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Department of Mechanical Engineering

Fourth 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, Katz, and Tek of the Chemical Engineering faculty and Professors Clark and Merte of Mechanical Engineering are participating in the program. Misters Barry, Colver, Padilla, and Smith, 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

Virtually all phases of the project have reached operational stages. The high flux nucleate pool boiler has been subjected to preliminary check out procedures during which water was pool boiled at fluxes from 20,000 to 500,000 Btu/(hr)(sq.ft.). The results checked well with previous data from a 3/8-in. OD tube. Thermocouple failures in the boiling tube have produced a temporary delay but it is anticipated that operation will commence again with liquid potassium within two weeks.

Construction of the film boiler is essentially complete and check out proceedings with water are expected to commence within the next week. It is expected that operation with liquid potassium will begin in mid March.

The liquid metal loop has just been received from Mine Safety Appliance. It will be housed in a new facility constructed by the University of Michigan for liquid metal research. Installation procedures are almost complete and preliminary check out is expected to begin next week. It is hoped that operation with potassium will be underway by the second week in March.

The agravic studies have been set back by a series of delays in the design and construction stages. It is expected that construction will be completed within three to four weeks and that operation will begin shortly after that. It is hoped that data from the initial runs will be available for the draft copy of the report to be prepared in late May.

Progress on the analytical studies of the film boiling process have progressed during the last reporting period. Preliminary results from this study are discussed in this report and calculated minimum fluxes for several alkali metals have been tabulated.

TABLE OF CONTENTS

Page

INTRODUCTION 1

POOL BOILING STUDIES 4

FILM BOILING 9

FORCED CIRCULATION STUDIES 15

TWO-PHASE FLOW STUDIES 25

LIQUID METAL BOILING IN AGRAVIC FIELDS 35

ANALYTICAL STUDIES OF THE TRANSITION AND FILM BOILING REGIMES 38

INTRODUCTION

Substantial progress has been realized during the period from August 1962 through the present time. Despite several serious procurement difficulties, all experimental equipment with the exception of the agravic apparatus has now been assembled and is in the preliminary check out stages. The University has also seen fit during this period to provide very adequately for our space requirements. University funds have been used to erect a 1000 foot laboratory on North Campus which is to be devoted exclusively to liquid metal research. Although the decision has already been made to house the two pieces of pool boiling equipment in the original laboratory in East Engineering Building, the liquid metal loop and all subsequent apparatus associated with this study will be located in the new facility.

The present schedule for operations calls for completion of the initial experimental program sometime during the month of May with the issuance of a draft copy of the final report on 31 May 1963. Evaluation of the individual phases of our program with reference to that timetable is as follows.

The high flux nucleate pool boiling study has proceeded to the liquid metal stage. Preliminary check out runs have been made using water with satisfactory results. Potassium has been charged to the vessel but operation has been delayed for the last month because of thermocouple failures in the boiling tube. This problem seems to have been corrected and operation is expected to commence again within two weeks.

The film boiling study incurred a lengthy delay arising from procurement problems in connection with the fabrication of the columbium boiling tube. These problems were finally solved and the vessel was received in January 1963. Since that time the apparatus has been assembled and is currently ready for preliminary checkout proceedings. Non-metallic fluids will be inserted initially to familiarize operating personnel with equipment characteristics and to provide an evaluation of the alternate procedures for obtaining film boiling. Equally important is the fact that determination of the significance of edge effects is required because of the one-in. diameter disc from which the potassium will be boiled. These preliminary runs with water should provide the necessary comparisons with other film boiling data to determine the correction factor necessary (if any) to interpret the potassium data which will be obtained in this apparatus. It is expected that this preliminary phase will be completed within two weeks and that liquid potassium will be charged by the middle of March. Barring further unanticipated difficulties, a substantial amount of data should have been collected by the end of April. Analysis of the data will then be undertaken in preparation for the final report.

The forced circulation apparatus has been subject to a number of delays. Initially the October 31 delivery agreed to by MSA in the subcontract had to be moved back to December 1962 because of simultaneous difficulties in procurement by MSA as well as the space problem that had arisen at the University. This delivery date was further delayed because of unexpected difficulties on the part of the subcontractor as well as the delinquency of Taylor Instrument Company in supplying the differential pressure gauge. It was finally necessary to ship the loop to the University without the differential pressure gauge in order to avoid further delays.

Subsequent to the arrival of the loop, Taylor Instruments succeeded in providing us with the gauge which has been welded to the loop during the past week. Installation proceedings are continuing and it is hoped that the facility will be ready for check out operations within a week. An optimistic forecast anticipates operation with liquid potassium by the second week in March. Several weeks will be required to perform the necessary calibrations and determine the essential coefficients for the heat transfer operations prior to initiating the boiling runs. It thus appears as though boiling data should not be forthcoming much before the beginning of April. It is assumed that experimental runs will be initiated as soon as possible and will continue while the preliminary draft of the report is in preparation. It is hoped that adequate data will have been taken prior to mid May to permit a satisfactory evaluation of forced convection boiling for the May 31 report.

Two phase flow studies will be conducted simultaneously with the loop studies described above, but the final results will not be forthcoming until sometime later in the year. This delay has arisen because of the necessity of calibrating the radiation attenuation method of determining void fractions. A program has been designed to parallel the liquid metal program of the loop with a similar program using water-air as the two phase system and simultaneously determining hold up by radiation attenuation methods coupled with the use of quick closing valves.

Difficulties in the design as well as fabrication of the agravic vessel have delayed its completion until early April. It is still hoped that data from preliminary runs will be available for inclusion in the preliminary draft of the report scheduled for late May.

Progress has been made on the analytical studies of the boiling processes. Discussion of the efforts in the area of film boiling are included in this report. It is expected that this analysis will produce a model which accounts for the behavior exhibited in the transitional regime as well. Further work must be done in the nucleate boiling regime and particularly in the region of the critical flux. Calculated minimum fluxes in the stable film boiling regime are tabulated in this report.

A more complete discussion of each of these phases follows in subsequent sections of the report.

POOL BOILING STUDIES

C. Phillip Colver

A. Equipment Modification

Fabrication of the experimental apparatus, as described in the Third Quarterly Report, was completed in late October. Except for the boiling tube, the experimental equipment, as constructed, required no alterations from that presented in the earlier report. It was not until September that a satisfactory method was found for fabricating the boiling tube. This difficulty has been the basic cause for the delays incurred to date.

At the time of the Third Quarterly Report, it was hoped that a thermocouple well could be made in the boiling tube wall by the Elox method. However, it was found that drilling a 0.030-in. diameter hole approximately 2 inches long in the tube wall was not feasible. Later, preliminary tests indicated that a swaged thermocouple, 0.032 in. diameter, could be successfully brazed into a groove on the outer surface of the boiling tube. This method proved satisfactory for the first tube used, but in subsequent tubes, two out of the three thermocouples developed open circuits during the fabrication. Inasmuch as the thermocouples read correctly immediately after being brazed in the tube, the failure definitely occurred when the thermocouples protruding out of the vessel were bent upward to facilitate making connections.

It was decided that in order to be assured of 100% reliability in starting with three thermocouples per tube, the thermocouple assembly should not go through the brazing step. This being the case, it was decided to use 0.035-in. OD by 0.022-in. ID 304 stainless steel hypodetmic tubes, closed at one end, as thermocouple wells in the tube wall. This tube brazed into the groove would serve as a well into which a 0.020-in. diameter swaged thermocouple could be inserted. Thermocouples could then be inserted in place after the boiling tube had been screwed into the test vessel.

Discussions with Mr. R. C. Noyes of Atomics International revealed that boron nitride is far superior to plasma-sprayed alumina for insulating the heater for the boiling tube. This material has a longer life than alumina from an electrical breakdown point of view and has a thermal conductivity comparable to that of beryllium. It is readily machinable and its use eliminates the plasma spraying operation.

The anticipated use of boron nitride as the inuslating sheath around the heating element necessitated a re-evaluation of the other materials in the boiling tube. The compatability of boron nitride with Haynes-25 has not been studied experimentally but it can be observed that the principal metals in Haynes-25 do not form stable nitrides at the temperatures involved. It seemed doubtful that tantalum, which forms both a stable boride and nitride, could be used. Therefore a graphite resistor instead of tantalum was selected for the heating element. Another alteration in tube design is the method for obtaining the seal between the Swagelok fitting and boiling tube. Instead of swaging ferrules down on the tube, and possibly shorting out the thermocouple leads, it has been decided to use a Nicrobraze to make this seal. The braze presently used is AMS 4777. It exhibits excellent corrosion resistance in alkali metals and is conveniently torch brazed in our shops. Its operational temperature is limited to 1900°F which poses some difficulties in the program. It is hoped that a second braze with higher operating temperatures, now undergoing evaluation, will prove satisfactory.

A boiling tube, as described above, (see Figure 1) was fabricated and installed in the equipment. Preliminary testing of the equipment and instrumentation using water as the boiling liquid, was completed in mid January. A number of nucleate boiling runs using water at pressures in the range 1 atmosphere to 150 psig and with fluxes up to one half million Btu/(hr)(sq.ft.) were performed. The data compared well with the water data obtained by R. E. Lyons(1) who also obtained data from an electrically heated 3/8 in. diameter tube.

The water was removed from the test equipment and the system was heated to 200°F and outgassed for several days, to remove the last traces of water. The apparatus was then heated up to 1000°F and held for several hours.

Potassium was charged to the vessel in late January. The equipment was checked out and a preliminary boiling run attempted. During the heat-up, the last boiling tube thermocouple failed. Upon removal of the lower head (of the outer protection vessel) it was discovered that the thermocouple sheath had shorted out against the boiling tube bus bar. This failure necessitated installing a new tube.

Redesign and fabrication of the boiling tube resulted in a delay of approximately one month. Thermocouples for the modified design have been received and are ready for installation. Six boiling tubes are being machined and brazed in our department shops and should be finished and installed in the equipment within a week.

B. Determination of Heat Flux and Surface Temperature

The Third Quarterly Report discussed the calculations necessary to determine the boiling curve. It was stated that the heat flux would be determined by measuring the total power to the boiling tube circuit and then subtracting losses in portions of the circuit external to the tube. This requires a knowledge of the resistivities of all components of circuit between the voltage taps used in computing the power. Contact resistances which must also be considered in this evaluation lead to some uncertainty in the predictions.

A second possibility also exists if the resistance of the graphite is accurately known. The I^2R dissipation can then be calculated directly and end losses deducted. The combined error arising from uncertainties in the temperature coefficient of resistivity and the temperature distribution in the graphite leads to some uncertainty in this determination also.

For the water runs, a comparison was made of the heat flux calculated by the two methods. The water was boiled with fluxes in the range

20,000 to 500,000 Btu/(hr)(sq.ft.) and at pressures ranging from one atmosphere to 150 psig. The maximum difference between the heat fluxes calculated by these two methods was less than 10 per cent. It is probable that the major factors contributing to these differences were the contact resistances and the values used for the electrical resistivity.

There has been some concern as to the extent of end effects in the boiling tube, particularly since the L/D for the graphite heating element is only about 3. (In previous investigations using electrically heated boiling tubes, the tubes were long enough so that end effects could safely be assumed negligible.) It is seen from Figure 1 that the heat generated in the graphite element is transferred not only to the boiling surface but from both ends of the tube.

The analytical solution for determining these heat losses from the ends of the graphite element is very difficult and requires the use of a computer to determine even estimated values. It is, however, possible by simplifying the problem and placing adverse values on the boundary conditions and certain temperatures in the graphite element, to obtain a maximum value for the end heat losses. The maximum total end heat loss, calculated in this way was found to be about 15% of the total power input.

The surface temperature is determined by extrapolating a temperature reading from a thermocouple approximately 0.015-in. from the surface knowing the thermal conductivity of Haynes-25 and the flux. Determining the surface temperature in this way requires that the heat flux must be known to sufficient accuracy and the position of the thermocouple in the tube must be known to a high degree of accuracy. An error of 0.001-in. in the thermocouple depth for a flux of one million Btu/hr(sq.ft.) would result in a 10°F error in the surface temperature. A 10% error in the heat flux at one million Btu/(hr)(sq.ft.) would produce an error of 15°F in the surface temperature.

The thermocouple depth in the boiling tube is estimated during fabrication. After the tube has operated and burned out it is removed from the vessel and sectioned to determine precisely the position of the thermocouple relative to the surface. This final measurement yields a precision of ±0.0001-in. or ±1°F in the above example

FILM BOILING

Andrew Padilla, Jr.

Introduction

This phase of the project is concerned with the film boiling of liquid metals. Specifically, potassium will be studied between 1400°F and 1800°F when boiling above a 1-in. diameter horizontal plate.

The two previous quarterly reports have outlined in general terms the apparatus to be used. The assembly of the experimental system is essentially complete and is currently being check out and evaluated using water in place of potassium. These runs are intended to assess the feasibility of obtaining film boiling by the two techniques descirbed earlier as well as provide some information as to the significance of edge effects under these conditions. The latter evaluation will be made by comparing the results with those of Hosler and Westwater. Liquid metal data should be taken during the month of April.

Experimental Apparatus

A detailed description of the experimental system will be presented because a number of changes have been incorporated in the design since the last quarterly report. A schematic diagram of the complete apparatus is shown in Figure 2. Figures 3, 4, 5, and 6 are details of the tube assembly, boiling plate, top flange connections, and temperature measuring circuit respectively.

Tube Assembly

The tube assembly is a composite Cb-1 Zr/Haynes-25 assembly 4 feet $2\frac{1}{2}$ inches long. The assembly was fabricated by the Space Power and Propulsion section of the General Electric Company. The Cb-1 Zr sections above and below the boiling plate section were machined from 0.150-in. wall to 0.060-in. wall near the boiling plate. The 6-in. section of smaller tubing at the bottom is designed to lower the temperature before the transition to the stainless steel. The relatively long condensing of Haynes-25 tubing at the top will radiate to the walls of the containing vessel before passing through the supporting flange. Water coils are tacked onto the 6-in. section which extends above the flange and can be used if radiation proves inadequate in maintaining reasonable temperatures in the vicinity of the flange.

Boiling Plate

Heat is transferred to the boiling potassium by sodium condensing on the bottom of the Cb-1 Zr boiling plate. The boiling plate was machined from solid stock 1.10-in. diameter and 2-in. long. The tube wall extending above and below the plate is 0.060-in. thick, giving a boiling and condensing surface 0.98-in. diameter. The plate is

196.5 mils thick and contains eight 21 mil thermocouple holes at 3 distances below the boiling surface and at two different radii. Thermocouple positions were determined to within 2 mils relative to the top surface. Both surfaces of the boiling plate were mechanically polished and photographed prior to fabrications.

Heater Assembly

A radiation heater for the sodium boiler has been fabricated in place of the resistance heating technique described in earlier reports. The heater is made out of two $2\frac{1}{2}$-in. by 4-in. sections of 3 mil tantalum foil formed into two half cylinders. Tantalum strips $\frac{1}{2}$-in. wide by 30 mils thick were used for holding the foil in place at the top and the bottom. The result is a split cylinder 4-in. long and approximately 2-in. diameter around the 1.1-in. diameter boiling tube.

Current passes from the copper bus bar through the tantalum leads to the foil, connected in series, and back through tantalum lead to the other busbar. The energy dissipated in the foil is radiated to the sodium boiler. Outward heat losses are reduced by three concentric stainless steel radiation shields with Fiberfax insulation between them.

A guard heater above the boiling plate will be used to reduce the axial conduction up the walls of the boiling chamber. This should also serve to decrease the radial variation in the boiling plate temperature. This heater consists of molybdenum wire wrapped around an Alundum core. Two of the three radiation shields will extend around this heater.

Outer Vessel and Auxiliary Lines

The entire boiling assembly is enclosed within an 8-in. stainless steel pipe with stainless steel flanges at the top and bottom. The tube assembly is supported by the top flange through which all electrical and thermocouple leads pass. The four Conax thermocouple glands provide flexibility in electrical and thermocouple connections. At present, they are packed for handling the leads from 12 thermocouples and 5 guard heaters. Besides the guard heater above the boiling plate, heating tapes will be used around the filling lines.

No water is used within the stainless steel vessel so these leads have been removed. The boiling tube radiates to the walls of the containing vessel which may be water cooled if necessary.

The copper bus bars inside the vessel are connected to copper tongues on the outside by $1\frac{1}{4}$-in. diameter copper rods which are electrically insulated from the flange by lava glands using silicon rubber O-rings. The cables to the 12 KVA rectifier will be bolted to the copper tongues.

Instrumentation

The temperature of the boiling potassium will be measured from a thermowell extending down from the top of the tube assembly and that of the condensing sodium from a thermowell extending up from the bottom of the tube assembly. These readings plus the eight to be made within the boiling plate constitute the critical temperature measurements. These 8 thermocouples and their spares will be calibrated after the preliminary runs currently in process in an electric furnace. These readings will be continuously monitored on a 12-point recording potentiometer along with other control points. When steady-state conditions are achieved, two 8-point switches will be used to measure the emf's on an L & N No. 8662 portable potentiometer. The switching circuit allows any two of the eight thermocouples to be bucked, thereby obtaining differential temperature. Absolute temperatures can also be measured by bucking against the thermocouple in the ice bath. A continuous single-point recording potentiometer is available and will be used with the switching circuit if large fluctuations in temperature occur at steady-state conditions.

The pressure of the potassium, boiling under a blanket of helium, will be measured with a mercury manometer. A standard Bourdon-type gauge will be used for pressure measurement in the stainless steel vessel.

Experimental Procedure

The same filling vessel will be used for charging the sodium and the potassium. It will charged in a glove box under inert gas atmosphere. Solid sodium will be cut, weighed, and inserted into the stainless steel charge vessel, which is then sealed with a flange. After connecting the vessel to the filling line, the boiling chamber is evacuated, purged with helium, and re-evacuated. The charge vessel and filling lines are then heated above the melting point of sodium. The evacuating line is closed, the valve on the charge vessel is opened and the liquid sodium forced into the boiling chamber. The valve on the charging line is closed and the vessel disconnected and cleaned.

The potassium is charged by the same procedure but the vessel remains on the filling line. Substantially all of the potassium can be removed from the boiling chamber by pressurizing the chamber to force the liquid up the filling line into the top of the charge vessel. The remaining portion would have to be sucked out by reducing the pressure in the filling system and boiling out the potassium.

During a run, the power from the rectifier will be set at the desired level and the system allowed to reach steady-state conditions. The radial variation in the boiling plate will be checked by bucking the thermocouples at different radii and adjusting the guard heater above the boiling plate. The pressure in the boiling chamber and the temperatures of the sodium, potassium and boiling plate are taken. The power to the rectifier is then reset and the system allowed to readjust before taking another series of readings.

Nucleate boiling data will be obtained initially and the system pressure reduced to see if stable film boiling can be achieved by passing over the critical flux and through the transitional regime. This data will supplement high flux data from the nucleate pool boiler. It is hoped that the entire boiling curve can be produced and studied with this apparatus. A maximum flux of 500,000 Btu/(hr)(sq.ft.) might be reasonable which would make the aforementioned goal realistic at low pressures.

Calculations

The temperature measurements will allow the vertical and radial temperature profiles in the plate to be determined. These profiles will be extrapolated to determine the temperatures of the boiling and condensing surfaces. The heat flux will be calculated from the equation

$$q/A = -K \frac{dT}{dX}$$

where q/A = heat flux (Btu/hr-ft^2)

k = thermal conductivity of Cb-1 Zr (Btu/ft-hr-°F)

$\frac{dT}{dX}$ = temperature profile across boiling plate (°F/ft)

The boiling curve is obtained by plotting values of q/A vs the corresponding values of ΔT_b $\left(T \text{ (potassium)} - T \text{ (boiling surface)}\right)$.

Condensing coefficients for the sodium are calculated from the equation

$$h_c = \frac{q/A}{\Delta T_c}$$

where h_c = condensing coefficient, (Btu/hr-ft^2-°F)

ΔT_c = T (sodium) - T (condensing surface), °F.

FORCED CIRCULATION STUDIES

R. E. Barry

Status of the Forced Circulation Loop

During this reporting period it was decided to house the forced circulation loop in a separate building provided by the University of Michigan. Construction began in November 1962 and it is now ready for occupancy. The 25 by 40 foot building is constructed of cinder blocks on a slab foundation and contains a 14 by 25 foot bay, 17 feet high, a control room, a storage room and a room for pool boiling experiments. The electrical circuit has a capacity of 400 amperes at 240 v. Air, water and gas are also available.

MSA Research Corporation recently completed the construction of the loop and it was installed in the building on February 14. The loop is installed on a $7\frac{1}{2}$ by $7\frac{1}{2}$ by $12\frac{1}{2}$ foot steel framework to which hinged sheet steel plates are attached, enclosing the loop on all faces except the top. The electric and pneumatic lines are brought out to a terminal box. The necessary connections from the control panel to the loop are being made and the equipment checked out. A flow schematic is shown in Figure 7.

R. T. Brokaw Engineering Company delivered the control panel in January. The power circuits are capable of delivering 30 KVA to the preheater, 15 KVA to the sodium boiler and 7 KVA to the electromagnetic pump. In addition, there are 14 circuits provided for warm-up heaters on the lines, and circuits for the condenser and subcooler air blowers. The control circuits consist of sensor-relay-contactor combinations which, for high preheater wall temperature, cut off the preheater; for high sodium boiler wall temperature, cut off the boiler; for high condenser exhaust temperature (indicating insufficient air flow) or for high loop pressure, cut off the preheater, boiler and pump. In addition, there is a scram button which cuts off all power and dumps the contents of the sodium loop and the potassium loop. The condenser air supply is automatically controlled by the loop pressure and the subcooler air supply is manually controlled. The measuring circuits consist of wattmeters and voltmeters to determine the power input, a 48 point temperature recorder for operation, a pressure and temperature recorder and a potentiometer circuit using platinum/platinum-rhodium thermocouples to determine heat transfer parameters.

Taylor Instrument Company has delivered the differential pressure transmitter during the past week. It has been welded on at the University rather than at MSA as was originally planned because of the late delivery. If no leaks are found in the loop under a vacuum test, it is expected that installation will be completed by March 8 and charging of the loop will take place within a week.

Initial Operation

Once the loop is charged with sodium and potassium, circulation will be initiated at low temperatues (@ 500°F) under inert gas pressure.

The potassium will then be gradually heated by the preheater with the sodium vapor temperature maintained to within 25°F of the potassium temperature. As the potassium is heated, an independent calibration of the electromagnetic flowmeter can be made by running a heat balance over the preheat section. The power delivered to the fluid will be determined by measuring the power input to the preheaters and deducting the losses. Measurement of bulk temperatures entering and leaving the preheater permits the flow rate to be determined for a particular millivolt signal from the flowmeter. The losses can be calculated from the existing correlations for heat transfer from vertical surfaces. (Temperatures will be measured at these surfaces.)

The next phase of the program will be to determine the sodium condensing coefficient. This is necessary in order to determine the heat transfer characteristics of the boiling potassium in later phases of the work. The condensing coefficients will be evaluated initially by measurement of the heat flux, the mean temperature difference and an analytical solution for the film coefficient of liquid potassium flowing inside the tube. The flux will be varied over a hundred fold range. The determination of the condensing coefficient is covered in more detail in the section on heat transfer.

Once these studies are completed, the loop will be evacuated and the boiling heat transfer runs begun. At a particular heat input, temperature and pressure, the potassium quality will be varied by charging the flow rate. As data is gathered, it will be possible to determine the heat transfer characteristics as a function of heat flux, flow rate, quality and physical properties. During these runs, studies will be made on pressure drop in horizontal two-phase flow.

Control

The operating conditions in the test section can be classified into three flow regimes, namely all liquid, liquid plus vapor, and all vapor. Each of these regions will require a different mode of control, so that stable operation can be achieved with a minimum of time taken between data points.

Control in the liquid region will require that an inert gas blanket be present over the liquid in the hot well. Pressure will be maintained by a bleeder type regulator that bleeds a small amount (about 0.1 cfm) of inert gas into the atmosphere, thus preventing the pressure build up due to expansion that would occur if a non-bleed pressure regulator were used. The liquid entering the pump will be subcooled at least 200°F to avoid any possibility of cavitation in the pump. It will then be heated in the preheater and test section to conditions approaching the saturation temperature. A thermocouple at the exit of the test section will control temperature by adjusting louvre position of the condenser. The subcooler may or may not be operating during this phase, depending on total power input. It should be noted that full power can be applied to the loop without the occurrence of vaporization if the pump is operated near its maximum flow rate ($4\frac{1}{2}$ gpm) and/or if the loop is operated near 1800°F.

Control in the region of two phase operation may be accomplished either through temperature or pressure signals, since either one determines the other at equilibrium conditions. Control via the pressure signal will introduce virtually no time lag from the moment of pressure change until the louvre positions changes. However, flow instability may introduce a great deal of noise into the control system unless the air pressure signal to the controller is dampened by a flow restrictor or capacity tank. If control via the temperature signal is used, a thermal time lag will be introduced but noise will not be a problem. Sufficient versatility in the design of the instrumentation will be allowed so that either method of control can be chosen by a slight alteration behind the control panel. At present it would appear that the control through the pressure signal is preferred.

Ordinarily a series of data points will be taken before the power input to the preheaters is changed. This will minimize the time required to achieve thermal equilibrium in the heaters and surrounding insulation. Under these conditions the temperature in the loop will rise until it reaches the point where the condenser and subcooler can dissipate the heat input. Now since the air film coefficient is much smaller than the condensing coefficient or the tube wall coefficient, the temperature at which the heat input can be dissipated is dictated almost entirely by the air flow. It would seem at first sign, then, that a given air flow across the condenser corresponds to a certain definite temperature and pressure in the loop. This would indeed be the case if it were not for the effect of pressure drop between the test section and condenser. Although a constant air flow rate maintains a constant pressure and temperature *in the condenser* the change in pressure drop due to a change in potassium flow rate will cause a different pressure *in the test section*, which is, of course, our primary area of interest. It follows then that under conditions of constant power input and varying flow conditions, the pressure controller functions as a trimmer to compensate for varying pressure drops. The controller will also allow one to set definite pressures at which data is to be taken, rather than set pressures by a trial and error manual procedure. As pointed out in previous reports, the pressure drop through one-half inch ID tubing may reach 4 psi per foot so it can be seen that the pressure drop cited above is not insignificant and that manual control of test section pressure would be tedious.

It has also been brought out in our investigations that in regions of low quality a decrease in flow at constant power input may result in an <u>increase</u> in pressure drop through the loop. This rather anomalous behavior should present no particular problem. Let us for example suppose that we are in this particular region of anomalous behavior and that we cut the power to the pump by an amount that would ordinarily cut the flow rate in half. Now the pressure drop will <u>increase</u> at this decreased flow. Bearing in mind that the EM pump has flow characteristics similar to those of a centrifugal pump, we see that the pump can no longer support the head required at half the previous flow. An increase in head at constant power to the pump can be achieved only by going to a still lower flow rate at which the pump can develop a higher head to meet the required pressure drop conditions. In this example then, we might achieve one quarter of the initial flow when we would have expected to see one half of the initial flow. Thus the region of anomalous pressure behavior presents no problem other than making it difficult to predict what the flow rate will be when the pump power is changed by a given amount (in actual operation, the throttling valve will be changed rather than the pump power but the result from a control standpoint is the same as if pump power were changed.) Because of this difficulty the flow rate will be a "floating data point" since its value cannot be predicted in advance from a given pump power.

The discussion up to this point has assumed that the louvre position on the subcooler has remained unchanged while the pressure controller takes action on the condenser louvre. To determine the total effect of condenser and subcooler air flow rates, let us consider an example in which the pressure controller increases the air flow rate while power input remains constant. Since the heat balance must be satisfied for all steady state conditions a lower average temperature (around the condenser and the subcooler) will be established to compensate for this increase in total air flow rate. The temperature leaving the subcooler will then be lowered because of this pressure trimming adjustment, as will the temperature entering the preheaters. This in turn, will lower the quality of the two phase mixture emerging from the preheater. Quality is therefore a second floating data point, since the trimming action of the pressure controller makes it impossible to predict the quality change in advance of a flow change. One could circumvent this problem by adjusting the subcooler position to compensate for the change in condenser louvre position. In practice, however, this compensatory action would again be more tedious than necessary.

Operation with saturated vapor in the test section will require that quite a different control scheme be utilized; and it would also be expected that some superheating of the vapor will occur. This superheat gives rise to an extra degree of freedom in the system so that one additional variable will have to be controlled (either manually or automatically). One possibility is to control the condensing temperature via the air flow rate and at the same time control the temperature in the test section via the power to the preheaters. If this is done manually, it will require several trials and long periods of time before a steady-state data point can be taken.

Control of the secondary sodium loop is entirely manual, the only adjustment being the power supplied to the secondary loop. This control mode arose largely out of budgetary considerations and will entail some additional labor in the operation of the loop but should present no great difficulties. The temperature of the secondary loop is again dictated by the value at which the power input can be dissipated to the surroundings and to the flowing potassium in the primary loop. If heat transfer to the potassium should be interupted or decreased because of the onset of film boiling or lowered potassium flow, the temperature will rise at a calculated maximum rate of 120 degrees per minute. If the excursion is not caught by the operator, temperature safeguards will shut down power to the test section.

Heat Transfer

Nusselt's analysis of laminar film condensation on a vertical surface(2) has been verified by a number of investigators for fluids with Prandtl moduli close to unity. In 1959, Sparrow(3) examined condensation from the viewpoint of boundary layer theory and demonstrated that for fluids with very low Prandtl moduli, acceleration effects in the film would reduce the coefficient below that predicted by Nusselt. Further extensions of this viewpoint considered the effect of shear stress(4) and the effect of non-condensible gases.(5)

However, aside from some scattered data at very low fluxes, the only experimental values for sodium to date are due to Bonilla(6) who reported condensing coefficients inside tubes of around 13,000 Btu/(hr)(sq.ft.)°F at temperature difference of around 7°F. Nusselt's theory would have predicted a coefficient of 80,000 for this temperature difference. The range of data does not permit extrapolation with confidence although later work(7) with other liquid metals indicates that the coefficient drops at higher temperature differences. Therefore, it is desirable that the sodium condensing coefficients be determined experimentally.

From a knowledge of the heat flux and the mean temperature difference between the sodium vapor and the potassium liquid, one can determine an overall heat transfer coefficient from:

$$\frac{1}{U} = \frac{1}{h_c} + \frac{t}{k} + \frac{1}{h_f}$$

where U = overall coefficient

h_c = condensing coefficient

t = wall thickness in test section

k = wall conductivity

h_f = potassium film coefficient

It would be useful if we were able to measure a wall temperature and hence the film temperature drop, but the use of a sheathed thermocouple in a .010-in. wall is impractical. (Figure 8 shows the test section.) Therefore it must be backed out of the relation from a knowledge of h_f. (The thin wall was necessitated by the high fluxes desired and the operating limits of Haynes-25.) The available experimental data on potassium film coefficients are applicable to regions where the temperature profile is fully developed. Such a profile will not exist in the 2-in. test section. (The length of the test section was limited by power requirements for a flux of one million.) However, there are analytical methods for the determination of the film coefficient. Poppendick and Harrison(8) have analyzed the heat transfer to liquid metals in an entrance region by assuming that axial conduction was negligible. Deissler,(9) using a mixing length analysis chose the ratio of thermal to eddy diffusivity to be unity and solved the resulting boundary layer equations. However, there is reason to believe that the ratio is a function of the Peclet modulus. Although there are differences in viewpoint, an analytical solution for the film coefficient is reasonable to use as a base point.

The data gathered in this phase of the program will also serve to get an independent value of the condensing coefficient if the reasonable assumption is made that the heat flux does not affect the potassium velocity profile and hence the film coefficient. In the range of 1400 to 1800°F, the pertinent physical properties of potassium vary little. After the boiling studies are well underway, it appears feasible to get a third measure of the condensing coefficient by a study of transients. This program is still under study.

The platinum/platinum-rhodium thermocouples to be used in the heat transfer studies have been calibrated up to 1900°F against a secondary standard calibrated by the Bureau of Standards. They were calibrated using the same lead wire as will be connected to the loop.

TWO-PHASE FLOW STUDIES

Lowell R. Smith

Since the Third Quarterly Progress Report, activities in this area can be summarized as follows:

(1) Completion of the two-phase simulation study for predicting some types of instability in the test loop.

(2) A brief examination of two-phase sonic choking in order to better define the loop's operating limits.

(3) Completion of the design of the gamma-ray attenuation equipment for measuring void fractions.

(4) Proposal of a set of experiments for calibrating the attenuation of gamma-rays through flowing systems.

Each of these areas will now be recapitulated.

A. Completion of Two-Phase Simulation Study

For details of this program one is referred to pages 18-23 of the Third Quarterly Progress Report and to the subsequent completion report of August 13, 1962.

In considering the operation of the test loop it seemed likely that instability problems might arise due to the merging of three two-phase streams from the preheaters and also because of the rather abrupt reduction in flow cross-section in the funnelling section. In order to predict whether instabilities might occur, a series of air-water experiments was performed at room temperature in a plexiglass mock-up of the loop's preheater, merging, and funnelling sections.

The description and layout of the basic apparatus are given in the Third Quarterly Progress Report. Experimental observations were made of the two-phase flow patterns which occurred in the 0.5-in. line following the funnel. The flow patterns were obtained visually under pseudo-steady flow conditions for various combinations of air and water flow rates. Although flow pattern is only a rough measure of stability, it was believed that these studies would most quickly furnish conclusions relative to the loop's final design. (To undertake a study of the true hydraulic instabilities possible in such a system as this would demand a far more elaborate experimental system in order to account for the necessary variables.)

The experimental results were obtained using a total of nine modifications (Configurations I - IX) of the basic system shown in Figure 9 of the Third Quarterly Progress Report. The modifications were made around two different cones, each having the same base ($3\frac{1}{2}$-in ID) but one being nearly twice as high as the other (8-in. as against $4\frac{1}{2}$-in.).

The first set of experiments was made with the shorter cone, using the following modifications:

Configuration I	Plain cone; vertical preheater; flow entering merging section about 30° from horizontal.
Configuration II	Same as Configuration I, but with a screen placed at base of cone.
Configuration III	Same as Configuration I, but with a screen placed 3 inches from cone vertex.
Configuration IV	Cone-screen assembly as in Configuration III; Horizontal preheaters; flow entering merging section about 5° from horizontal.

The second set of experiments was made with the longer cone, using the following modifications:

Configuration V	Plain cone; horizontal preheaters; flow entering merging section about 5° from horizontal.
Configuration VI	Same as Configuration V, but with a screen placed $5\frac{1}{2}$ inches from cone vertex. (Corresponds to Configuration IV.)
Configuration VII	Cone-screen assembly as in Configuration VI; Vertical preheaters; flow entering merging section about 30° from horizontal. (Corresponds to Configuration III.)
Configuration VIII	Preheaters and merging section entrance as in Configuration VII; plug of steel wool at cone vertex.
Configuration IX	Cone-screen assembly as in Configurations VI and VII; vertical preheaters; flow entering merging section horizontally.

The results were reported as regions of existence of the various flow regimes on a plot of air flow rate vs. water flow rate. These results, together with other aspects of the study, are discussed at length in the two reports mentioned previously. From the experiments with the nine configurations, the following conclusions and recommendations were made:

1. A screen is definitely a desirable component in the funnel. It is concluded that such a homogenizing device is helpful in maintaining stable operation. However, the one case studied revealed that the use of steel wool is unsuitable.

2. The longer cone gave smoother operation, and it is recommended that an 8-inch long cone be used in the loop's merging section.

3. Operation with vertical preheaters is superior to operation with horizontal preheaters.

4. The screen may be placed either at the funnel mouth or inside the cone. Positioning it $2\frac{1}{2}$ inches from the funnel mouth is recommended, based on satisfactory test results. Placing it very near the cone apex is to be avoided.

5. The position of the cone in the merging section appeared to have no effect on operation of the apparatus. However, tests of this effect were not exhaustive. It is recommended, therefore, that the funnel position used be that employed in the experiments: cone mouth 6 inches from the inlet coming from the preheaters.

6. Horizontal entrance of the two-phase mixture from the preheaters to the merging section appears to offer no advantage over a slanted entry. It would seem that tangential entrance might be of distinct advantage, although this effect has not been investigated.

7. The flow regimes observed in the simulation apparatus do not coincide with those established by other investigators. Funnelling the flow evidently affects the mapping of flow patterns. Designers should make only cautious use of previously determined flow regime graphs.

B. Critical Flow Considerations

Considering again the operation of the test loop, the upper operating limits in terms of quality and liquid flow rate through the pump could be set by the occurrence of sonic choking rather than by the heat input rate. In order to better estimate the loop's operating limits, a prediction was made of the conditions under which critical flow might occur. The details of this work were presented in the August, 1962, Monthly Progress Report. The results will be summarized here.

Critical flow occurs when the velocity of the fluid equals the speed at which sound is propagated through the fluid. Single-phase critical flow can be predicted, but none of the existing approaches for predicting two-phase critical flow can be considered wholly reliable. In flow through a given passage the occurrence of critical flow is that of "sonic choking"-- i.e., the condition of limiting mass flow rate. Despite the inadequacies of the available methods for treating two-phase critical flow, the predictions given here at least furnish an estimate of the loop's limitations.

The predication method is based upon a thermodynamic analysis given by H. B. Karplus.(10) In deriving the expression for the velocity of sound in a two-phase mixture, the following assumptions were made:

(1) That the misture is at instantaneous equilibrium throughout.

(2) That the sound waves are of small amplitude, thus propagating isentropically.

Beginning with the well-known expression

$$C^2 = \left(\frac{\partial P}{\partial \rho}\right)_s \tag{1}$$

where C = velocity of sound

P = absolute pressure

ρ = density

s = specific entropy

the thermodynamic analysis produces the following equations for sonic velocity (under restriction of the assumptions above):

$$C = \frac{xV_e + V_L}{\left[-x\left(\frac{dV_e}{dP} - \frac{V_e}{S_e}\frac{dS_e}{dP}\right) - \frac{dV_L}{dP} + \frac{V_e}{S_e}\frac{dS_L}{dP}\right]^{1/2}} \qquad (2)$$

where V = specific volume = $1/\rho$

x = quality, wt fraction vapor in two-phase stream

Subscripts L refers to liquid

e refers to change upon evaporation.

Using the thermodynamic data for potassium given by Weatherford, et.al.,(11) Equation (2) was used to develop a plot of two-phase sonic velocity as a function of temperature at parametric values of mixture quality. These results were used to estimate the occurrence of sonic choking, under the following two additional assumptions:

(1) The flow mixture is homogeneous in the sense that the sonic velocities are valid over the entire tube cross section.

(2) The void fraction correlation of Lockhart and Martinelli is applicable.

The limiting mass flow rate is given as

$$W_T = A\,C\left[(1-\alpha)\,\rho_L + \alpha\rho_G\right] \qquad (3)$$

where W_T = limiting mass flow rate

A = tube cross sectional area

α = void fraction

G refers to vapor

The α values were obtained from the Lockhard-Martinelli correlation. The limiting mass flow was finally based on the gpm of 1400°F liquid potassium issuing from the pump, which can be as high as 4 gpm. The estimate revealed that sonic choking probably will limit the loop only at qualities above 94%. Figure 9 shows the predicted choke conditions as related to loop operation ($\frac{1}{2}$-in. ID tube). It is evident that for flow above 1750°F the system probably will not be limited. At all other operating temperatures, depending on quality, the loop may experience choking.

C. Void Fraction Measurement Equipment

The final design of the gamma-ray attenuation apparatus was approved by Radiation Control Service. The method of shielding the source by a length of steel tube and positioning it by mouting on a steel rod are shown in Figures 13 and 14 of the Third Quarterly Progress Report. The only changes are in the lengths of these components and the fact that the shield will be a piece of seamless mechanical tubing, requiring no fabrication at all. The source shield is 18 inches long, and the positioning rod is 20 inches. These components have been shortened in order to make the assembly less unwieldy. The dose rate from the shield is estimated to be 0.03 mr/hr at one meter.

Figure 10 gives the layout of the attenuation apparatus. The gamma rays will pass upward through the flow channel. The transmitted radiation is picked up by the scintillation detector whose pulses are counted on a scaler located adjacent to the panel board in the control room. The assembly as shown weighs about 40 lb. The system will ride on the flow channel and will be counter-balanced to give a bearing weight of about 2 lb. It is necessary to mount the system on the channel so that the gamma-ray beam will always pass through the center of the tube, even if the tube position shifts under thermal stress.

The photomultiplier tube must be shielded from scattered radiation, and it is also desirable to cut the background count rate to as low a level as possible. Figure 11 shows the design of the shield for the phototube. A removable face plate is specified so that the size of the collimating hole over the crystal can be changed easily. The shield should reduce the background radiation to about 225 counts per minute.

The Integral-Line scintillation crystal-photomultiplier tube assembly has been purchased from the Harshaw Chemical Company. The assembly has an excellent measured pulse height resolution of 8.3% at 661 KEV photon energy. A Tracerlab SC-18 Superscaler will be used with this scintillation detector. The preamplifier was made specially in the electronic shop and is matched for use with the scaler. The scaler has a built-in high voltage supply which is used to drive the phototube. Some preliminary evaluations of the phototube, scaler, and preamplifier indicate that 1000 volts will allow all the gamma energy to be seen by the detector. The lowest feasible voltage to impress on the phototube is 800 volts and the highest is 1100 volts. The 1000 volt level, as determined from a small Co-57 source should be suitable for background counting and experimental counting. A final check will be made using the Tm-170 source.

The photomultiplier shield and source shield-positioner have been fabricated. The electronic components--i.e., crystal-photomultiplier tube assembly, preamplifier, and scaler--are in working order, and have been tested together using a small Co-57 source. All that remains is to position the system around the test section. The Tm-170 source will be ordered as soon as the loop heat balance runs commence.

D. Gamma-Ray Attenuation Calibration Experiments

In horizontal two-phase flow a variety of phase distributions may occur. The form obtained in any given flow situation probably is most dependent on vapor quality, with fluid physical properties also playing a role. With regard to the measurement of void fractions by radiation attenuation, there are two extreme cases in the manner of attenuation.

If the two-phase system is flowing in an essentially homogeneous fashion, the gamma-radiation attenuates in an exponential manner and the void fractions can be determined by the following equation:

$$\alpha = \frac{\ln(N/NL)}{\ln(NG/NL)} \qquad (4)$$

where α = void fraction

N = count rate with a two-phase mixture flowing

NL = count rate with all liquid flowing

NG = count rate with all vapor flowing

This type of attenuation is also obtained through completely separated phases if the phases exist in parallel layers perpendicular to the radiation beam.

The alternate extreme case occurs if the two phases exist in layers parallel to the radiation beam. For this case the void fractions are given by

$$\alpha = \frac{N - NL}{NG - NL} \qquad (5)$$

It is common among investigators to assume that the two-phase flows are essentially homogeneous. Thus, most of the recently reported void fraction values are based upon application of Equation (4), with the all-liquid and all-vapor flows taken as calibration points. Void fractions in horizontal two-phase potassium flows will be obtained on the test loop. It has been shown that the data can be obtained over the approximate range of 2 to 20 per cent quality. While it is most likely that the flow will be essentially homogeneous over this quality range, it is desirable to attempt a check on the manner of attenuation since at some qualities it may not be as given by either Equation (4) or Equation (5). In such an event, calibration of the set-up could not be achieved by measurements on all-liquid and all-vapor flows alone and it becomes necessary to establish a calibration curve including intermediate two-phase points.

It will not be possible to obtain a calibration curve on the test loop. Thus, it has been decided to assemble a horizontal test section of the same diameter and measure void fractions in air-water flows. Quick-acting valves will be used to trap the flow in the test section. The form of the gamma-ray attenuation curve will be established over the desired quality range. The curve may have a mathmatical form intermediate between Equations (4) and (5). Hopefully, the attenuation will be exponential, implying homogeneous behavior. In any case, the form of the mathematical curve thus established will be used in the potassium experiments.

Figure 12 shows schematically the essential features of the apparatus believed necessary for this work. Air and water flow rates will be obtained from rotameters, globe valves will adjust flow rates to the system, and check valves will prevent flow reversals. The air coming from a 100 psig storage vessel will be regulated to a constant inlet pressure and filtered. The two phases will come together at the mixing tee, and the mixture will then enter the stainless steel tube. The flow will be trapped in the one-foot long test section by manually operated quick-closing valves operated by a common handle. The mixture finally is separated in a drum and the fluids discarded.

The gamma-radiation will be passed through the test section, the design of the attenuation system being that employed on the loop. The trapped liquid volumes will be measured by adsorption in weigh-bottles containing a dessicant. The removal of water from the test section will be accomplished by use of a dry air bleed stream. The necessity of this procedure for obtaining liquid volumes is based upon estimated quantites of trapped liquid. Assuming a unit slip ratio, the trapped liquid volumes will be about 2 cm^3 to 0.15 cm^3 for qualities of 2 to 25 per cent.

This apparatus is believed to be sufficiently flexible to permit other two-phase flow investigations, upon making minor modifications.

LIQUID METAL BOILING IN AGRAVIC FIELDS

Herman Merte

Fabrication of components of the test apparatus is under way and is expected to be completed with 3 to 4 weeks. Some difficulty was experienced by the fabricators in locating sources for certain materials because of unusual dimensions.

Although the final design of the test vessel was completed in July, 1962, working detail drawings were not completed and checked until the latter part of October owing to a reduction in available man hours during the month of August. This occurred as a result of the normal examination period for the students, vacations, and attendance at professional meetings by project supervisory personnel.

It was not deemed desirable to proceed with construction until the feasibility of metallurgically attaching a foil of stainless steel .001-in. thick to copper had been tested, for use as the mercury boiling surface. This appeared to be an unusual brazing operation and the aid of the Wall-Colmonoy Corporation of Detroit, Michigan, specialists in vacuum brazing, was sought. It was necessary that the surface be as smooth as possible, that the bond be complete with a minimum of brazing alloy, and that the fillet resulting from any extruded alloy be small, since the thin stainless steel skirt extending beyond the copper heater was relied upon to minimize the undesirable conduction heat losses.

After several trials a technique was developed which proved successful. The 0.001-in. thick piece of stainless steel foil was plated with approximately 0.001-in. thickness of silver, placed tightly in contact with the cleaned OFHC copper surface with no fluxing agent, placed in an argon atmosphere furnace and heated to 1650°F. The thickness of the resulting silver-copper alloy was approximately 0.003 inches, most of which was squeezed out to form a small fillet at the edge of the disc.

The presence of the fillet required minor design changes in order that the differential thermal expansion between the copper heater and the supporting stainless steel tube would not place undue stress on the foil extending beyond the copper.

Energy is furnished to the copper heater disc from 7 cartridge-type heaters, each rated at 450 watts and nominally 3/8 in. in diameter by $2\frac{1}{2}$-in. long. The heaters are of a special "high-capacity" type and require extremely close clearances when the part to be heated is above 1000°F. Since the cartridge heaters themselves expand upon heating, reducing the clearance will reduce the thermal contact resistance and result in a lower operating temperature of the cartridge heater for a given heater block temperature. The heaters on order are being centerless ground to within $\pm .0005$-in. to provide a slip fit in the copper heater with a maximum clearance of 0.001-in. on the diameter. A closer fit could be obtained by a press fit, but should a single heater become defective the entire heater block assembly would require replacement.

Referring to Figure 16 of the Third Quarterly Progress Report, it is noted that all communication to the interior of the pressure vessel takes place via 6 pressure-type fittings located at the top. Of these, one is available for A.C. power leads to the three independently controlled heaters, and one is available for seven independent thermocouple circuits of two different sizes. The special fittings for these applications are under procurement.

It is noted that pressure between the inner boiling chamber and the pressure vessel itself is equalized through the vent tube and the mercury trap. Equalization of the pressure is necessary since the thin stainless steel foil skirt at the boiling surface will withstand, it is estimated, only the hydrostatic head of the mercury at the highest acceleration (approximately $45\ lb_f/in^2$). Should a pressure surge occur within the boiling chamber due to some unstable condition, a pressure switch to be mounted in the vent tube line will cut off all power to prevent damage.

Such a surge could occur, for example, should the flow of cooling water cease. Therefore, a pressure switch will be mounted in the coolant line to also cut off all power should the cooling water supply foil. Flow rate of coolant will be monitored with a turbine-type flowmeter during normal operation.

ANALYTICAL STUDIES OF THE TRANSITION AND FILM BOILING REGIMES

The recent film boiling literature has made extensive use of interfacial wave theory in explaining the observed phenomena. The hydrodynamic behavior of the interface is assumed to conform to the equations which include as the principal forces, the gravitational and surface forces. Such an equation taken from Milne-Thompson(12) is shown in Equation (6):

$$m\rho_1 (U_1 - C)^2 \coth m h_1 + m\rho_2 (U_2 - C)^2 \coth m h_2 = g(\rho_2 - \rho_1) + \sigma m^2 g_c \quad (6)$$

where ρ, h, and U refer to the density, depth and velocity of the two fluids respectively, and m is the wave number, C is the wave propagation velocity, σ is the surface tension, and g is the acceleration due to gravity.

For studying the instability of the interface, Equation (6) can be rearranged by defining the following quantities(13)

$$\rho_1^* = \rho_1 \coth m h_1 \quad (7)$$

$$\rho_2^* = \rho_2 \coth m h_2 \quad (8)$$

$$\overline{U} = \frac{\rho_1^* U_1 + \rho_2^* U_2}{\rho_1^* + \rho_2^*} \qquad (9)$$

$$\overline{C} = C - \overline{U} \qquad (10)$$

By combining Equations (6), (7), and (8) we find

$$\rho_2^* (U_2 - C)^2 + \rho_1^* (U_1 - C)^2 = \sigma m g_c + \frac{g}{m} (\rho_2 - \rho_1) \qquad (11)$$

Let C_o by the velocity that $U_1 = 0$, $U_2 = 0$

$$C_o^2 = \frac{\sigma m g_c}{\rho_1^* + \rho_2^*} + \frac{g (\rho_2 - \rho_1)}{m (\rho_2^* + \rho_1^*)} \qquad (12)$$

Dividing Equation (11) by $\rho_1^* + \rho_2^*$ and equating it to Equation (12), one finds

$$C_o^2 = \frac{\rho_2^* U_2^2 + \rho_1^* U_1^2}{\rho_2^* + \rho_1^*} + C^2 - 2C \frac{\rho_2^* U_2 + \rho_1^* U_1}{\rho_2^* + \rho_1^*} \qquad (13)$$

By an algebric manipulation, it can be shown that

$$\frac{\rho_2^* U_2^2 + \rho_1^* U_1^2}{\rho_2^* + \rho_1^*} = \left[\frac{\rho_2^* U_2 + \rho_1^* U_1}{\rho_2^* + \rho_1^*}\right]^2 + \frac{\rho_2^* \rho_1^*}{(\rho_2^* + \rho_1^*)^2} (U_2 - U_1)^2 \qquad (14)$$

Substituting Equations (14) and (9) into Equation (13) we have

$$C_o^2 = (C - \overline{U})^2 + \frac{\rho_2^* \rho_1^*}{(\rho_2^* + \rho_1^*)^2} (U_2 - U_1)^2 \qquad (15)$$

or

$$\overline{C}^2 = \frac{\sigma m g_c}{\rho_2^* + \rho_1^*} + \frac{g (\rho_2 - \rho_1)}{m (\rho_2^* + \rho_1^*)} - \frac{\rho_2^* \rho_1^*}{(\rho_2^* + \rho_1^*)^2} (U_2 - U_1)^2 \qquad (16)$$

This equation tells us that the interface will be unstable whenever

$$\sigma m g_c + \frac{g}{m} (\rho_2 - \rho_1) - \frac{\rho_2^* \rho_1^*}{(\rho_2^* + \rho_1^*)} (U_2 - U_1)^2 < 0 \qquad (17)$$

In terms of phase rate, ω, Equation (16) can be written in the following form

$$\omega^2 = C^2 m^2 = \frac{\sigma m^3 g_c + m\, g\, (\rho_2 - \rho_1)}{\rho_1^* + \rho_2^*} \qquad (18)$$

The wavelength which grows the fastest and therefore dominates is that which maximizes ω. By differentiating Equation (18) and equating to zero, we find

$$\lambda_D = 2\pi \, \frac{3\, g_c \sigma}{g\, (\rho_1 - \rho_2)} \qquad (19)$$

Evaluation of these equations produces an estimate of the most probable wavelength, in other words, that wavelength for which the rate of growth of an instability is maximized. Using this value, Zuber, Berensen and others have estimated the size of the bubbles departing from the interface. These estimates combined with frequency determinations have enabled these investigators to predict heat fluxes in the stable film boiling regime. Berensen's results(14) yield an expression for heat transfer coefficient as follows if it is assumed that one bubble is released from each $\lambda_D^2/2$ of area per cycle

$$h = 0.425 \left[\frac{k_v^3\, L\, \rho_v\, g\, (\rho_\ell - \rho_v)}{\mu\, \Delta T\, \sqrt{g_c \sigma / g(\rho_\ell - \rho_v)}} \right]^{1/4} \qquad (20)$$

where k, L and μ are the thermal conductivity, latent heat and viscosity respectively. Hosler and Westwater(15) have substantiated Berensen's results for water and Freon 11 on a surface 8-in. by 8-in. for which edge effects should have been negligible. Berensen's equation had been based on data which he obtained from a 2-in. diameter surface and for which there was some questions raised regarding edge effects inasmuch as λ_D is of the order of one inch for these fluids. The studies of Westwater have provided substantial confirmation of the wave character of the interface.

In 1961 Sidney Rankin(16) postulated an additional force which he termed the vapor repulsion force. The existence of such a force does not seem open to question, but apparently its importance has either been overlooked or assumed negligible by investigators. The force arises from the principles of Newton's laws of motion when one recognizes that as the liquid interface approaches closely the hot solid surface large quantities of energy are transferred to the liquid and large volumes of vapor are generated very suddenly. The reaction to the vapor discharge from the interface results in an upward force component which pushes the liquid away from the solid. This force obviously would not act uniformly along the interface and would probably be of importance only at the points on the interface where the liquid most closely approaches solid surfaces.

If one evaluates the magnitude of the above force at the average vapor film thickness predicted by Berensen of 10^{-4} feet it will prove negligible in comparison with the gravitation and surface terms originally included in the stability equation. This term might be expressed as $\frac{2k_v^2 \Delta T^2}{t_v^3 L^2 \rho_v}$. One can quickly observe that as the distance between the interface and the solid surface, t_v, approaches zero the magnitude of the term becomes infinite. It therefore remains to more accurately determine the minimum distance which separates the liquid interface and the solid surface along various portions of the boiling curve. At large values of ΔT corresponding to stable film boiling the repulsion force becomes significant enough at relatively large distances so that the liquid never approaches the surface. As the ΔT decreases and the minimum point on the boiling curve is approached the distance of approach decreases until eventually the force is not sufficient to prevent occasional contact of liquid with solid. This contact leads to an increased film coefficient and hence a higher flux for a given ΔT such as is observed in the transitional regime. This explains the behavior evidenced by most investigators in the transitional regime where the action becomes violent and irregular due to the small explosions.

An effort is currently being made to integrate this additional force with the wave equations which have proven moderately successful to date. It is hoped that inclusion of such a term may permit analytical description of the behavior encountered in the transitional regime as well as refine the predictions in the stable film regime.

The analysis of Zuber and Berensen has been used to predict film boiling curves for rubidium, potassium, sodium and lithium and the results are plotted in Figures 13, 14, 15, and 16. Physical property data was obtained from Weatherford's report.(11) The following equations were used to calculate the minimum flux and the ΔT corresponding to the minimum flux:

$$q_{\min} = 0.156\, L\, \rho_v \left[\frac{g_c\, \sigma\, g\, (\rho_\ell - \rho_v)}{(\rho_\ell + \rho_v)^2} \right]^{1/4} \qquad (21)$$

$$\Delta T_{\min} = 0.262\, \frac{L\, \rho_v}{k_v} \left[\frac{\mu_v^2\, \sigma^3 g_c{}^3}{g(\rho_\ell + \rho_v)^4 (\rho_\ell - \rho_v)} \right]^{1/6} \qquad (22)$$

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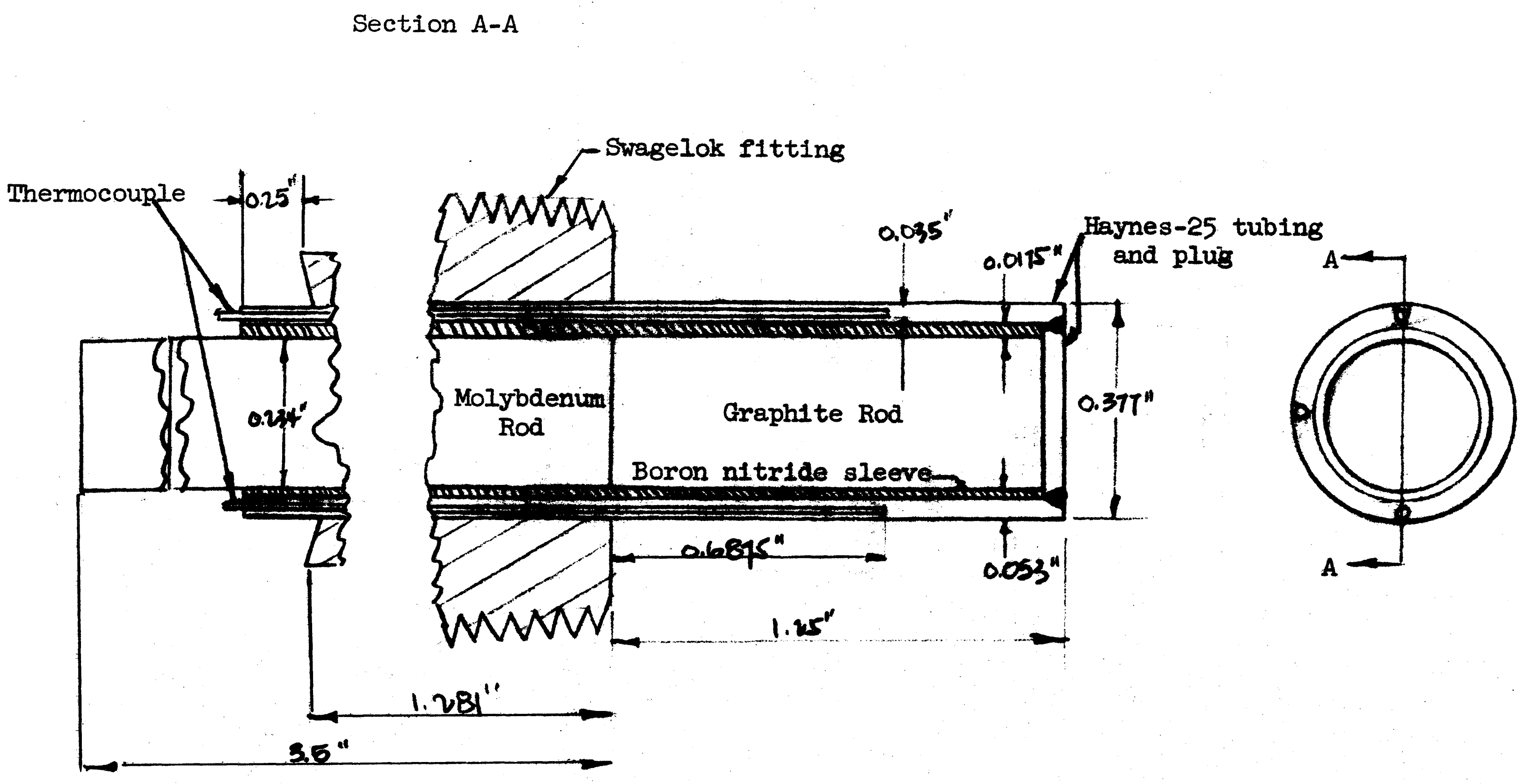


Figure 1. Cross Sectional Drawing of Composite Boiling Tube

11/29/62

FIGURE 2
FILM BOILING SCHEMATIC

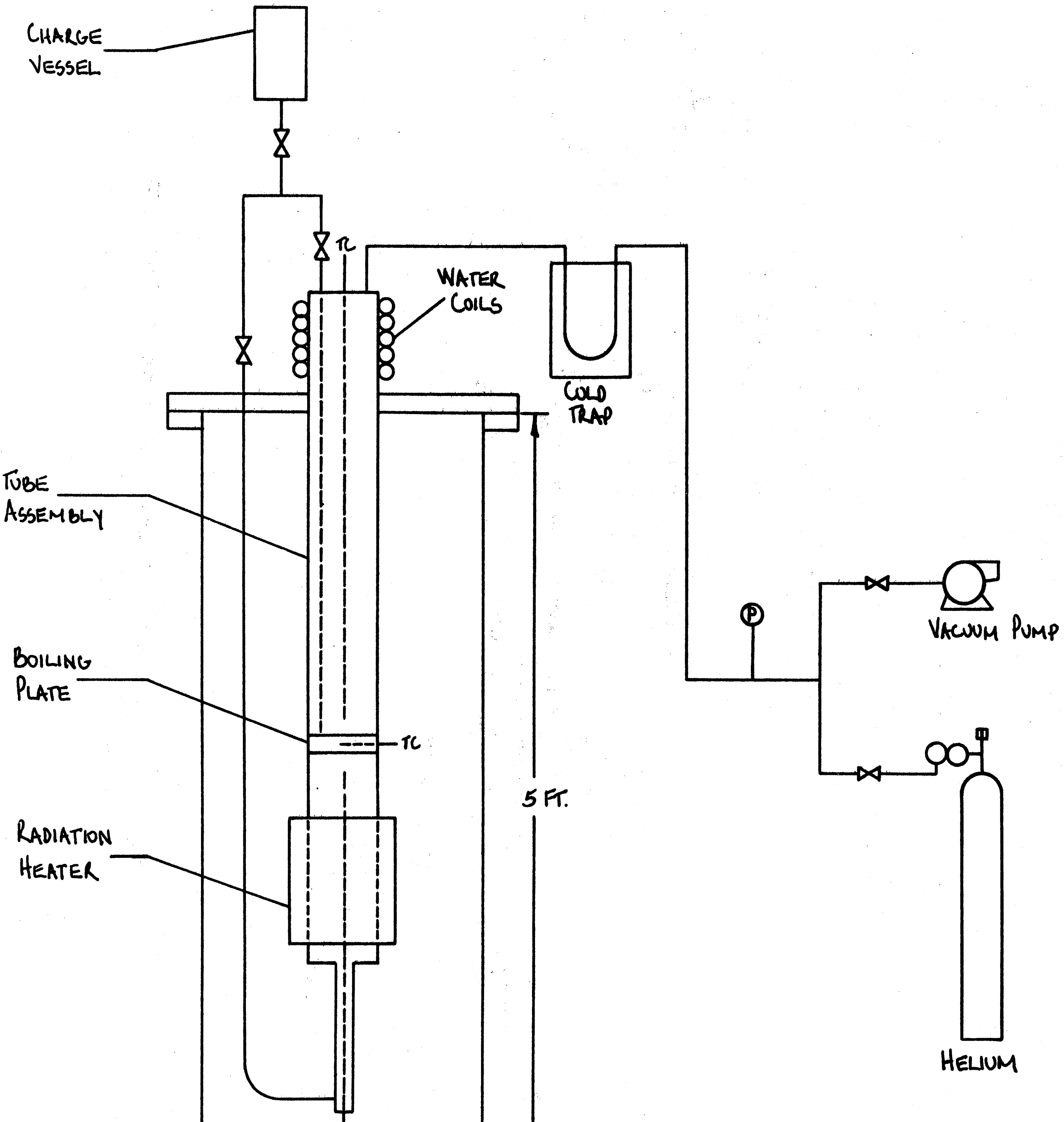


FIGURE 3
TUBE ASSEMBLY

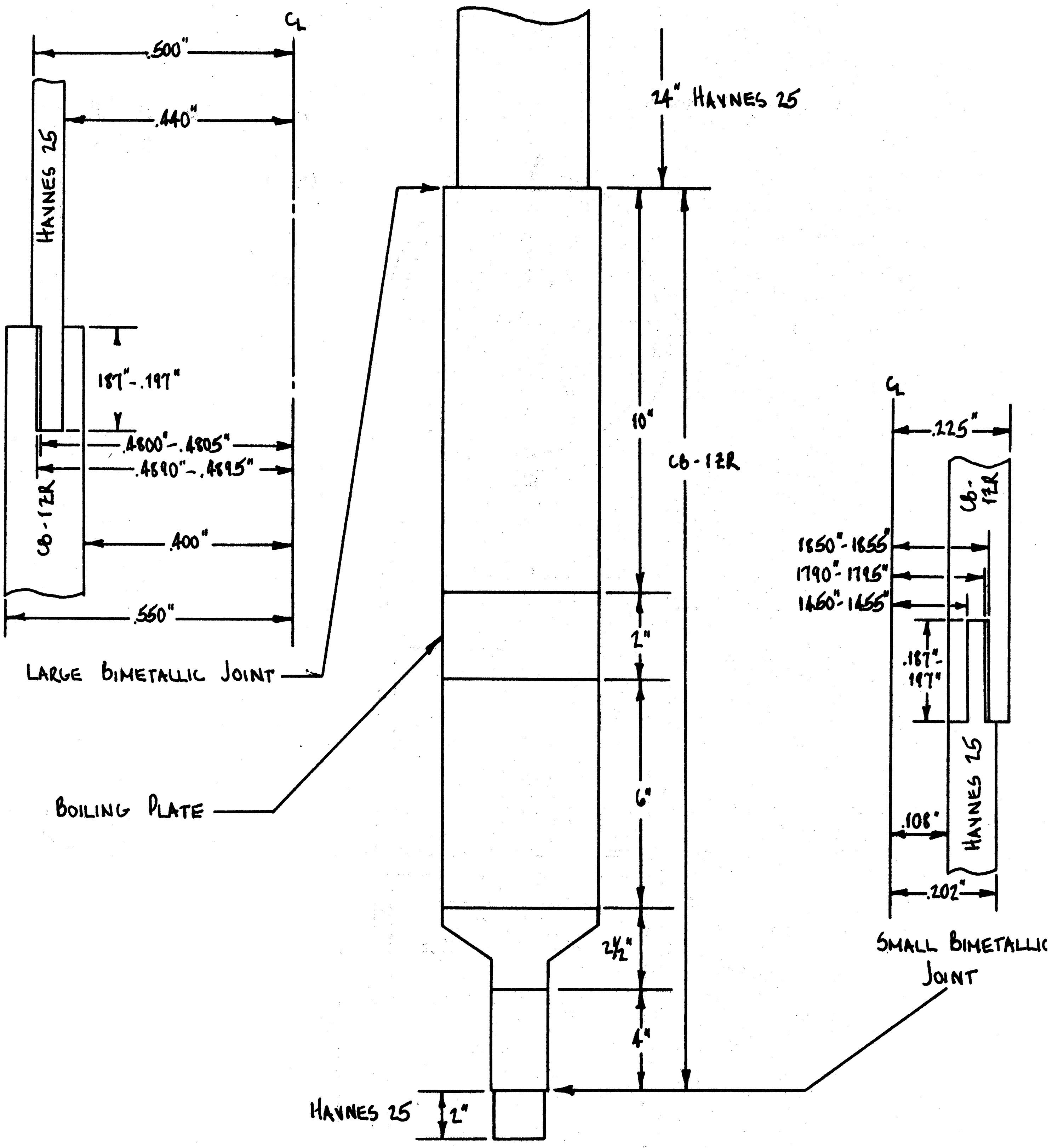
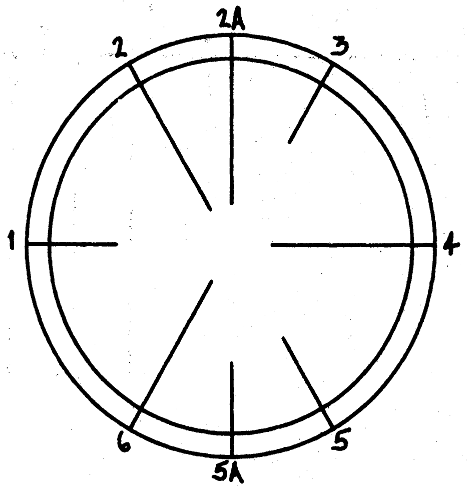


FIGURE 4
CB-1ZR BOILING PLATE

THERMOCOUPLE HOLE DIAMETER .021"

RADIAL DEPTH OF THERMOCOUPLE HOLES

1	.250"
2	.450"
2A	.450"
3	.250"
4	.450"
5	.280"
5A	.250"
6	.450"



INNER THERMOCOUPLE HOLES - 120° APART

OUTER THERMOCOUPLE HOLES - 120° APART

#2A HOLE - 30° FROM #2

#5A HOLE - 30° FROM #5

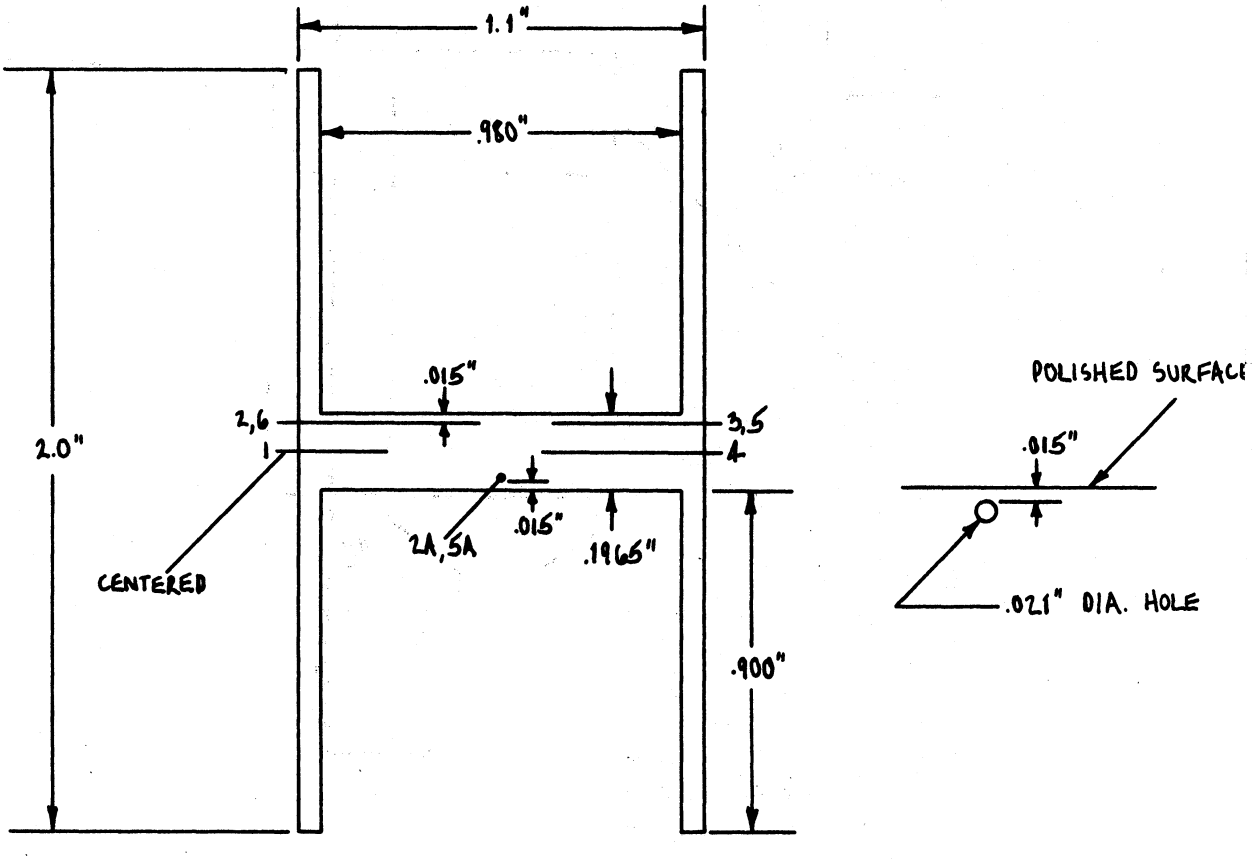


FIGURE 5
TOP FLANGE CONNECTIONS

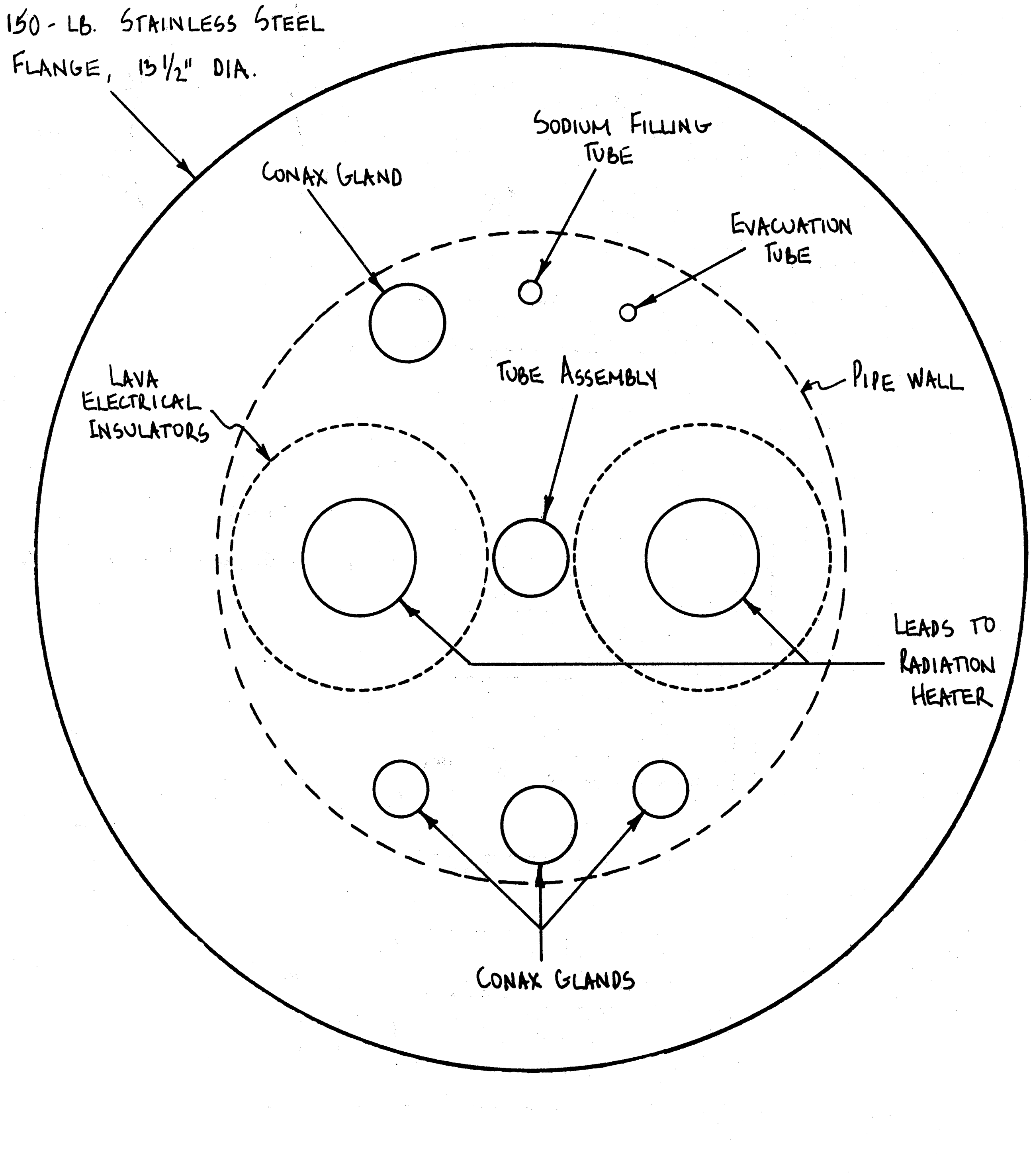
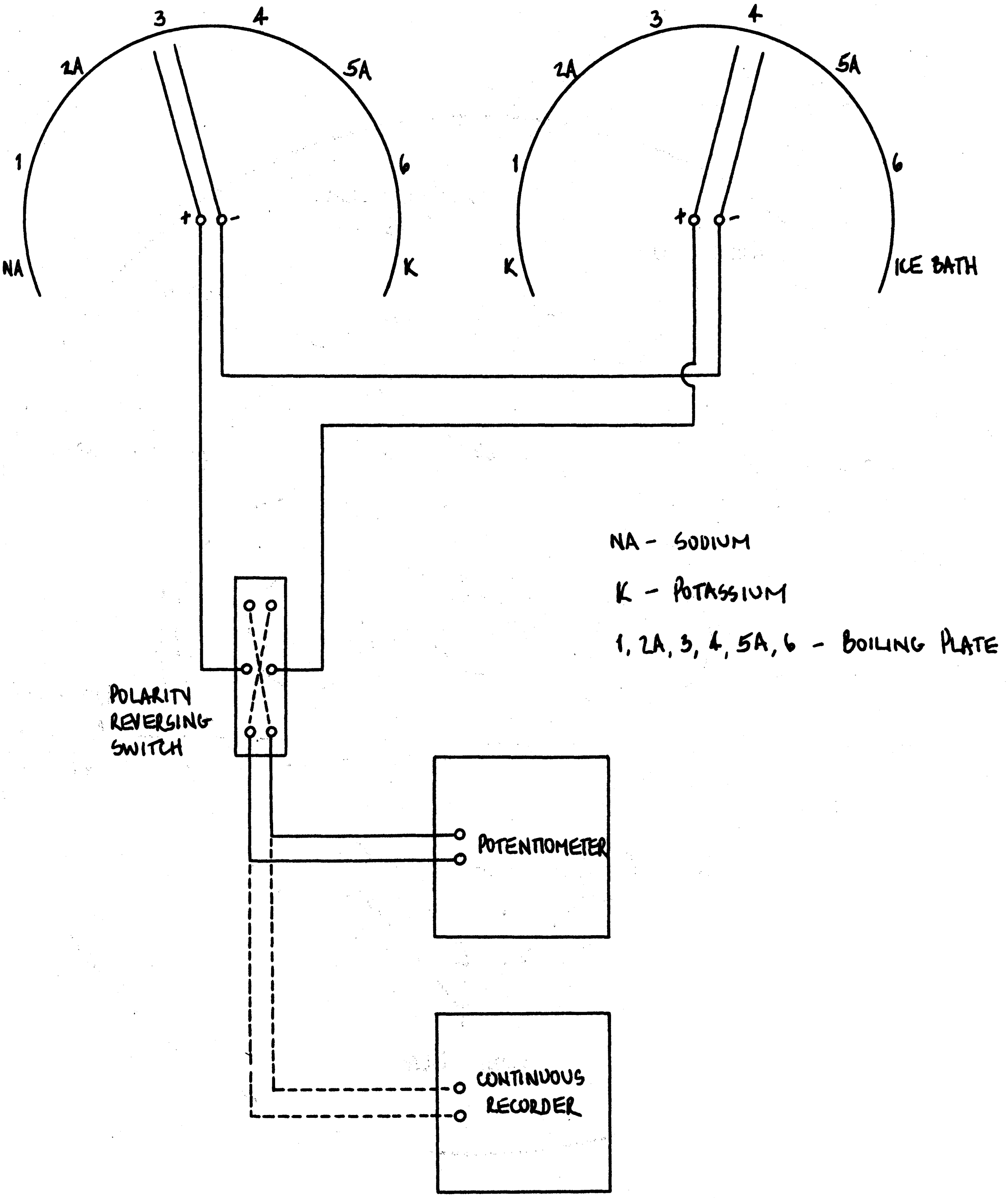


FIGURE 6

TEMPERATURE MEASURING CIRCUIT



NA - SODIUM

K - POTASSIUM

1, 2A, 3, 4, 5A, 6 - BOILING PLATE

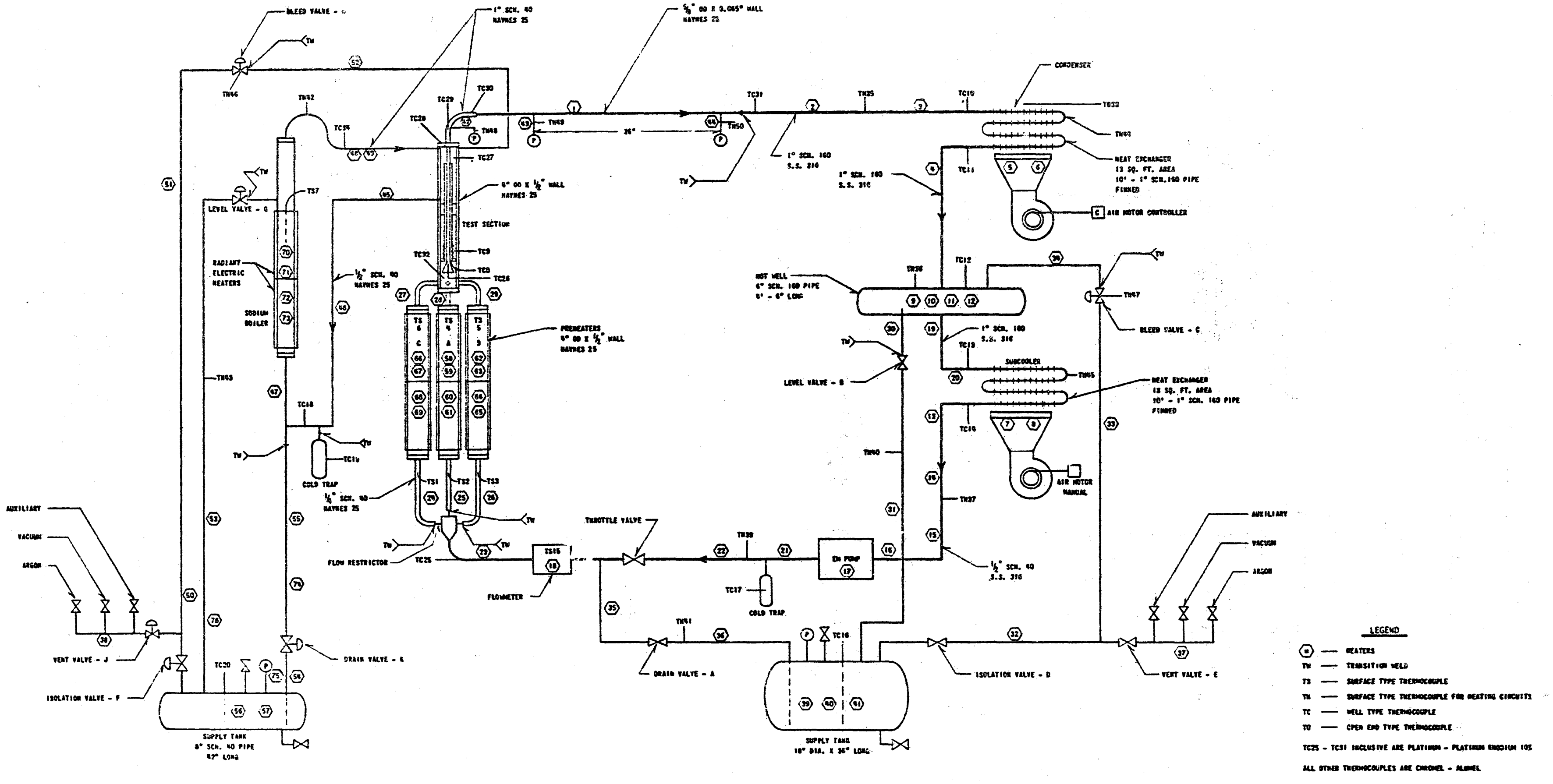


FIG. 7 - FLOW SCHEMATIC, UNIVERSITY OF MICHIGAN BOILING LIQUID METAL LOOP

AK2246-28

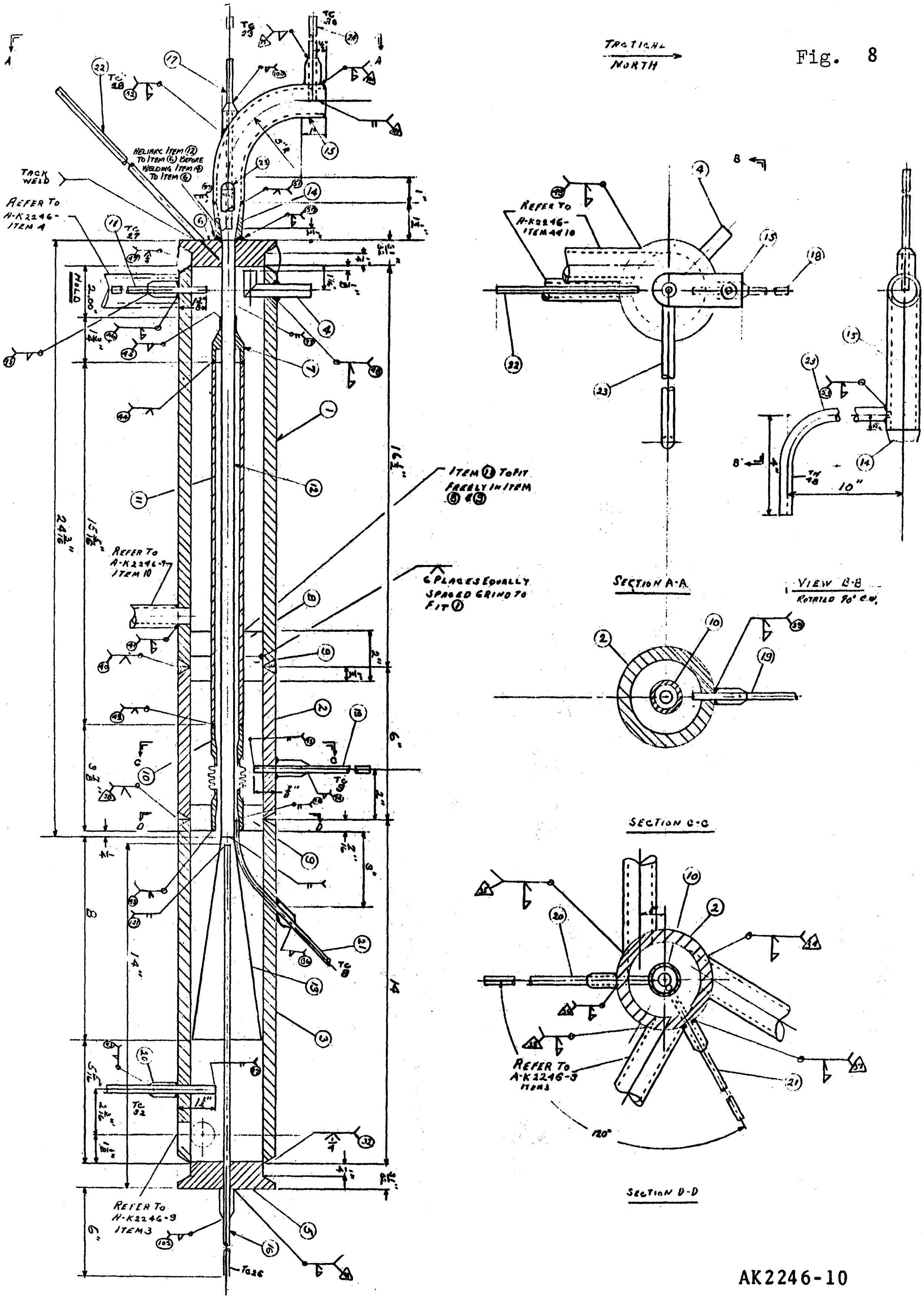
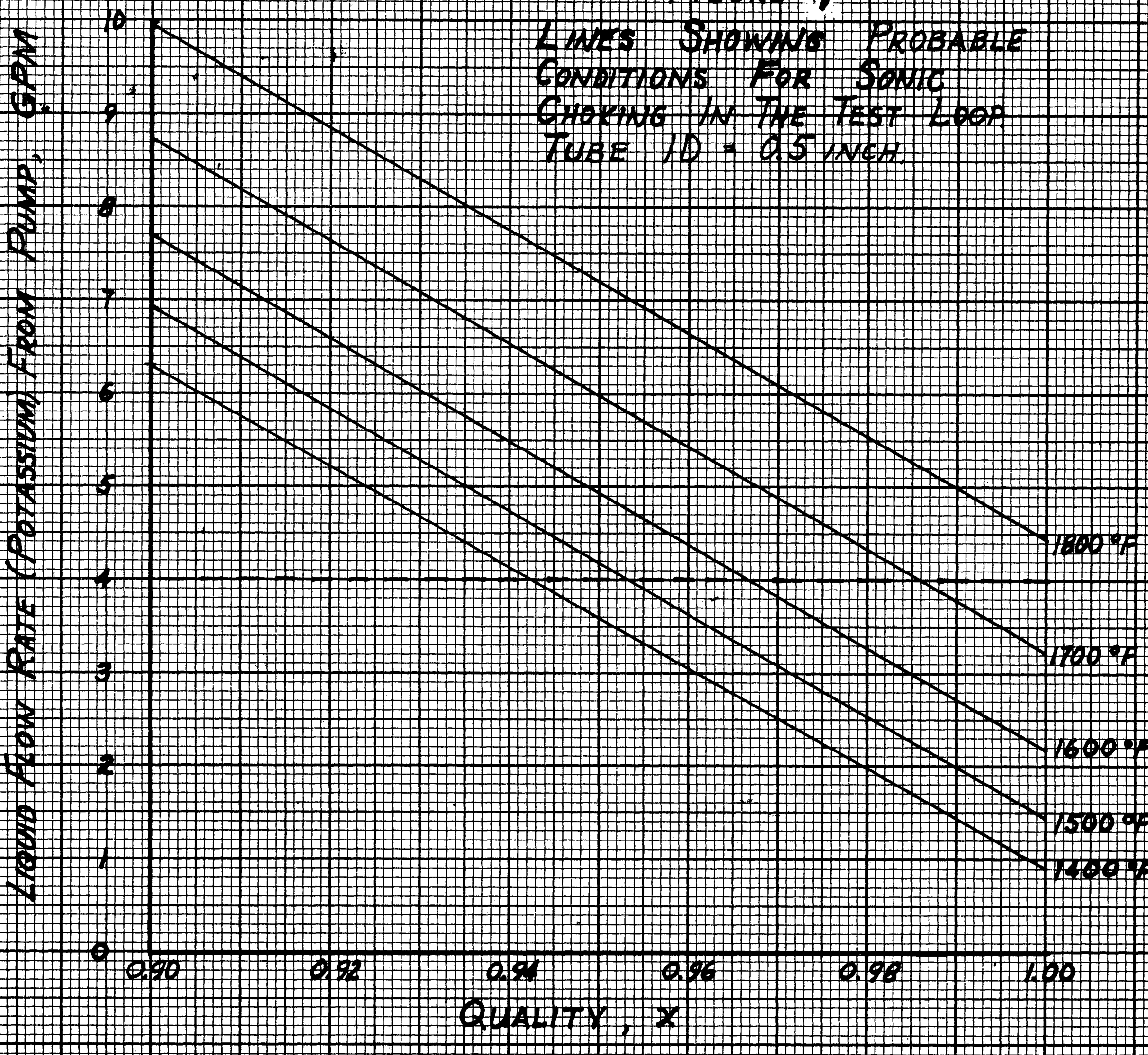


Fig. 8

AK2246-10

FIGURE 9

LINES SHOWING PROBABLE CONDITIONS FOR SONIC CHOKING IN THE TEST LOOP. TUBE ID = 0.5 INCH.



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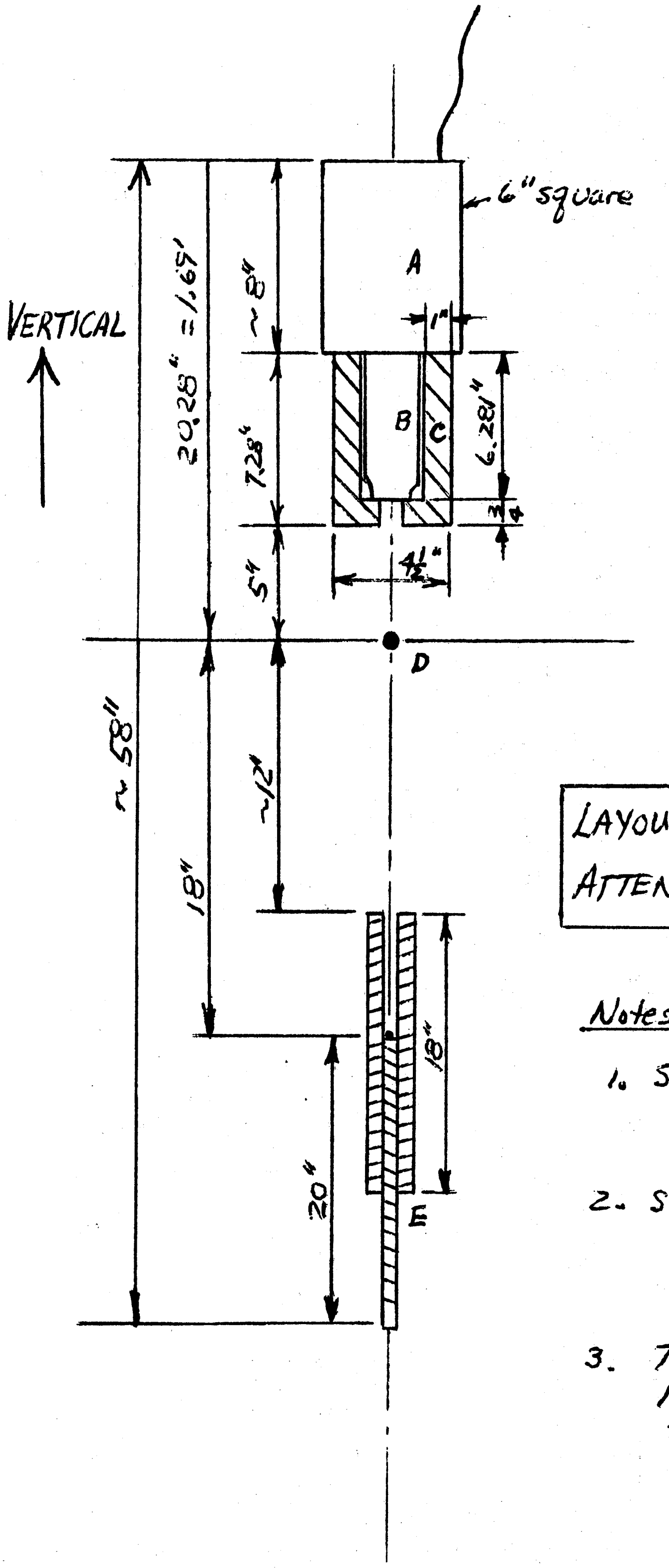


KEY

A Preamplifier

B Harshaw Integral Line Scintillation Crystal & Photomutiplier Tube

C Steel Shield For Phototube, ~ 23 lbs.

D Haynes -25 Tube 0.5-in ID with 0.0625-in wall.

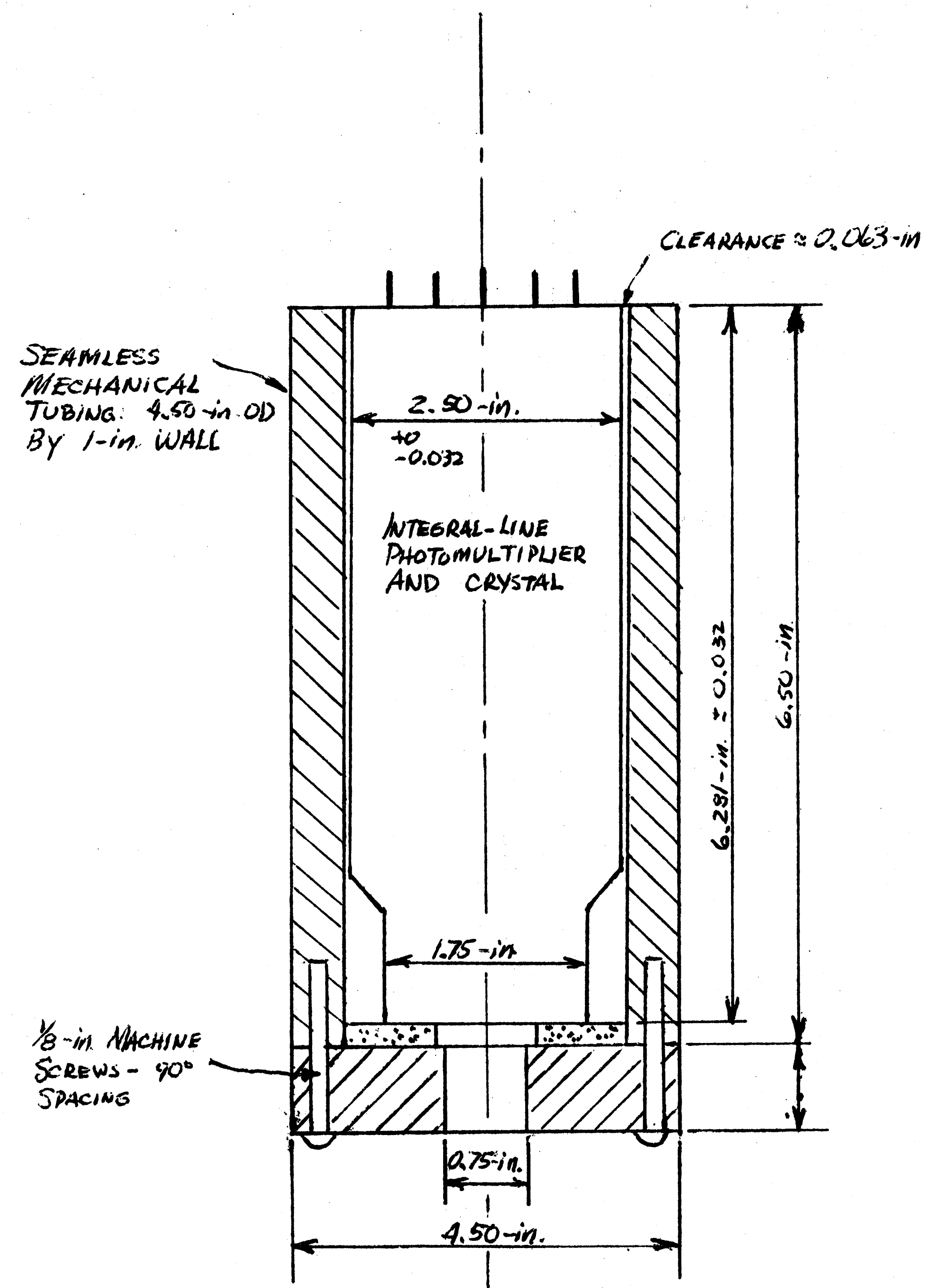
E Source Shielding & Positioning Components, ~17 lbs.

LAYOUT OF GAMMA-RAY ATTENUATION APPARATUS

Notes:

1. System Fastened to Frame Which Rides On Test Section.
2. System Counterbalanced So Weight Bearing On Test Section About 2 lbs.
3. Total weigh, not including mounting frame, about 40 lbs.

Figure 10



NOTES:

1. CROSS-HATCHED AREAS DENOTE STEEL
2. SPECKLED AREA DENOTES ASBESTOS CUSHION SHAPED AS A WASHER, CUT FROM 1/8-in. & 1/16-in. SHEET
3. CLEARANCE BETWEEN PHOTOTUBE & INSIDE TUBE WALL CUSHIONED BY 1/16-in ASBESTOS STRIPS.
4. TOTAL WEIGHT ~ 23 lbs.

SHIELD FOR
PHOTOMULTIPLIER TUBE

Figure 11

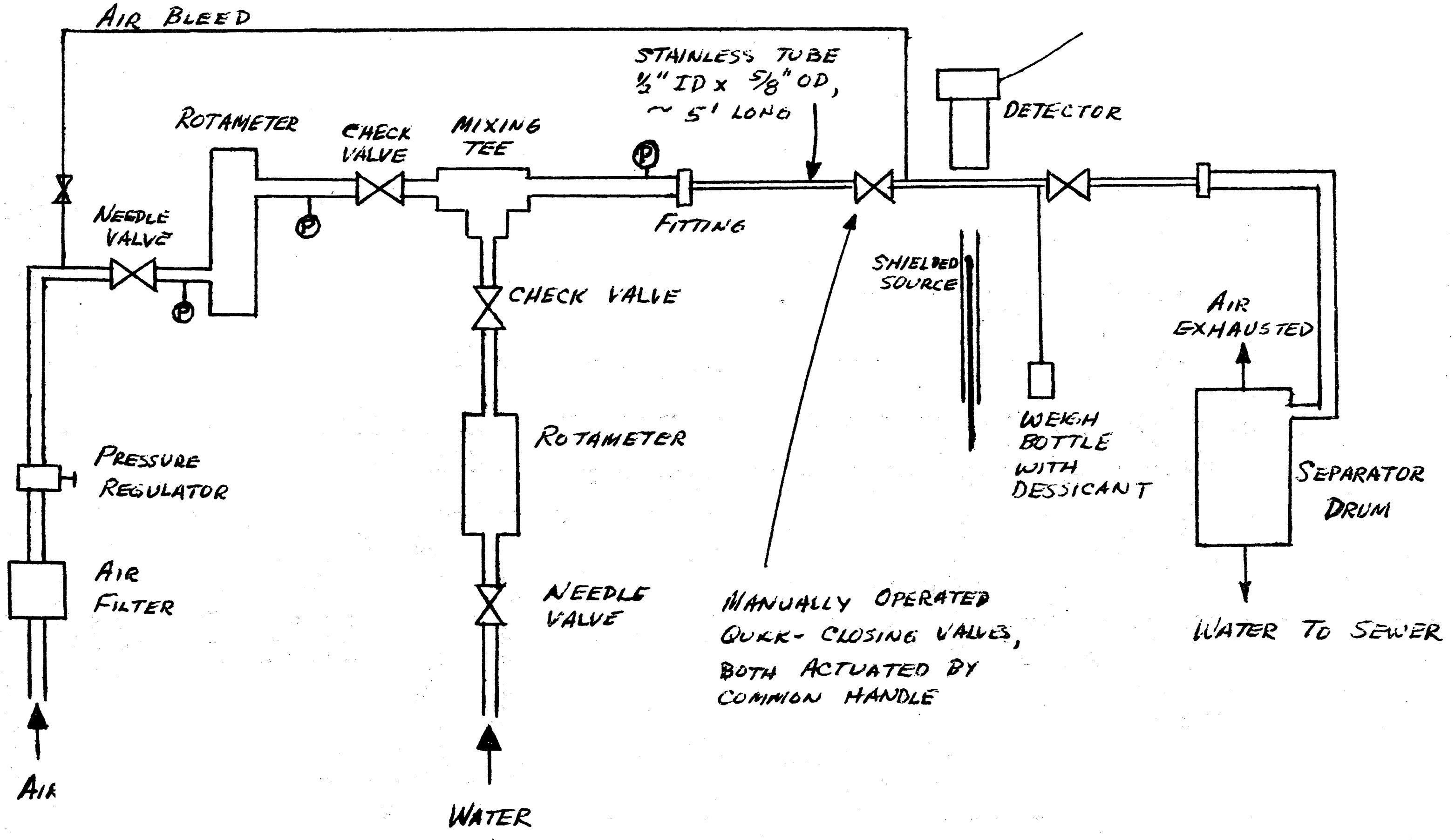


FIGURE 12

APPARATUS FOR WATER- AIR STUDIES

LRS 1/25/63

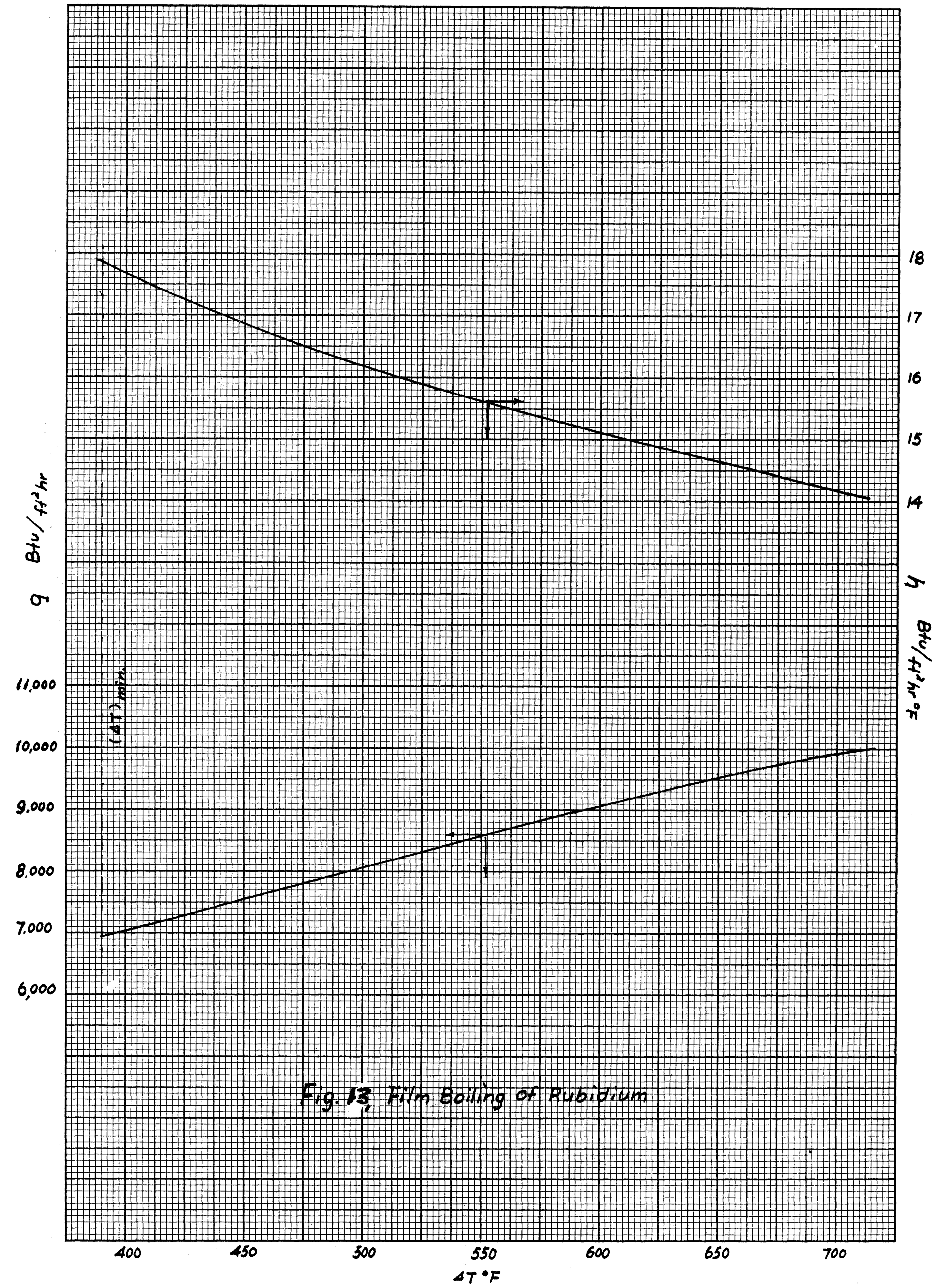


Fig. 13, Film Boiling of Rubidium

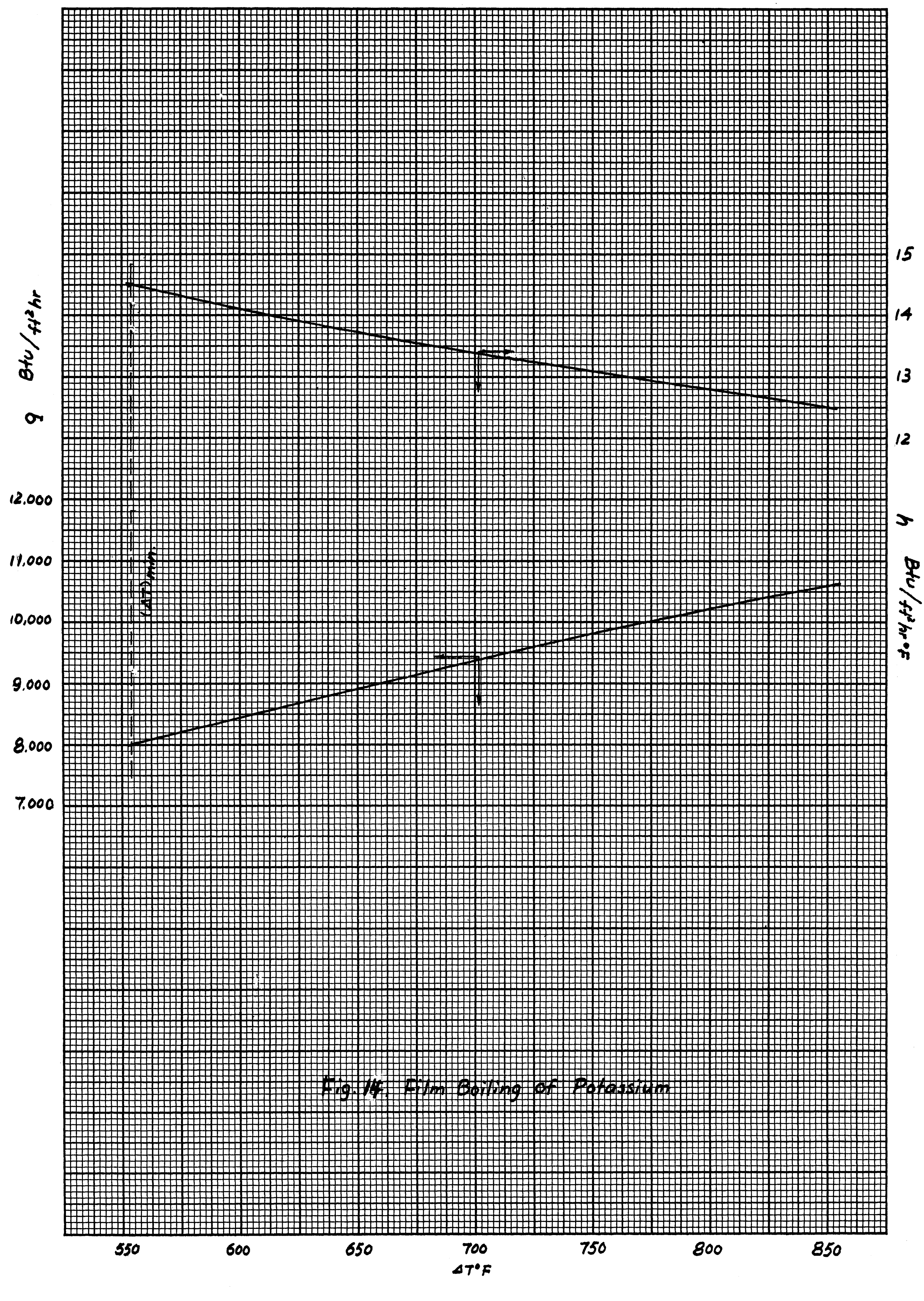


Fig. 14. Film Boiling of Potassium

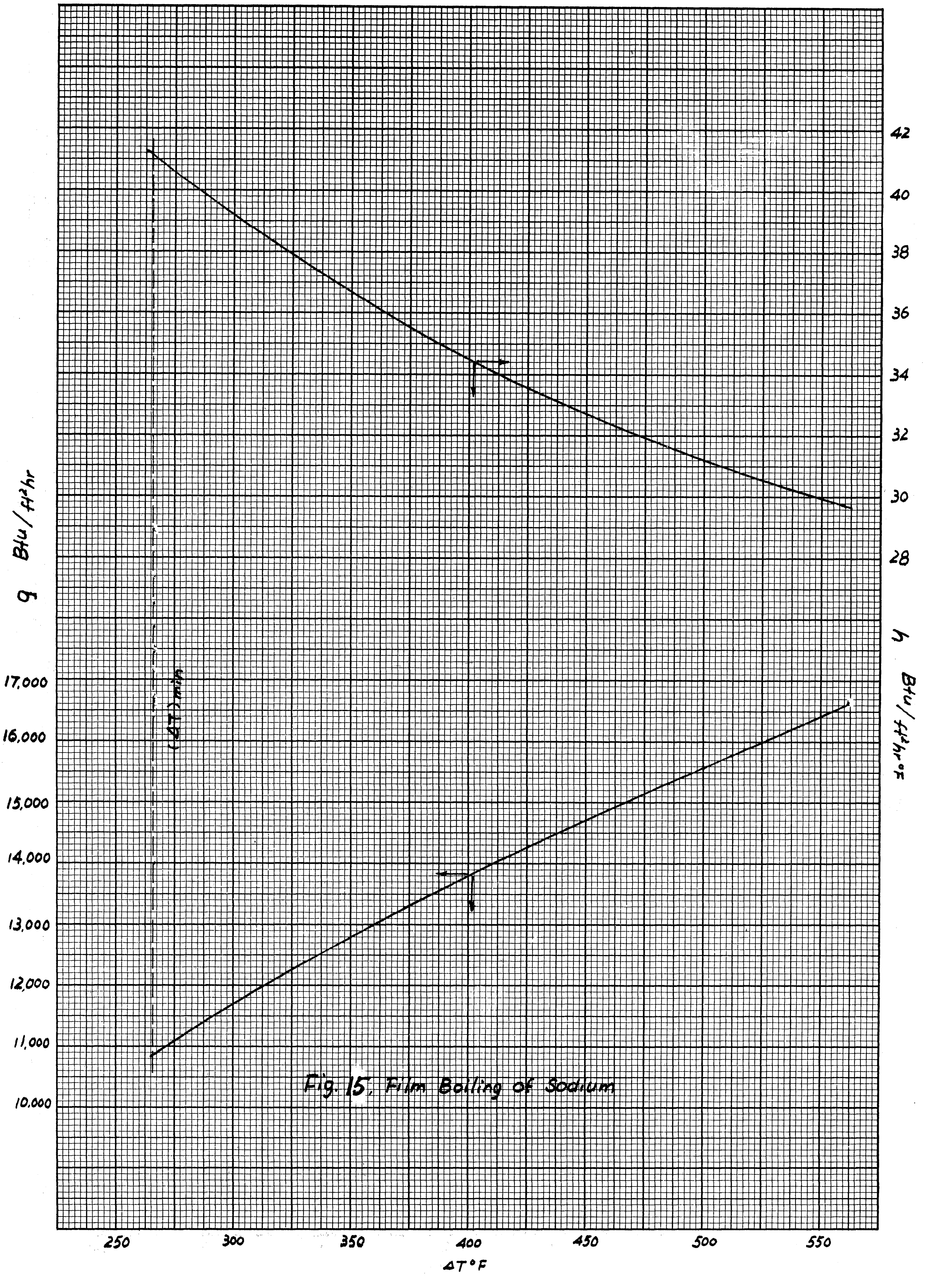


Fig. 15, Film Boiling of Sodium

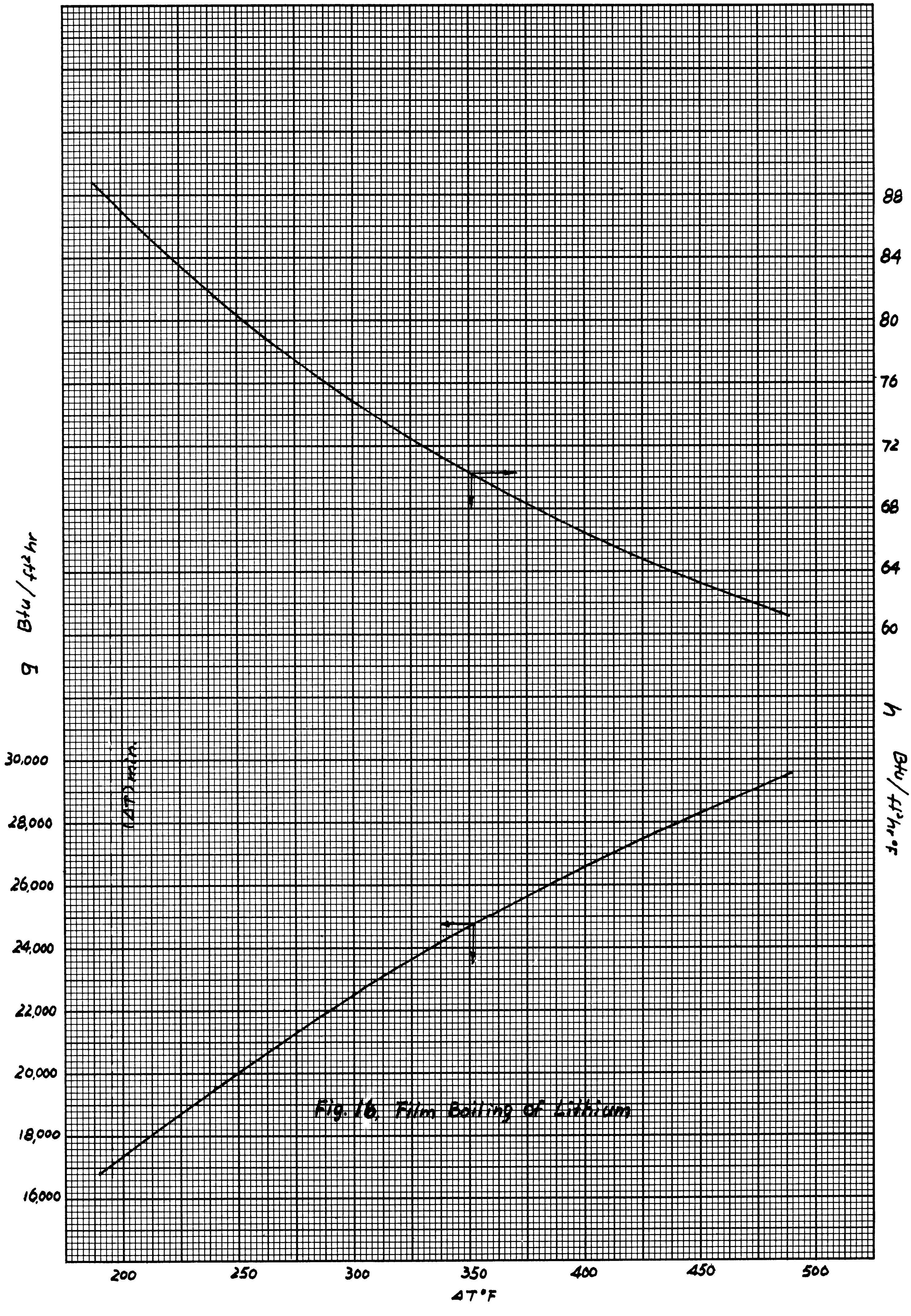


Fig. 16. Film Boiling of Lithium