cover the complete arrangement.

The entire boiling vessel aside from the condenser is to be contained in a stainless steel vessel 18 inches I.D. and approximately 1/2-in. thick. This vessel is nearly identical in each design and consists of a flanged

top and bowl shaped bottom. The flange is to be gasketed and will use stove bolts and nuts to assume a leakproof fit. It is seen that all entry into the vessel, save the guard heater leads, is made through the vessel top. This fact permits easy disassembling of the apparatus for internal inspection or repair. The inner space between the columbium boiling vessel and the outer stainless steel vessel will be evacuated and refilled with purified helium. At all times the pressure of the helium in the inner space will be equalized with the boiling vessel pressure. In addition, the inner space is to be filled with insulating material and as a further means of preventing heat loss, a nichrome wire guard heater is to be installed as shown. Power to this heater will be regulated by a variac connected to a 110 v AC circuit.

The air-cooled condensers in the first design (Figure 1) are welded to the top of the boiling vessel. Each condenser tube will be made from columbium and will be fabricated by Wolverine Tube Company of Detroit, Michigan. They will be Wolverine Trufin type, 3/4-in. O.D. (19 fins/in.) tubes with an average wall thickness of 0.082 inches. Assuming an air-side heat transfer coefficient of $10 \text{ Btu}/(\text{hr})(\text{sq ft})(^\circ\text{F})$ (this coefficient corresponds to an air velocity of 15 ft/sec), it was found that 6.48 total feet of condenser is needed to operate the system at $2,000,000 \text{ Btu}/(\text{hr})(\text{sq ft})$. Five 1.3 ft. condenser tubes extending from the top of the boiler satisfies this requirement. Condenser tube velocities, using total boil-up rate, are 132 ft/sec for one condenser tube to 26 ft/sec for five condensers.

To guard against oxidation, the condenser and exposed boiling vessel loop will be coated with an oxidation resistant material. Inspection of the literature shows that nickel-chromium alloys, e.g. 80% Ni-20% Cr, have

good oxidation resistance properties in the neighborhood of 2000°F. Work done at Battelle Memorial Institute on zinc coatings on columbium indicates that a 6 mil coating of zinc on columbium has a service life of 1000 hours at 1800°F and 70 hours at 2000°F. Unfortunately, it was found that although zinc was attractive in the range 1600-2000°F that at lower temperatures, say 1400°F, the zinc coating inconsistencies, pin-holes, etc. were not self-healing as at the higher temperature and thus did not give a satisfactory protective coat.

Air velocities across the condenser sections will be furnished by a large capacity blower. A duct will be installed so that the air can be forced directly across the condenser bundle.

Each condenser tube is to be welded into a common header made from standard 3-in. O.D. type 316 stainless steel pipe, fitted with a stainless steel top and bottom. A coiled water cooler will be used around the outside of the header. A standard 3/4-in. O.D. type 316 stainless steel tube welded to the top of the header allows entry into the system. Through this line, helium, thermocouple leads and a connected vacuum line, enter the apparatus. Also beyond the header a knock-out drum will be installed to further prevent small amounts of potassium vapor from passing upstream through the helium lines.

The alternate design (Figure 2) uses water as the condenser medium. From a 4-in. diameter 316 stainless steel cylinder, 5-3/4-in. diameter holes are drilled as shown (Figure 2). Four grooves are machined along the length of the cylinder, stopping approximately two inches from either end. An annular plate welded to the condenser cylinder and a 5 1/2-in. O.D. shell forms the water passage. Two 3/4-in. diameter water taps are installed to the bottom and the top of the condenser shell. Columbium

tubes (3/4-in. O.D.) are to be press-fitted down through each of the five holes drilled into the cylinder. In turn, these tubes are press-fitted and welded into coinciding holes drilled in the top of the columbium vessel. The top of the condenser section is welded to a 5 $\frac{1}{2}$ -in. I.D. header, possibly made from an extension of the outer water shell. This header, as well as the condenser shell, is to be made from type 316 stainless steel.

Design calculations have been made to determine the required condenser length. It has been found that for a boiling heat flux of 10,000,000 Btu/(hr)(sq ft) and a total temperature drop of 1300°F that 0.73 ft. of condenser is needed. Using this as a basis, it is probable that a two foot condenser will be used.

Instrumentation in either system is to include a multi-point temperature recorder for indicating many necessary temperatures throughout the system. In addition, a potentiometer will be used to measure temperatures where accuracy or precision is required.

Experimental Procedure

The system is designed such that the experimental procedure will be simple and direct. After performing the necessary preliminaries before each start-up, the power input to the boiler tube will be set at the desired heat flux level. When the boiling process becomes stable and the system reaches steady state, the required temperature, etc. readings will be made and recorded. Subsequent runs at other heat fluxes will require only adjusting the power input and waiting until the system reaches steady state.

Results Anticipated

It is hoped that the following results will be obtained:

1. The determination of the boiling curve for potassium at atmospheric pressure up to and including the critical heat flux.
2. The determination of the boiling curve for potassium at other pressures in the range 0-200 psia.

FILM BOILING STUDIES

Operation in the transitional and film boiling regimes is theoretically possible with the pool boiler discussed earlier providing it is capable of reaching the critical flux. In the event the critical flux exceeds that obtainable, it is impossible to raise the surface temperature to a sufficiently high level to sustain a stable vapor film. However, if one first obtains a surface temperature above that required for stable film boiling and then contacts it with a saturated liquid metal, stable operation might be achieved at the fluxes permissible.

Consideration has been given to the design of a submersible ribbon element which could be adapted to these conditions. Direct resistance heating may be possible as the vapor blanket, if achieved, could electrically insulate the surface from the fluid. Condensing metals might also be used in a similar manner to study film boiling. Surface temperatures sufficiently high would first be obtained after which the metallic fluid will be introduced. In the case of an electrically heated ribbon, the power input could be adjusted simultaneously to the immersion to a value characteristic of film boiling. Further study in this area will be carried out during the next quarter.

FORCED CIRCULATION STUDIES

Design studies have been carried out for a forced circulation loop to study the effect of velocity, quality and subcooling on the boiling process. Based on these studies, the following specifications have been set as operating objectives for boiling potassium:

- Fluid flow rate, potassium 0.2 to 2.0 ~~gpm~~
- Maximum heat input, preheat section - 50 Kw
- Maximum heat input, 5-in. test section - 15 Kw
- Operating fluid temperatures - 1400-1800°F
- Saturation pressures - 14.7 - 81 psia
- Tubing - 5/8 inch O.D. Haynes 25 alloy

Under these specifications, liquid velocities will range from 0.3 to 3.3 ft/sec affording Reynold's numbers of 6500 to 65,000. Vapor qualities of up to 100% can be attained at 0.7 gpm. Vapor velocities will range up to 600 ft/sec affording Reynold's numbers up to 200,000 although critical velocities, known to be much lower in two-phase mixtures, will likely limit the operation to much lower vapor Reynold's numbers. Energy balances around the preheater and test sections will be used to estimate inlet and outlet qualities and the heat flux to the test section. Surface temperature measurements pose a difficult problem. Various possibilities exist for each proposed test section. For a known flux a single temperature measurement at a known position in the wall can be used to estimate the surface temperature. Several such measurements will be made to confirm this value. A specially instrumented section is planned between the preheater and test section for studying two-phase flow behavior. This is discussed later in the report.

A firm proposal has been received from one prospective supplier while a second is still in the process of making a design and cost estimate. Preparations are also being made to design and fabricate the equipment ourselves if proposed costs are prohibitive.

It is anticipated that potassium will be pumped with an electromagnetic pump, metered by an electromagnetic flowmeter and preheated to vapor qualities of up to 100% by a three-phase direct resistance connection to the pipe. The fluid then enters the test section where fluxes of up to one million are anticipated. The stream may then pass directly to a condenser-subcooler or to a liquid-vapor separator. In the latter case the liquid portion is metered for a direct measurement of quality and then flows to a hot well. The vapor stream is condensed in a finned-tube, air-cooled condenser and then is added to the liquid in the hot well. Loop pressure is controlled by adjusting the rate of heat removal in the condenser. From the hot well, the fluid would then enter a subcooler where the stream temperature is lowered to 1400°F before entering the suction side of the electromagnetic pump. Embrittlement problems with Haynes 25 require that fluid temperatures be kept above 1400°F. Stability will be enhanced by the presence of a throttling valve located downstream from the flowmeter.

The most critical component of the loop is the test section where extremely high heat fluxes are desired. In our design we have considered several heating possibilities, of which only the first two listed below seem feasible. A conceptual design is shown in Figure (7).

1. Condensing of Liquid Metals

If condensing sodium (or lithium) is used on the outer wall, the temperature drop between the condensing and boiling liquids will likely

be around 200°F. However, containment of sodium (or lithium) vapor at 2000°F is a definite problem. Condensing coefficients have not been well substantiated under these conditions so some uncertainty exists here also. This type of heating would permit operation near the critical with little or no risk of burnout should this condition be reached.

2. Resistance Heating

In this method a sandwich technique is used to heat a thin layer of refractory metal which is electrically insulated from the base tube by another thin layer of a metallic oxide. These materials can be flame or plasma-sprayed to thicknesses of a few mils. A typical sandwich would be a base tube of columbium covered with 5 mils of beryllium oxide (chosen for its high thermal conductivity), and 3 mils of tantalum. Approximately 1000 amps will pass through the outer layer. A test program is planned to determine the limitations of this approach. Investigators at General Electric have already established its feasibility.

3. Induction Heating

A flux of 10^8 Btu/(hr)(sq ft) can be easily obtained with high-frequency induction heating. However, data obtained are likely to be inaccurate because of the difficulty of measuring power input and of preventing fringing electromagnetic fields.

4. Radiant Heating

A temperature of 5000°F would be required to transfer 10^8 Btu/(hr)(sq ft) to the tube walls by radiation. This is in excess of normal operating limits for the radiator.

5. Gas-Fired Heating

It is virtually impossible to obtain the required heat flux via gas-

fired heating.

Another problem of considerable importance is the pressure drop likely to be encountered in two-phase flow. Based on evaluation of the data for two-phase water flow, we may expect a pressure drop as high as 12 psi/ft. (for potassium at 1700°F, 2 gpm flow rate and 50% quality). It will thus be necessary to make all lines as short as possible and to design the condenser and preheater for minimum pressure drop.

INTERFACIAL EFFECTS IN LIQUID METAL BOILING

Almost all research on liquid metal heat transfer has attempted to fit existing heat transfer correlations. In most heat transfer correlations, dimensionless groups are used. This means these curve fittings lump many parameters together and measure their overall effect. In order to get a better idea of the difference between ordinary liquids and liquid metals, the variation of the parameters which make up the dimensionless groups must be studied.

The experimental procedure used in liquid metal heat transfer studies must be different because of the impossibility of making visual observations. The boiling site in a liquid metal can not be seen so it is seemingly impossible to measure any variables on the boiling surface where neither the number of boiling sites nor their position can be directly observed. A practical solution seems to rest in the measurement of the effect of variables on the dynamics of a single active site. If a hot spot or "point boiler" were used, the position of the active bubbling site is known. Also since this is the only point from which boiling is taking place, the variation of surface properties over the boiling area will be small.

One of the most elusive variables to characterize has been the surface. On a normal "clean" surface it has been shown that there are many layers of foreign material. Since these layers are difficult to characterize and may continually change, it is difficult to obtain reproducible results for experiments depending heavily on surface properties. By ion bombardment cleaning it becomes possible to remove almost all of the surface contaminants. This should make the surface much more reproducible.

Once the surface is clean it becomes possible to characterize boiling from a true liquid metal-metal interface. It has been shown that both electrical and thermal energy are transferred across metallic interfaces primarily by electrons. The relation between the electrical and thermal conductivities is given approximately by the following equation (Ref. 2):

$$\frac{K}{\sigma T} = \frac{\pi^2}{3} \left(\frac{h}{e} \right)^2 \quad (1)$$

K - Interfacial thermal conductivity

σ - Interfacial electrical conductivity

T - Absolute temperature

h - Planck's Constant

e - Charge on an electron

Although investigators have tried to verify this relation for metallic interfaces, the results have not yet been reproducible. In general it was found that the group $K\sigma T$ varied only slightly with temperature but changed with time. This scatter would appear to result from surface phenomena due to failure in achieving perfect electronic conductivity across the interface. It is hoped that by ion bombardment cleaning of the surface a more intimate contact can be established between the phases.

If the surface is made small, a large variation in the temperature of the heating element can be expected as bubbles form on the surface. On

a large boiling surface these same temperature variations have been observed. However, it is impossible to know exactly where the bubbling site is in relation to the thermocouple. In the case of a single bubbling site the temperature measured will be directly below the bubble. Therefore, the temperature variation will take on more significance.

In addition to these variables, the frequency of bubble formation and perhaps the bubble size might be determined by noting changes in interfacial resistivity. Also, it would be quite easy to study the effect of additives to the liquid as well as the solid.

A limitation of using the "point" boiler is that the data from one active site probably will not correspond to the data from a surface with many active sites. However, a change in any boiling characteristic of the point boiling system should correspond to a similar change in the boiling characteristic of a large boiling surface.

Also, the effect of impurities might have a much larger effect on a single bubble site than on a large boiling surface. It is felt, however, that this limitation can be overcome if a certain amount of care is exercised.

At the present time the advantages of using a "point" boiler seem to greatly outweigh its disadvantages when considering the amount of information that can be learned. Active consideration is now being given to the design and instrumentation of the apparatus.

LIQUID METAL BOILING IN GRAVIC FIELDS

Test Apparatus

A preliminary sketch of the test vessel to be used for studying the pool boiling characteristics of mercury in high force fields is shown in

Figure (4). Slight modifications may be necessary as further design details are worked out.

The preliminary measurements to be made are heat flux, heater surface temperature, liquid temperature, and dimensionless total acceleration a/g . Using an electrical resistive heat source it is expected that the heater surface temperature will be the only dependent variable, besides the hydrostatic pressure at the heating surface. Initially, efforts will be made to obtain data with saturated liquid. A controllable degree of subcooling will depend upon the thermal interaction between the condenser coils and the mercury vapor or liquid. To obtain data with large subcooling it may be necessary to design the condenser coils such that they are in direct contact with the liquid.

Tests using the proposed vessel will be operated at atmospheric pressure only. A test vessel for operation at higher pressures would become too massive for use in the centrifuge presently available.

The test vessel is designed to provide a flat heat transfer surface 2 inches in diameter. The liquid metal to be used initially will be mercury. Should the results warrant, consideration can then be given to other liquid metals.

The test vessel is being designed for an arbitrary maximum heat flux of 500,000 Btu/(hr)(sq ft). The value of the peak heat flux of mercury at atmospheric pressure is uncertain, but a review of the available data (Ref. 3) appears to indicate a probable value somewhat higher than this. Operation near the peak heat flux is undesirable with this system because of the possibility of burnout.

The heat source consists of 7 electrical cartridge type heaters embedded in the end of a cylindrical copper block. Copper is used to minimize the temperature difference between the cartridge heater and the

boiling surface. The heaters are spaced such that each is surrounded by an equal volume of copper, and the larger diameter of the cylinder permits a lower operating heat flux in this area. A transition section to the smaller diameter of the heat transfer surface is provided along with $1\frac{1}{4}$ inch long smoothing section to assure a uniform temperature at the heat transfer surface. Measurements are planned to check the uniformity of the surface temperature.

The copper heater block is isolated from the mercury at the boiling surface by a stainless steel foil 0.001 inches in thickness silver-brazed to the copper to provide intimate thermal contact. Extension of the foil from the heater surface furnishes a convenient seal between the heater and the container side-wall. A thin foil is desirable for two reasons: the temperature drop across the foil is minimized, as is the heat loss from the edge of the heater due to the fin effect. A smaller temperature drop across the foil will permit a more accurate evaluation of the heater surface temperature, as the point nearest the boiling surface accessible to a thermocouple will be the copper-stainless steel interface.

The surface temperature will be calculated from measurements at 3 locations at the copper-stainless steel interface. Two thermocouples are planned for the measurement of the mercury temperature at two variable depths. The thermocouples to be used are chromel-constantan, selected because of their stability and high thermoelectric power. These will be encased in stainless steel tubing and calibrated at the steam point, tin point, mercury vapor point and sulphur point. The emf measurements will be made with a Leeds and Northrup Type K-3 Potentiometer, using an ice point reference junction.

The maximum design heat flux of $500,000 \text{ Btu}/(\text{hr})(\text{sq ft})$ corresponds to a power input of 3170 watts. The power will be measured with a

calibrated voltmeter and ammeter. To insure that the heat losses from the bottom and sides of the heater block are kept at a minimum, guard heaters and radiation shields are provided. Since the heater block varies in temperature along its length, the guard heater is split into two sections, each being independently monitored by a differential thermocouple and controlled for a minimum temperature differential. Guard heater power is supplied by resistance strip heaters wrapped around the circumference.

The walls enclosing the boiling surface will be composed of two concentric stainless steel tubes with insulation in the annular region and outside.

The mercury will be condensed at the top of the boiling chamber by a coiled stainless steel tube through which water will flow. The boiling chamber is vented to the atmosphere by means of a vent tube terminating near the center of rotation of the centrifuge to prevent the possibility of an aspiration effect decreasing the pressure within the test vessel during rotation. The vent tube will be water cooled for a considerable length to prevent mercury vapor from escaping to the atmosphere.

Initial tests will be conducted with mercury depth constant at as low a value as is practical, perhaps $\frac{1}{2}$ to 1 inch to keep the changes in hydrostatic pressure at the heater surface due to varying acceleration small. A question exists as to whether it is possible to attain saturated mercury at the boiling surface with finite depth. With mercury boiling at standard gravity, it was found that the bulk mercury temperature was essentially that of saturated mercury at the liquid-vapor interface (Ref. 4), hence somewhat subcooled at the heating surface. With high force fields this may also be the case, since the fluid motion between the heater surface and liquid-vapor interface will be greatly

enhanced. A similar effect has been observed in high g work with water (Ref. 5). The only way to minimize this effect is to use very low depths of mercury, which decreases the variation in hydrostatic pressure from the heater surface to the liquid-vapor interface.

TWO-PHASE PRESSURE DROP AND VOID FRACTION

Although an extensive literature exists on the subject of two-phase fluid flow, no investigations have been reported on flow of metallic systems. The mechanisms of two-phase flow behavior are not amenable to mathematical analysis without resort to highly simplified models which are frequently unrealistic. Consequently, one generally has to rely on semi-empirical correlations for predicting two-phase pressure drop. The Martinelli-Nelson method is probably the best existing method for predicting pressure drop in forced-circulation boiling, and the Lockhart-Martinelli correlation is most often used for isothermal situations. These correlations, and others, are based on water-steam, water-air, or hydrocarbon-air data. Thus, a need exists to experimentally examine the validity of such correlations for use in metallic two-phase flow problems. The proposed research program is aimed at answering this need in addition to providing reliable pressure drop and void fraction data for potassium flow. Hopefully, this study will reveal which parameters best characterize two-phase metallic flow. The literature is being searched for appropriate models and experimental studies which may aid in this research.

It is expected that fluid physical properties play a prominent role in two-phase flow behavior. The viscosities, densities and surface tensions of sodium, potassium and their vapors were compared with those of the water-steam system on a reduced temperature, T_r , basis. In the

range $0.5 < T_r < 0.75$ very favorable comparisons were found--i.e., at least order-of-magnitude agreement existed in all cases. Certain dimensionless groups and combinations of physical properties entering into known important dimensionless groups were also plotted against reduced temperature. Again, order-of-magnitude agreement between sodium, potassium and water was noted, and indeed, remarkably good agreement exists in some cases. These favorable physical property comparisons suggest that the Martinelli correlations may predict pressure drop in metallic flow to at least the correct order of magnitude. It is suggested that the correlations be applied on a reduced-property basis. If the reduced temperature in a problem is in the range $0.5 < T_r < 0.75$, the numerical results are postulated to be as accurate as can be obtained without help of experimental data.

In the experimental program, pressure drop measurements alone will not be sufficient for correlation and analysis. In addition, it is proposed to obtain void fraction data, the importance of which will be outlined here. In gas-liquid flow, the mean velocities of the two phases are not equal. This condition is known as "slip" and occurs both in horizontal and vertical flow. The true proportion of the pipe cross-section occupied by either phase differs from that calculated, if the calculation is based on the volumes of liquid and gas passed through the duct. To compute the true gas velocity, one must know the vapor volume fraction. The slip velocity ratio is given by

$$\frac{V_g}{V_l} = S = \left(\frac{x}{1-x} \right) \left(\frac{1-\alpha}{\alpha} \right) \left(\frac{\rho_l}{\rho_g} \right) \quad (2)$$

where V_g, V_l = vapor and liquid superficial velocities

ρ_g, ρ_l = vapor and liquid densities

x = quality, mass of vapor/mass of mixture

α = vapor volume fraction (also called void fraction or liquid holdup)

The hydrodynamics of two-phase flow depend strongly on void fraction. In a flow system in which a change of phase is occurring, the pressure drop can be written as

$$-dP_{\text{static overall}} = dP_{\text{frictional}} + dP_{\text{acceleration}} + dP_{\text{hydrostatic head}} \quad (3)$$

or by the familiar energy balance

$$-dP = \rho_m dH_f + \rho_m \frac{VdV}{g_c} + \rho_m dL \quad (4)$$

where ρ_m = mixture density
 H_f = frictional head loss
 V = local superficial velocity
 L = length of duct
 g_c = force-mass conversion constant

For a two-phase mixture with slip, the local mixture density is given in terms of the local void fraction.

$$\rho_m = (1-\alpha) \rho_l + \alpha \rho_g \quad (5)$$

Without knowledge of α , the hydrostatic, frictional and acceleration components of pressure drop cannot be separated from the overall static pressure drop. From the above remarks and equations, the importance of measuring void fraction, α , becomes evident.

The experimental data will be obtained from the boiling potassium circulation loop. It is hoped that study can be made on both horizontal and vertical flow, but this aspect of the research has yet to be decided. Pressure gauges on a test section of known length will furnish the pressure drop data. Gamma-ray attenuation methods have proven successful for making void fraction measurements up to qualities of 10 to 15 per cent. Above this quality level it is difficult to obtain

reliable data as can be seen from Figure (5). Above $x \approx 0.1$ the slip ratios bunch together, making it very difficult to establish V_g/V_t for any given α value.

In the radiation attenuation method of making void fraction measurements, low energy radiation is desired in order that a large portion of the incident beam can be attenuated. It is proposed to use low energy X-rays which will eliminate the half-life problem associated with gamma-ray sources as well as making it possible to have a reasonably monoenergetic beam. In receiving and recording the transmitted beam, a direct current amplifying system is suggested. Only current measurements are recorded in calibration and data runs. Figure (6) gives a schematic diagram of the proposed X-ray attenuation setup.

Because of its temperature sensitivity, provisions will be made to cool the scintillation crystal. It will also be necessary to shield the photomultiplier tube from electrostatic and electromagnetic fields present around the loop. Concentric shells of copper, mu-metal, and iron can be used for this shielding. It will be required that the photomultiplier tube have a low dark current.

In proposing this research program, costs have been considered. The design of the circulation loop includes instrumentation which will provide heat balance data for determining quality. The Mine Safety Appliance Company recommends a pressure gauge which costs about \$1500. The equipment for measuring the transmitted X-ray beam in void fraction determinations will cost about \$2000. An X-ray apparatus will probably be available at little or no cost. It thus appears that the research program is financially feasible.

REFERENCES

1. Kutateladze, S. S., "Liquid Metal Heat Transfer Media," Supplement #2, 1958, N.Y., Consultants' Bureau Inc., 1959.
2. Bonilla, C. F. and Wang, S. J., "Interfacial Thermal and Electrical Resistance between Stationary Mercury and Steel," NYO-3091.
3. Romie, F. E. et al., "Heat Transfer to Boiling Mercury," Trans. ASME, J. Heat Transfer, Series C, Vol. 82, No. 4, Nov. 1960.
4. Bonilla, C. F., et al., "Pool Boiling Heat Transfer with Mercury," Reactor Heat Transfer Conference of 1956.
5. Merte, H., Clark, J. A., "Pool Boiling in an Accelerating System," Trans. ASME, J. Heat Transfer, Series C, Vol. 83, No. 3, Aug. 1961.

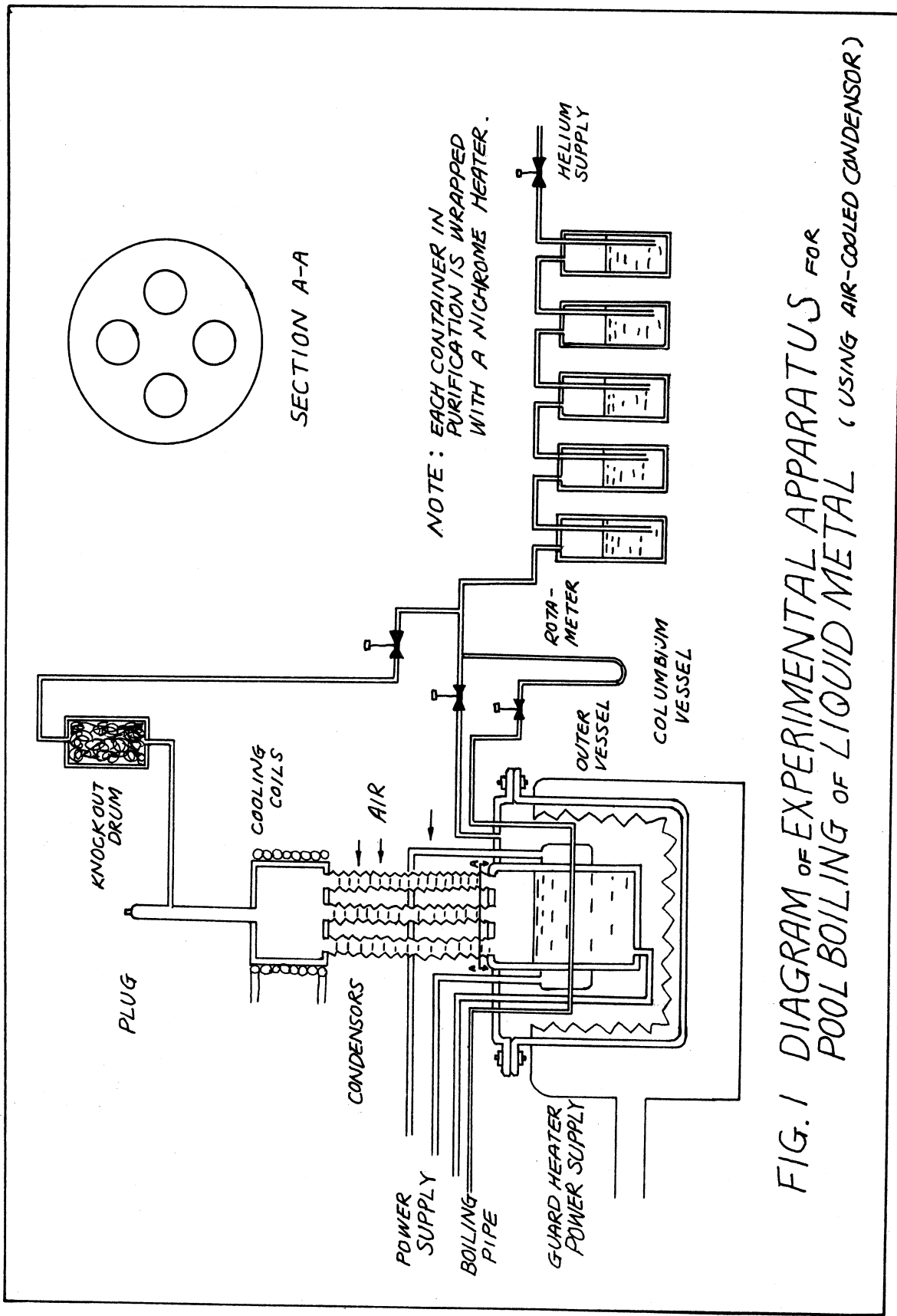


FIG. 1 DIAGRAM OF EXPERIMENTAL APPARATUS FOR POOL BOILING OF LIQUID METAL (USING AIR-COOLED CONDENSOR)

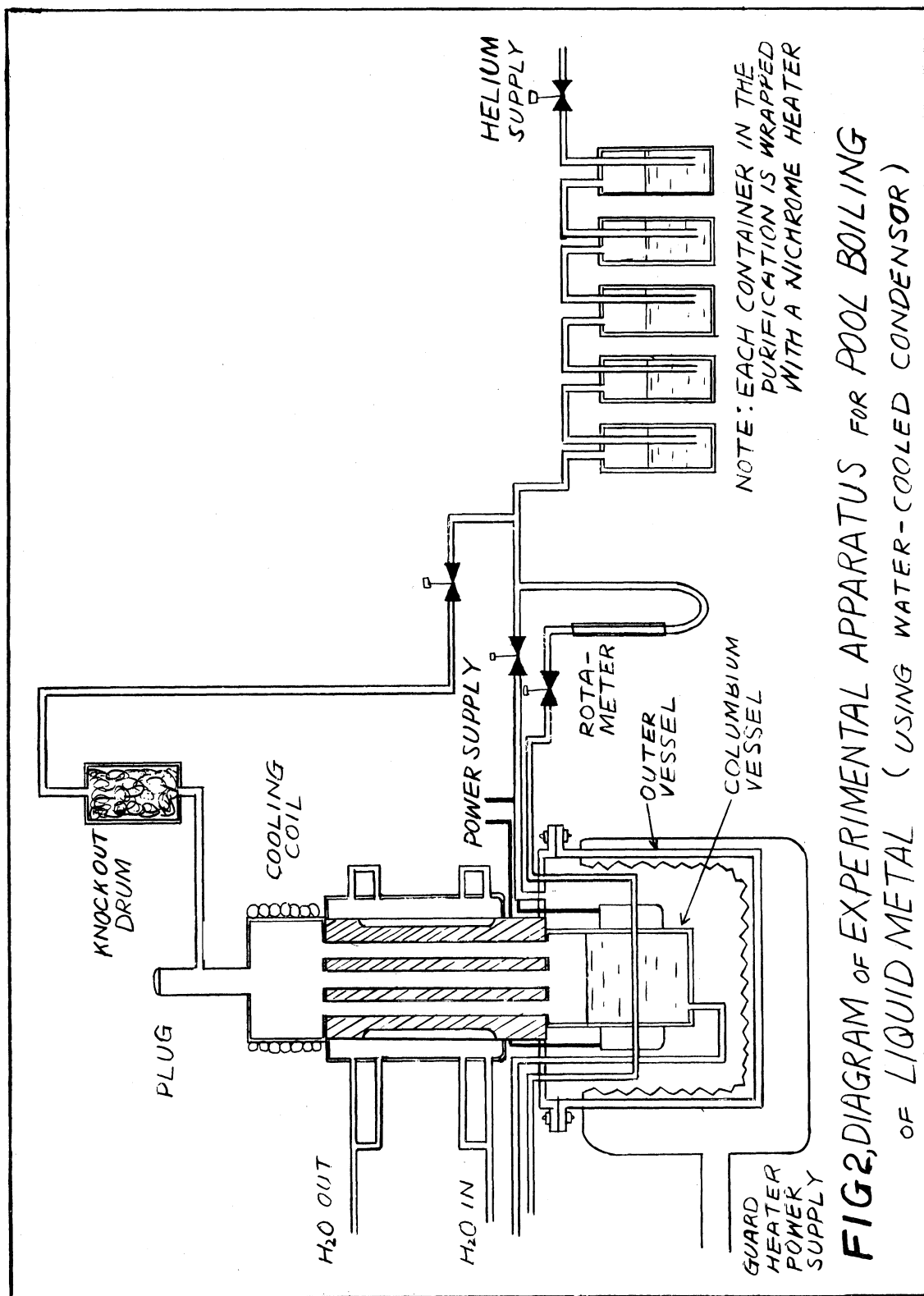


FIG. 2, DIAGRAM OF EXPERIMENTAL APPARATUS FOR POOL BOILING OF LIQUID METAL (USING WATER-COOLED CONDENSOR)

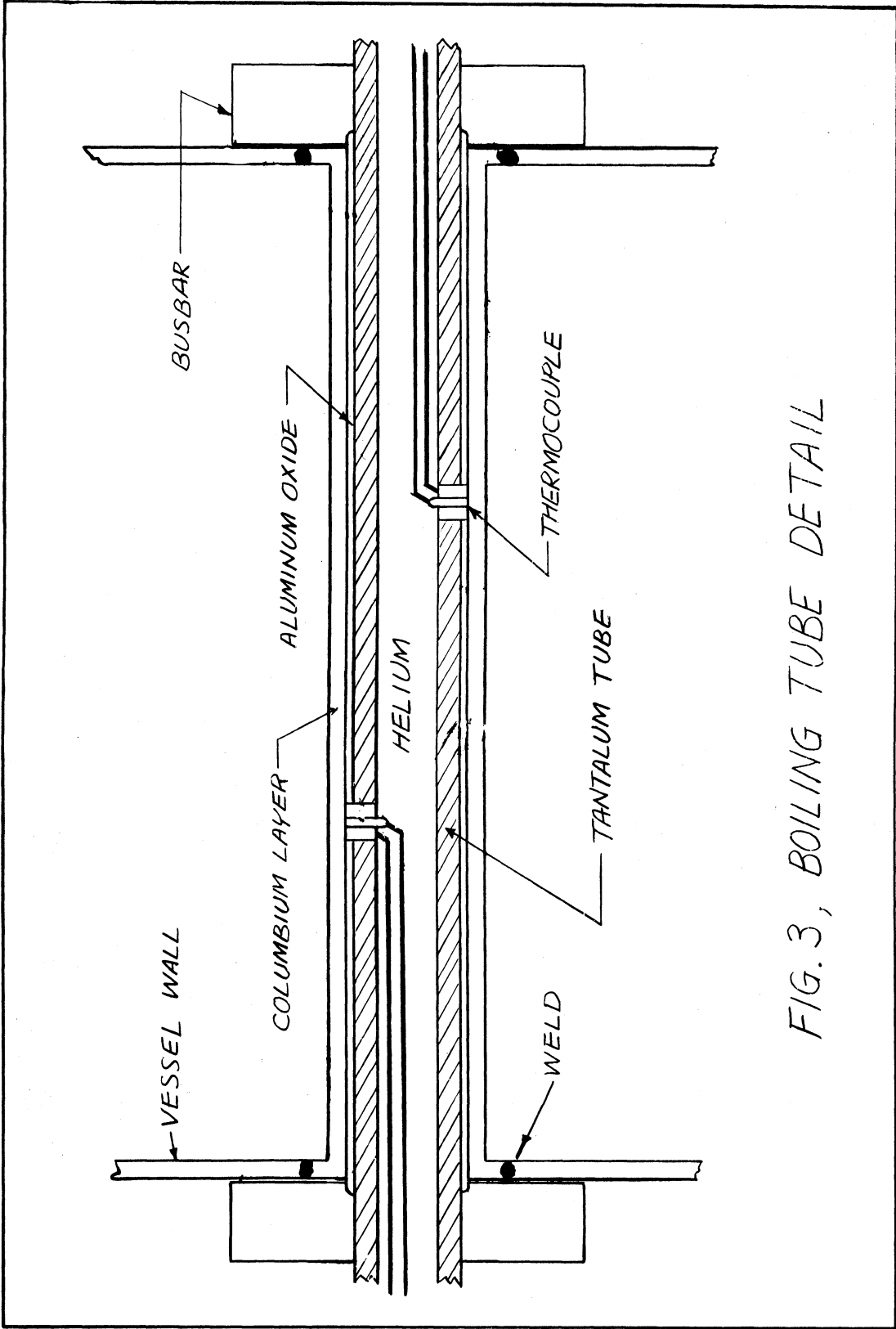


FIG. 3, BOILING TUBE DETAIL

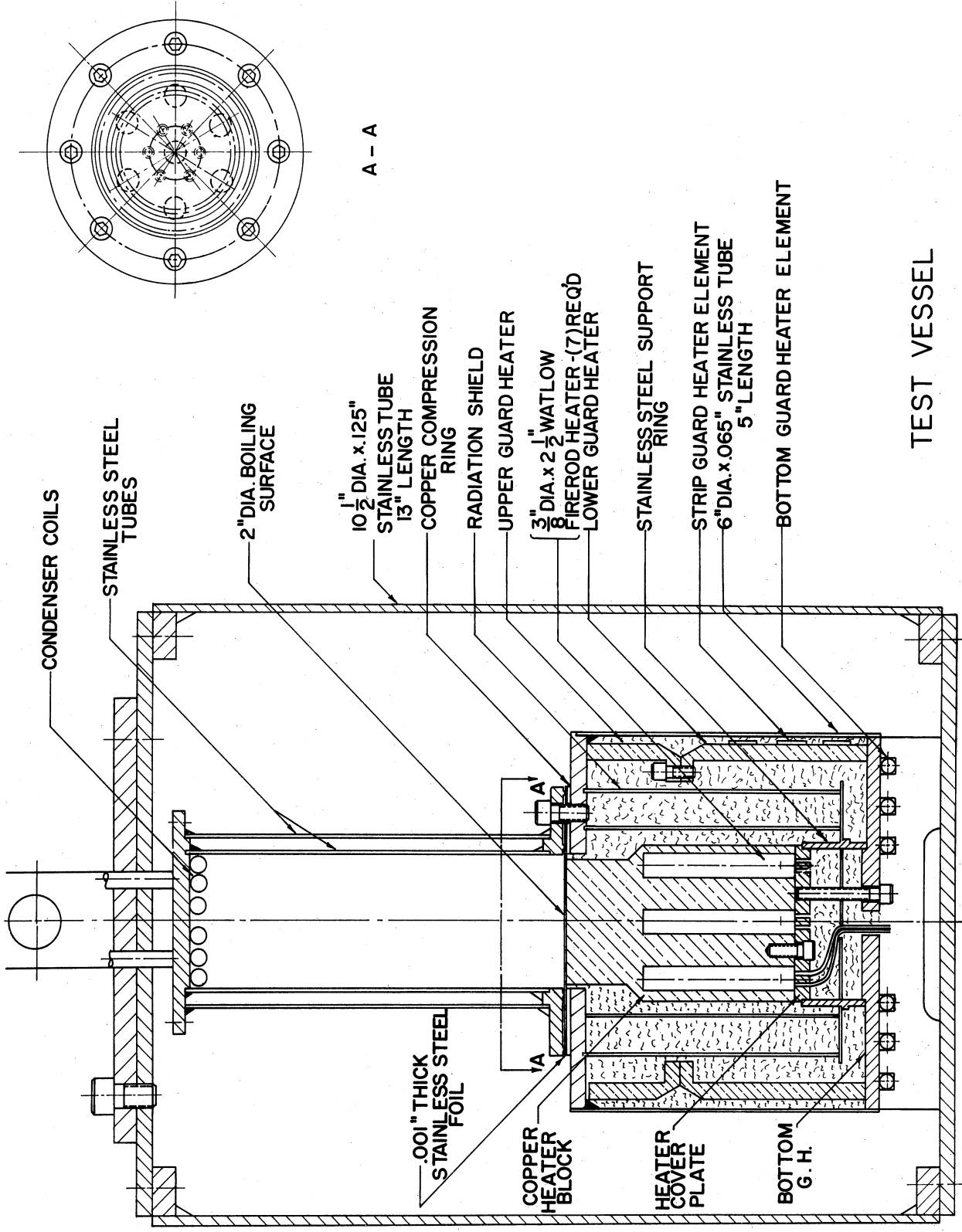


Fig. 4

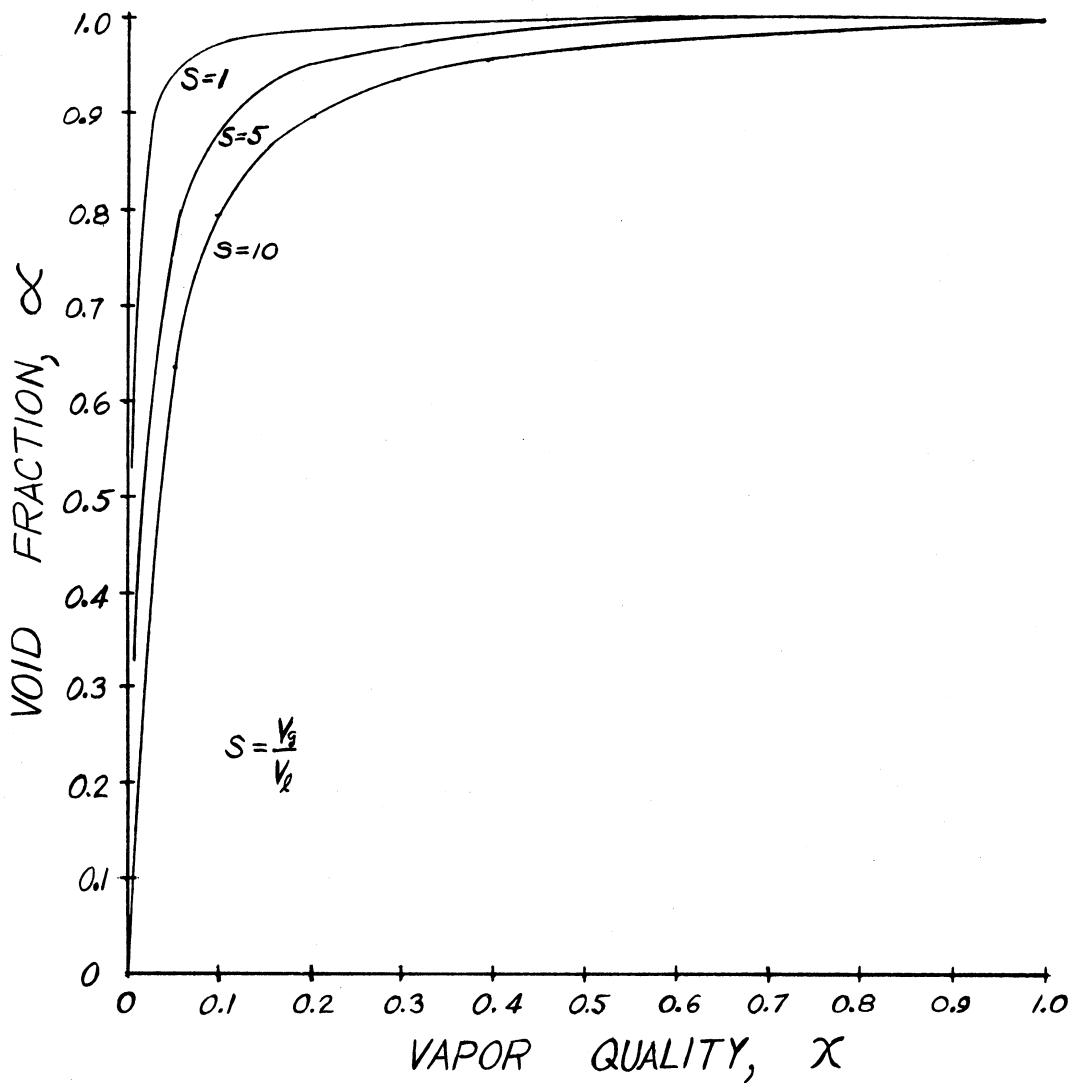


Fig. 5. Void fraction as a function of quality for various slip ratio parameters (calculated from potassium data at 1740°F using Equation (2)).

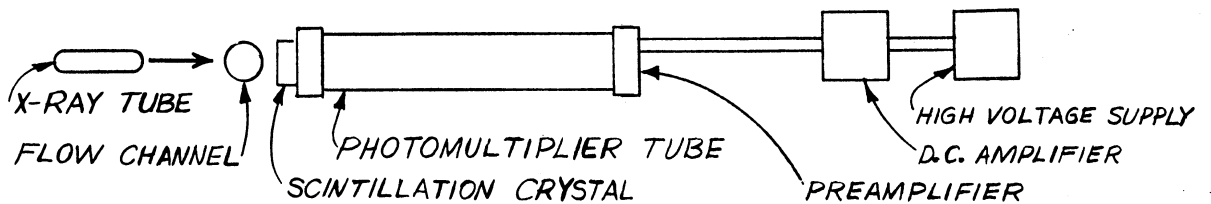


Fig. 6. Schematic diagram of void fraction measurement apparatus.

Fig. 7. Conceptual design of the forced-circulation liquid metal loop.

