ANL-7383

ANL-7383

MASTER

Argonne National Laboratory

**ON THE SUPERHEATING OF SODIUM
AT LOW HEAT FLUXES**

by

**Robert E. Holtz and
Ralph M. Singer**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

The facilities of Argonne National Laboratory are owned by the United States Government. Under the terms of a contract (W-31-109-Eng-38) between the U. S. Atomic Energy Commission, Argonne Universities Association and The University of Chicago, the University employs the staff and operates the Laboratory in accordance with policies and programs formulated, approved and reviewed by the Association.

MEMBERS OF ARGONNE UNIVERSITIES ASSOCIATION

The University of Arizona	The University of Iowa	Northwestern University
Carnegie Institute of Technology	Kansas State University	University of Notre Dame
Case Institute of Technology	The University of Kansas	The Ohio State University
The University of Chicago	Loyola University	Purdue University
University of Cincinnati	Marquette University	Saint Louis University
Illinois Institute of Technology	Michigan State University	Washington University
University of Illinois	The University of Michigan	Wayne State University
Indiana University	University of Minnesota	The University of Wisconsin
Iowa State University	University of Missouri	

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

Printed in the United States of America
Available from

Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151

Price: Printed Copy \$3.00; Microfiche \$0.65

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

ON THE SUPERHEATING OF SODIUM
AT LOW HEAT FLUXES

by

Robert E. Holtz and
Ralph M. Singer

Reactor Engineering Division

November 1967

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

THIS PAGE
WAS THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

TABLE OF CONTENTS

	<u>Page</u>
NOMENCLATURE	6
ABSTRACT	7
I. INTRODUCTION	7
II. INCIPIENT BOILING MODELING	9
III. EXPERIMENTAL APPARATUS	17
IV. DATA AND RESULTS	21
V. DISCUSSION OF RESULTS	25
VI. CONCLUSIONS	28
APPENDIX: Tabulation of Data	29
ACKNOWLEDGMENTS	32
REFERENCES	33

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Wetting Liquid Entering a Surface Cavity	9
2.	Nonwetting Liquid Entering a Surface Cavity	9
3.	Liquid Wetting Surface Cavity When $P_v \geq P_\ell$	9
4.	Subcooled Liquid Entering a Surface Cavity	10
5.	Superheated Liquid Inside a Surface Cavity	10
6.	Plot of Liquid-sodium Penetration Radius vs Liquid-saturation Temperature for $P_\ell = 10, 15, 25$, and 100 psia . . .	15
7.	Plot of Liquid-sodium Penetration Radius vs Liquid-saturation Temperature for $P_\ell = 1, 1.4, 5$, and 10 psia	16
8.	Degree of Liquid Superheat vs System Pressure for Sodium. .	17
9.	Isometric Drawing of Sodium Superheat Test Apparatus	18
10.	Sodium Superheat Test Vessel	19
11.	Overall View of Sodium Superheat Apparatus.	19
12.	Sodium Superheat Apparatus and Control Panel	20
13.	Sodium Temperature Behavior during Test Runs	21
14.	Pressure and Temperature Behavior during Test Runs	22
15.	Heat Flux vs Pressure Plot, Showing Stable and Unstable Boiling Regions	22
16.	Sodium Superheat Data at 2.60-W/cm^2 Heat Flux	23
17.	Sodium Superheat Data at 3.39-W/cm^2 Heat Flux	23
18.	Sodium Superheat Data at 4.225-W/cm^2 Heat Flux	23
19.	Sodium Superheat Data at 5.229-W/cm^2 Heat Flux	23
20.	Sodium Superheat Data at 6.26-W/cm^2 Heat Flux	23
21.	Sodium Superheat vs Pressure Curves at Various Heat Fluxes.	23
22.	Sodium Superheat Data Compared to Results of Theoretical Model	24
23.	Effect of System Pressure and Sodium Height upon Maximum Pressure Pulse for Heat Flux of 6.27 W/cm^2	24
24.	Effect of System Pressure upon Maximum Pressure Pulse for Heat Flux of 5.19 W/cm^2	25
25.	Comparison of Currently Available Data on Sodium Superheating	27

—THIS PAGE
WAS THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>
c	Constant in the equation for surface tension
n	Constant in Eq. 2
P_g	Partial pressure of noncondensable gas phase
P_ℓ	Liquid pressure (system pressure)
P_v	Vapor pressure
r'	Equivalent circular radius of cavity
r_c	Radius representing the smallest cavity cross section
R_a	Radius of curvature of liquid advancing into cavity
R_f	Radius of curvature at deepest liquid penetration into cavity
R_r	Radius of curvature of liquid receding from cavity
T	Equilibrium temperature
T_c	Critical temperature
T_ℓ	Liquid temperature
T_L	Experimentally measured, superheated-liquid temperature
T_{sat}	Saturation temperature corresponding to liquid pressure
<u>Greek Letters</u>	
σ	Surface tension
θ_a	Advancing contact angle

ON THE SUPERHEATING OF SODIUM AT LOW HEAT FLUXES

by

Robert E. Holtz and
Ralph M. Singer

ABSTRACT

Experimental data on the superheat necessary to initiate boiling of sodium were compared to a theoretical nucleation model. The sodium was contained in a vertical pipe and was heated using a high-temperature resistance wire which limited the heat flux to approximately 6 W/cm^2 ($19,000 \text{ Btu/hr-ft}$). The system pressure, heat flux, and pressure-temperature history all significantly affected the incipient superheats.

The transient pressure was also measured during the sodium nucleation. Although a large scatter in the pressure data was noted, it was concluded that pressure pulses occurred during vapor collapse, even though the liquid sodium was initially superheated.

I. INTRODUCTION

A goal of the U.S. fast-reactor safety research program is the development of techniques capable of predicting the dynamic behavior of reactors during abnormal operating conditions. A general modeling of a reactor system must include the coupling of hydrodynamics, energy exchange, structural mechanics, and neutronic behavior. At the present state of knowledge of reactor system dynamics, detailed information is not available concerning the effects of incipient boiling superheats, coolant expulsion dynamics, two-phase critical flow, parallel-channel flow stability, and structural-hydrodynamic interactions.

Because of insufficient and conflicting information on the amount of superheat required to initiate boiling in liquid-metal-cooled reactors, most reactor safety analyses for predicting system dynamics assume zero liquid superheat. This assumption forces vaporization to occur at an earlier time and at a lower temperature, and to proceed at a slower rate than it should.

Experimental evidence now indicates that very large liquid superheats may be required to initiate boiling of liquid-alkali metals; however, there is a considerable disagreement among the various authors as to the actual value of the superheat corresponding to a particular physical situation. For example, potassium superheats ranging from 21 to 701°F were measured in a free-convection loop (at various pressures) using indirect electrical resistance heating and various types of surface finishes.¹ However, when highly purified potassium was directly electrically heated (by passing current through the potassium) in a nonflowing system, the superheat values ranged from 150 to 1508°F.² There is a similar large spread in the superheating values for sodium; for example, values up to about 560°F for nonflowing sodium and up to 224°F for flowing sodium have been measured by one laboratory,³ while superheats of no more than about 25°F for flowing sodium have been measured by a second laboratory.⁴

Thus, although some difference of opinion exists as to the magnitude of liquid superheats, large superheats can occur. It is important that the liquid superheat either be reduced or predicted to provide safe reactor-design criteria.

This report will, therefore, discuss a theoretical model that predicts liquid-metal superheats and an experiment in which sodium superheats were measured.

Some of the many parameters that can affect the degree of liquid superheat necessary to initiate boiling are

1. System pressure.
2. Heat flux.
3. Pressure-temperature history.
4. Dissolved gas.
5. Surface characteristics.
6. Chemical impurities in liquid.
7. Reactor environment (neutron and radiation effects).

The initial sodium-superheat experiment reported on herein investigates the effects of the first three parameters. Sodium was contained in a motionless pool, and the system pressure, heat flux, and pressure-temperature history were systematically varied to determine their independent and coupled effects upon the superheat requirements. Although the primary emphasis of this work is on superheating, the transient pressures associated with vapor growth and collapse were measured and discussed.

This report discusses a theoretical model that predicts superheat requirements and compares this model to the experimental data.

II. INCIPIENT BOILING MODELING

A modeling technique that predicts the incipient boiling superheats in liquid metals has been developed.⁵ The degrees of liquid superheat are predicted by examining the pressure-temperature history of the system and by employing the bubble-equilibrium equation.

Fig. 1. Wetting Liquid Entering a Surface Cavity

The maximum liquid superheat occurs when all the entrapped gases have been pumped out of all the surface cavities. Hence, in this analysis, the cavities that contain no entrapped gases will be examined.

The symbols used in the model will be defined by use of figures. Figures 1-4 show the liquid advancing into the cavity, and Fig. 5 shows the vapor pressure within the cavity attempting to push the liquid from the cavity. The symbols P_v and P_l represent the vapor pressure and system pressure, respectively. The figures also show the equivalent-critical-cavity radius (r_c), the equivalent circular radius (r'), the radius of curvature of the liquid advancing into the cavity (R_a), and the radius of curvature of the receding liquid (R_r).

The basic assumption in this analysis is that cavities are required as bubble-nucleation sites, and that although any given surface has many cavities, nucleation occurs at only a few of them. Examination of a cavity and the surrounding liquid before bubble nucleation determines whether the cavity will fill with liquid. A cavity that completely fills with liquid cannot serve as a nucleation site.

Fig. 2. Nonwetting Liquid Entering a Surface Cavity.

Fig. 3. Liquid Wetting Surface Cavity When $P_v \geq P_l$

Fig. 4. Subcooled Liquid Entering a Surface Cavity

Fig. 5. Superheated Liquid Inside a Surface Cavity

When a system is filled with a liquid metal, the liquid metal may or may not wet the surface cavities. The following events may occur:

- A. Liquid wets at fill.
- B. Liquid does not wet at fill.
 - 1. Liquid wets while liquid is subcooled.
 - 2. Liquid does not wet (even when heated to the point of bubble expulsion from the cavity).
 - 3. Liquid wets when $P_v \geq P_l$.

We will examine these possible occurrences individually.

A. Liquid Wets at Fill

In this case (shown in Fig. 1), the surface-tension force acts downward toward the bottom of the cavity. Assume sufficient cleanup of both the surface and the liquid metal so that an insignificant amount of gas phase is present. Then, if

$$P_v < P_l + \frac{2\sigma|\cos \theta_a|}{r_c},$$

the cavity will fill with liquid and never be a nucleation site. Since the cavity will fill for the above condition, it will fill for all $P_v < P_l$. Thus, for all fill pressures above the saturation vapor pressure corresponding to the surface temperature, all cavities will fill and no nucleation sites will be available. Then, according to the basic assumption that cavities are required for bubble nucleation, an infinite liquid superheat will be

required. This is contrary to fact. Hence, when no entrapped gases exist within the surface cavity, nonwetting at fill is a condition for finite liquid superheat.

B. Liquid Does Not Wet at Fill

1. Liquid Wets While Liquid Is Subcooled

This situation is basically the same as the situation in which the liquid wets at fill. If the liquid wets the cavity surface while the liquid is subcooled ($P_v < P_\ell$), the cavity fills with liquid and cannot serve as a nucleation site. Thus nonwetting while the liquid is subcooled is a condition for finite liquid superheat.

2. Liquid Does Not Wet (even when heated to the point of bubble expulsion from the cavity)

This condition is shown in Fig. 2. For the nonwetting case, the surface-tension force acts upward (tending to pull the liquid-vapor interface out of the cavity) and is opposed by the pressure difference ($P_\ell - P_v$). If

$$P_\ell - P_v > \frac{2\sigma}{R_a},$$

the liquid will be forced deeper into the cavity. However, if

$$P_\ell - P_v < \frac{2\sigma}{R_a},$$

all liquid will be forced from the cavity and bubble formation occurs. For incipient bubble formation,

$$P_\ell = P_v + \frac{2\sigma}{R_a},$$

When thermal equilibrium exists at the surface, and if P_v^s is the saturated-vapor curve and P_ℓ^s is the system pressure in Fig. 2, then the liquid is subcooled. Hence, the bubble will collapse in the bulk of the liquid. It is concluded that P_ℓ^s is the liquid-saturation curve and the vapor is superheated. But again in this situation there is no liquid superheat, and this is contrary to fact. Hence, we must conclude that the wetting is essential for obtaining liquid superheat (net vapor generation).

3. Liquid Wets When $P_v \geq P_\ell$

In this situation (shown in Fig. 3), the liquid is nonwetting until wetting occurs when $P_v \geq P_\ell$, and from then on when

$$P_v \geq P_\ell + \frac{2\sigma}{R_a}.$$

After wetting, the surface-tension force acts downward and is opposed by the pressure difference ($P_v - P_\ell$). If

$$P_v > P_\ell + \frac{2\sigma}{R_a},$$

the bubble will begin to leave the cavity. For incipient bubble escape,

$$P_v = P_\ell + \frac{2\sigma}{R_a}.$$

If the vapor were subcooled, the liquid would be saturated, and no liquid superheat would occur. Since this is again contrary to fact, we may conclude that the vapor is saturated (or at some quality) and the liquid is superheated.

A boiling surface contains many surface cavities. All the situations of wetting and/or nonwetting may occur in various cavities on the boiling surface. However, the previous discussion showed that the situation most pertinent is when the liquid wets the cavity when $P_v \geq P_\ell$ and $P_g \approx 0$. This situation will be examined to provide insight into the boiling phenomena of the liquid metals, as well as to predict the liquid superheats required for incipient boiling in the liquid metals.

Examination of surface cavities and the surrounding liquid when the liquid is subcooled and does not wet will determine whether these cavities will fill with liquid. The cavity shown in Fig. 4 has an equivalent-critical-cavity radius (r_c) shown within the cavity; actually, r_c may be at the cavity entrance or anywhere within the cavity.

A force balance on a liquid entering into any portion of a cavity yields the expression

$$P_\ell - (P_v + P_g) = \frac{2\sigma}{R_a}, \quad (1)$$

where the surface tension may be expressed in the general form,³

$$\sigma = c(T_c - T_\ell)^n. \quad (2)$$

Equation 1 implies that the liquid-vapor interface is a spherical surface, which is in thermal and mechanical equilibrium with its surroundings.

If an insignificant amount of gas phase is present within the cavity, Eq. 1 reduces to

$$P_{\ell} - P_v = \frac{2\sigma}{R_a} \quad (3)$$

If $P_v > P_{\ell} + 2\sigma/R_a$ at any time while the liquid, which is nonwetting at the liquid-vapor interface, is at the cross section represented by the equivalent radius r' , the liquid passes beyond that cross section further into the cavity. If $P_v < P_{\ell} + 2\sigma/R_a$, the liquid is unable to pass further into the cavity.

It is assumed that the liquid at the liquid-vapor-solid interface does not wet the surface while the liquid is subcooled. However, it is expected that the liquid will wet the cavity surface between the liquid-vapor interface and the mouth of the cavity. This wetting of the cavity surface in the region between the liquid-vapor interface and the cavity mouth, and the nonwetting of the surface cavity at the liquid-vapor interface, will keep the cavity radius stable, despite changes in either P_v or P_{ℓ} .

As the temperature of the system increases, cleaning of the surface at the liquid-vapor interface may cause a switch from nonwetting to wetting; or as the vapor pressure increases, the liquid-vapor interface may begin to recede slightly from the cavity causing a switch from nonwetting to wetting at the interface. Upon wetting of the cavity surface at the liquid-vapor interface by the liquid metal when $P_v \geq P_{\ell}$, the surface-tension force keeps the liquid metal in the cavity. This situation (shown in Fig. 3) may be expressed by

$$P_v - P_{\ell} = \frac{2\sigma}{R_r} \quad (4)$$

Equation 4 shows that the vapor pressure (P_v) must always exceed the pressure in the liquid (P_{ℓ}) before a bubble will nucleate at a surface.

As the temperature of the liquid increases, the vapor pressure inside the cavity increases. When the liquid takes on excessive superheat, the increasing vapor pressure attempts to push the liquid from the cavity. As the liquid that is now wetting the surface at the liquid-vapor interface begins to leave the cavity, it moves from the radius r' to some radius larger than r' . With the initiation of liquid movement to a radius larger than r' , a lower degree of liquid superheat is required to sustain an equilibrium condition at this new position. Hence, the combination of the liquid movement caused by the increased vapor pressure due to increased liquid superheat

and the requirement of a smaller liquid superheat caused by the movement of the liquid-vapor interface to a larger radius results in additional vapor generation, which expels the liquid and much of the vapor from the cavity.

To calculate the liquid superheat requirements for the initiation of nucleate boiling, consider the condition just before the movement of the liquid-vapor interface. At this time, the interface between the liquid and vapor should be stable (not in motion). Figure 5 shows this stable volume of vapor in thermal and mechanical equilibrium with the surrounding liquid. For thermal equilibrium to exist, the superheated-liquid temperature must equal the vapor temperature inside the bubble. If the vapor is saturated or has some quality, the temperature in the bubble represents the saturation temperature corresponding to the pressure inside the bubble. Equation 4 may be used under these conditions.

For water and the alkali metals, the expression for the surface tension (Eq. 2) may be simplified to³

$$\sigma = c(T_c - T_\ell). \quad (5)$$

When Eq. 5 is used in the bubble-equilibrium equation (Eq. 4), the liquid temperature (T_ℓ) is equal to the superheated-liquid temperature (T). This equilibrium temperature is the temperature of both the vapor in the cavity and the liquid in the cavity.

Equations 4 and 5 represent the relationship between the bubble radius of curvature, T , P_v , and P_ℓ . The relationship between P_v and T may be expressed by the saturated-vapor curve for the fluid of interest. At this point, there are two unknown functions representing the bubble radius and P_ℓ . If either of these functions can be reasonably postulated or measured experimentally, Eq. 4 can be solved.

The smallest penetration radius to which the advancing liquid will be forced into the surface cavities (R_f) may be calculated from Eq. 3 by knowing the pressure-temperature history of the liquid. Using this liquid-penetration radius (calculated from the most severe pressure-temperature condition) permits Eq. 4 to be solved, and the degree of liquid superheat required for the initiation of nucleate boiling to be calculated. To calculate the incipient boiling superheats, we assume that the radius of curvature of the liquid-vapor interface when the surface cavity is wetted is equal to the radius of curvature of the liquid-vapor interface for the nonwetted condition. This assumption has been discussed in Ref. 5.

Using Eq. 3 and knowledge of both the surface tension and the saturated-vapor curve, we may calculate the radius to which the liquid

will enter the surface cavities. Figures 6 and 7 are plots of liquid-penetration radius versus the liquid-saturation temperature at various values of system pressure (P_ℓ) for sodium. Utilizing the family of curves and knowing the pressure-temperature history of the system, we can calculate the minimum penetration radius (R_f) for sodium.

Fig. 6. Plot of Liquid-sodium Penetration Radius vs Liquid-saturation Temperature for $P_\ell = 10, 15, 25$, and 100 psia

Fig. 7. Plot of Liquid-sodium Penetration Radius vs Liquid-saturation Temperature for $P_l = 1, 1.4, 5, \text{ and } 10 \text{ psia}$

Now, using Eq. 4, the surface tension, the saturated-vapor curve, and the proper value of R_f , we can calculate P_l . Figure 8 shows the degree of liquid superheat required to initiate nucleate boiling in sodium, plotted against the system pressure (P_l) for various values of R_f . The values of R_f selected in this analysis are the minimum points from the curves shown in Figs. 6 and 7.

The results of this modeling technique have been compared with data published in the literature, and agreement has been favorable. Reference 5 compares the incipient superheat model with these data and describes the modeling technique in more detail. The present report compares the predictions from the model with the new data.

Fig. 8. Degree of Liquid Superheat vs System Pressure for Sodium

III. EXPERIMENTAL APPARATUS

To obtain data in a carefully controlled manner to determine the validity of the incipient boiling superheat model and to gain a better understanding of liquid-metal boiling, we designed and built a sodium superheat test apparatus. Figure 9 is an isometric drawing of the apparatus, which was constructed from Type 304 stainless steel. The apparatus consisted of sodium contained inside a 2-in. nominal-diameter, Schedule 40, vertical pipe. The system pressure was controlled using an argon cover gas. Heating wires wrapped around the outside pipe wall supplied heat to the sodium, and cooling coils above the liquid-sodium level removed heat. Guard heaters were also employed for heating the system when tests runs were not being conducted and for adjusting initial conditions.

Figure 10 is a photograph of the sodium superheat test vessel, and Fig. 11 is a photograph showing an overall view of the experimental apparatus. The inside surface of the test vessel was polished to an 8- μ in. finish, and extreme care was taken to avoid weld material in the vicinity of the heated area.

112-7891A

Fig. 9. Isometric Drawing of Sodium Superheat Test Apparatus

112-6765

Fig. 10. Sodium Superheat Test Vessel

112-6766

Fig. 11. Overall View of Sodium Superheat Apparatus

Chromel-Alumel thermocouples were located in the liquid sodium, the test-vessel wall, and the gas blanket. These thermocouples were constructed from 0.012-in.-diam wires contained in a 0.062-in.-OD Inconel sheath and insulated with MgO.

The pressure in the gas blanket was measured with both a manometer and a pressure gage, and the pressure transients caused by boiling were measured with a piezoelectric pressure transducer in contact with the liquid sodium.

The argon cover gas used to control the system pressure was purified by means of a magnesium perchlorate moisture remover, a NaK bubbler, and a NaK vapor trap, which condenses any NaK vapors that might be carried out of the NaK bubbler. This system is shown at the bottom of Fig. 11.

The dump tank shown in Fig. 11 was used to initially charge the test vessel with sodium and was also used for changing the sodium level in the test vessel.

The thermocouple signals were recorded on continuous-writing strip-chart recorders, and the pressure transients on an oscillograph and oscilloscope. Some of this instrumentation is shown in Fig. 12. The initiation of boiling was detected by several techniques: (1) The acoustic vibrations caused by sudden vapor growth were detected using an accelerometer, (2) vaporization of the superheated sodium resulted in a sudden temperature drop in the liquid, which was measured by thermocouples immersed in the sodium, and (3) the vaporization caused a pressure pulse, which was recorded from signals from the piezoelectric pressure transducers. The acoustic vibrations were the most sensitive means to detect the instant of nucleation.

112-6764

Fig. 12. Sodium Superheat Apparatus and Control Panel

A single test vessel with a polished inside surface (average roughness of $8 \mu\text{in.}$) was used for this work. Before being filled with sodium, the entire system was evacuated to 2×10^{-6} mm Hg at 1220°F , and liquid sodium at 600°F was forced into the test vessel from the dump tank using a slight pressure gradient. After the sodium level was adjusted to a prescribed height (measured using an X-ray fluoroscope) and the system pressure was set to a fixed low value (using purified argon), a series of experiments was conducted varying only the heat flux. The pressure was then increased, and boiling again initiated at various heat fluxes. This procedure was repeated up to pressures of 1.08 atm. The data obtained in this experiment are presented in the appendix.

During a typical experiment, the following procedure was followed:

1. Using only the guard heaters, an initial steady state was obtained at some specific temperature (always at least 500°F below the sodium boiling point).
2. With all recorders operating, the primary heater was manually turned on, increasing the heat flux from essentially zero to a prescribed level in a step change, and maintained at this level.
3. After the sodium nucleated, no changes were made, and the steady-state boiling conditions were determined; or, if the system was at an unstable condition (i.e., repeated nucleation with significant periods of superheating), its fluctuating behavior was noted.
4. The system was then cooled, and steps 1 through 3 repeated as the next run.

The above procedure was used to investigate effects of system pressure, heat flux, and pressure-temperature history upon the incipient boiling superheats in sodium.

IV. DATA AND RESULTS

This report investigates the effects of the wall heat flux, system pressure, and pressure-temperature history upon the degree of liquid superheat required to initiate boiling in sodium.

112-8486

Fig. 13. Sodium Temperature Behavior during Test Runs

Figure 13 shows typical sodium temperature traces from a series of experiments in which only the heat flux was changed. At the lowest heat fluxes, the boiling is quite unstable, with repeated periods of free-convection superheating, sudden nucleation, and steady boiling. As the heat flux is increased, the boiling becomes quite stable; once the sodium nucleates, boiling continues indefinitely. Figure 14 shows the effect of the pressure on the transient sodium temperatures. Boiling is quite unstable at low pressure and becomes more stable as the pressure is increased. Figure 14 also shows the pressure transients

in the sodium. In all cases, considerable oscillation occurred, apparently due to alternate collapse and growth of vapor. This behavior of the pressure

112-8490 Rev. 2

Fig. 14. Pressure and Temperature Behavior during Test Runs

Figure 21 summarizes the effects of pressure for the five constant-heat-flux curves.

As anticipated, the incipient superheats decrease as the system pressure is increased; however, it is surprising that the superheats increase markedly as the heat flux increases. A possible explanation for this measured-heat-flux effect may lie in an examination of the statistical nature of boiling. The probability of nucleation in a superheated liquid is most likely a function of the amount of superheat as well as the length of time the liquid is maintained at a particular superheat. Now, since the liquid temperature increases at a rate directly proportional to the

transients in superheated sodium is similar to that observed in subcooled water.⁶ The magnitudes of the pressure pulses show considerable scatter, varying from 2 to 170 psi in duplicate runs. This scatter in the pressure is typical of that resulting from vapor collapse, and was also observed in water and other fluids.⁶

This discussion indicates that sodium boiling is most unstable at low pressures and low heat fluxes, and becomes stable as these two quantities are increased. This is further illustrated in Fig. 15, which maps the regions of stable and unstable boiling in the heat flux-pressure plane.

We will now discuss the actual values of the liquid superheat required to initiate boiling. Figures 16-20 show the liquid superheats required for incipient boiling at various pressures. Each curve is for a constant heat flux, ranging from 2.60 to 6.26 W/cm². The actual data points are shown on each curve.

112-8492 Rev. 1

Fig. 15. Heat Flux vs Pressure Plot, Showing Stable and Unstable Boiling Regions

112-8488 Rev. 4

Fig. 16. Sodium Superheat Data at 2.60-W/cm² Heat Flux

112-8489 Rev. 2

Fig. 17. Sodium Superheat Data at 3.39-W/cm² Heat Flux

112-8485 Rev. 3

Fig. 18. Sodium Superheat Data at 4.225-W/cm² Heat Flux

112-8484 Rev. 1

Fig. 19. Sodium Superheat Data at 5.229-W/cm² Heat Flux

112-8487 Rev. 2

Fig. 20. Sodium Superheat Data at 6.26-W/cm² Heat Flux

112-8513 Rev. 1

Fig. 21. Sodium Superheat vs Pressure Curves at Various Heat Fluxes

112-8512 Rev. 1

Fig. 22. Sodium Superheat Data Compared to Results of Theoretical Model

heat flux, it is apparent that the lower the heat flux, the longer will be the available time for nucleation to occur at a lower superheat range. It follows, therefore, that an increase in heat flux would result in nucleation at an increased liquid superheat. This speculation seems to be a reasonable explanation for this effect.

Figure 22 summarizes a series of experiments to illustrate the effect of pressure history on superheats. The system was pressurized to a prescribed value using purified argon; then the pressure was reduced to some low value before

applying the heat flux. The curves are those predicted by the theoretical model previously discussed. As indicated, reasonable agreement between theory and experiment is achieved, considering the normal experimental scatter.

Finally, Figs. 23 and 24 show the measured pressure pulses occurring because of vapor collapse, as a function of system pressure. The

112-8934 Rev. 1

Fig. 23. Effect of System Pressure and Sodium Height upon Maximum Pressure Pulse for Heat Flux of 6.27 W/cm²

112-8933

Fig. 24. Effect of System Pressure upon Maximum Pressure Pulse for Heat Flux of 5.19 W/cm^2

pressures caused by the sudden, initial vaporization are not reported here since they all were exceedingly small, i.e., less than 0.1 atm. Although considerable scatter exists in the data, the vapor-collapse pressures tend to increase with system pressure and liquid-column height.*

V. DISCUSSION OF RESULTS

The data in this report have raised several interesting points on the initiation of boiling of sodium from the inside, polished surface of a vertical pipe. The first point to be considered here is the question of boiling stability.

Reference 7 presented a simplified model which attempts to predict the conditions under which sodium boils stably. The analysis leads to an expression relating the minimum heat flux necessary to sustain stable boiling to the wall superheat, liquid and wall physical properties, and surface-cavity dimensions. This expression had to be empirically corrected to more closely fit the reported experimental data. Although this empirical correction weakens the analysis, a more serious practical

* The heights on the figures are measured from the top of the heated section.

difficulty in applying the results of this model is that cavity sizes must be known in detail. Thus, not only must the cavity-size distribution on a surface be known, but also, an a-priori judgement must be made concerning which cavity radius will be effective in nucleating bubbles.

The data reported on sodium nucleation in Ref. 7 were limited to very low pressures, e.g., 40-106 mm Hg (0.053-0.139 atm), and relatively large heat fluxes ($\sim 30 \text{ W/cm}^2$) were necessary to reach stable boiling. This is not surprising, since it is well known (e.g., Ref. 8) that boiling liquids behave erratically at low pressures. Our data, as summarized in Figs. 14 and 15, graphically illustrate that sodium boiling is stable at pressures greater than about 0.3 atm. For example, a heat flux of only 6 W/cm^2 ($19,000 \text{ Btu/hr-ft}^2$) was necessary to attain stable boiling at 0.4 atm.

A second interesting point investigated in this report was the effect of the pressure-temperature history on the maximum superheats necessary to nucleate sodium. We compared our data to the theoretical predictions of Ref. 5 and obtained some agreement. If the pressure-temperature history of our system was not considered, the scatter in the data presented in Fig. 22 could not be easily explained. In fact, one explanation of the large scatter in superheat values reported in the literature is due to the unreported pressure-temperature histories of the various experimental systems.

The wall heat flux, in the range studied in this report, had a marked effect upon the incipient superheats. As illustrated in Fig. 21, doubling the heat flux approximately doubles the measured superheat. Our opinion is that this result may be peculiar to the low heat fluxes used and this effect may be altered at higher heat fluxes. There is some disagreement in the published literature on the heat-flux effect. According to the data in Ref. 10, the superheat to initiate boiling may be either increased or decreased as the heat flux is increased, depending upon the system pressure. However, the superheats reported in Ref. 11 decrease monotonically with increasing heat flux. This phenomenon should be studied further to clarify this disagreement.

Figure 25 compares recent sodium-superheat data from several countries to that presented in this report. Values of the superheat up to about 560°F have also been measured for sodium,³ but are not included in Fig. 25 since we do not know the pressure range. The results in Fig. 25 indicate that there may now be some hope in correlating the available sodium superheats as more data become available. The still large spread in the data may be reduced by considering such effects as pressure-temperature histories (surface "aging"), sodium purity, and perhaps even the method of heating ("indirect" versus "direct").

112-9074 Rev. 1

Fig. 25. Comparison of Currently Available Data on Sodium Superheating

VI. CONCLUSIONS

The information obtained during the experiment described in this report produced the following conclusions:

- (1) The pressure-temperature history influences the degree of superheating required for incipient boiling in sodium. Fair agreement exists between the incipient superheat model and the data obtained in this experiment.
- (2) The incipient-boiling superheats depend strongly upon the heat flux, especially when the heat fluxes are small.
- (3) At extremely low pressures and/or low heat fluxes, unstable boiling occurs; however, stable boiling may be obtained by increasing either the system pressure or the heat flux.
- (4) The magnitudes of the vapor-collapse pressure pulses following the initiation of boiling show considerable scatter and are unpredictable at this time.

The significant problem still remains of providing the proper information on the degree of superheating that alkali liquid metals will sustain before boiling in a reactor core. Future work should allow the reactor designer to more confidently specify systems accounting for the transient boiling of sodium coolant.

APPENDIX

Tabulation of Data

Run No.	Heat Input, W	Heat Flux, W/cm ²	Initial Sodium Temp, °F	System Pressure, atm	Saturation Temp, °F	Max Sodium Temp, °F	SS Boiling Temp, °F	T _L -T _{sat} Incipient Boiling, °F	T _L -T _{sat} SS Boiling, °F	Max Vapor-collapse Pressure, psia	Time Delay between Nucleation and Max Pressure Pulse, sec	Height of Sodium above Heater, cm	Max Pressure Experienced by System with Liquid Subcooled, atm
B-1-1	350	2.56	752	0.479	1483	1532	1487	45	4	8.6	-	2.9	0.479
B-1-2	350	2.56	-	0.489	1487	1548	1492	61	5	9.8	0.17	2.9	0.479
B-1-3	350	2.56	-	0.505	1492	1551	1493	59	1	8.5	-	2.9	0.479
B-1-4	350	2.56	-	0.509	1494	1531	1493	37	-1	8.3	-	2.9	0.479
B-1-5	350	2.56	-	0.512	1495	1552	1495	57	0	9.2	-	2.9	0.479
B-1-6	350	2.56	-	0.515	1496	1536	1496	40	0	11.5	0.50	2.9	0.479
B-3-1	568	4.16	770	0.505	1493	1586	1504	93	11	13.4	1.11	2.9	0.505
R-3-2	568	4.16	-	0.505	1493	1597	1514	104	10	12.4	0.49	2.9	0.505
B-4-1	692	5.07	861	0.472	1481	1488	1482	8	1	9.3	0.37	2.9	0.505
B-4-2	696	5.09	1010	0.492	1488	1605	1496	117	8	28.7	0.08	2.9	0.505
B-4-3	696	5.09	1010	0.505	1492	1599	1498	107	6	14.6	-	2.9	0.505
B-5-1	847	6.20	774	0.480	1484	1610	1490	126	6	44.1	-	2.9	0.505
B-5-2	842	6.16	739	0.476	1482	1622	1495	140	13	13.0	0.47	2.9	0.505
B-5-3	851	6.23	1036	0.499	1491	1635	1500	144	9	45.6	-	2.9	0.505
B-6-1	452	3.31	667	0.468	1479	1530	1487	51	8	27.6	0.20	2.9	0.505
B-6-2	452	3.31	-	0.484	1485	1559	1491	74	6	38.6	0.27	2.9	0.505
B-6-3	452	3.31	-	0.492	1488	1574	1498	86	10	9.9	0	2.9	0.505
B-7-1	345	2.53	598	0.465	1478	1548	1486	70	8	8.6	-	2.9	0.505
B-7-2	345	2.53	-	0.468	1479	1538	1485	59	6	8.8	-	2.9	0.505
B-7-3	345	2.53	-	0.479	1483	1540	1488	57	5	10.2	-	2.9	0.505
B-7-4	345	2.53	-	0.482	1484	1566	1490	82	6	8.7	-	2.9	0.505
B-8-1	848	6.21	880	0.492	1488	1610	1497	122	9	67.3	-	2.9	0.505
B-9-1	697	5.10	810	0.492	1488	1601	1498	113	10	11.6	0.30	2.9	0.505
B-10-1	851	6.23	969	0.501	1491	1624	1499	133	8	12.7	0.22	2.9	0.505
C-1-1	352	2.58	624	0.663	1541	1600	-	59	-	11.8	0.15	2.9	0.663
C-1-2	352	2.58	-	0.670	1542	1602	-	60	-	11.8	-	2.9	0.663
C-1-3	352	2.58	-	0.677	1544	1608	-	64	-	17.5	1.58	2.9	0.663
C-1-4	352	2.58	-	0.682	1546	1608	-	62	-	11.9	-	2.9	0.663
C-2-1	455	3.33	885	0.693	1548	1582	-	34	-	11.2	-	2.9	0.693
C-2-2	455	3.33	-	0.702	1551	1613	1554	62	3	45.3	0.79	2.9	0.693
C-3-1	572	4.19	785	0.671	1542	1647	1554	105	12	14.8	0.75	2.9	0.693
C-4-1	705	5.16	778	0.686	1547	1662	1557	115	10	15.3	0.31	2.9	0.693
C-5-1	828	6.06	827	0.706	1552	1684	1557	132	5	18.5	0.29	2.9	0.706
C-6-1	525	3.84	586	0.642	1535	1604	-	69	-	36.9	0.25	2.9	0.706
C-6-2	525	3.84	-	0.664	1541	1625	1543	84	2	13.8	0.45	2.9	0.706
C-7-1	856	6.27	927	0.678	1545	1654	1555	109	10	14.0	0.64	2.9	0.706
C-9-1	856	6.27	803	0.681	1545	1684	1557	139	12	74.0	0.04	2.9	0.706
C-10-1	861	6.30	440	0.519	1497	1556	1534	59	37	51.6	-	2.9	0.706
C-11-1	861	6.30	792	0.659	1539	1676	1548	137	9	16.7	0.33	2.9	0.706
C-12-1	712	5.21	851	0.689	1548	1669	1555	121	7	14.4	0.22	2.9	0.706
C-13-1	576	4.22	702	0.677	1544	1641	1555	97	11	18.0	0.15	2.9	0.706
C-14-1	458	3.35	806	0.682	1547	1630	-	83	-	12.7	0.71	2.9	0.706
C-14-2	458	3.35	-	0.705	1552	1651	1558	99	6	12.8	0.83	2.9	0.706
C-15-1	861	6.30	777	0.662	1540	1678	1548	138	8	15.1	0.31	2.9	0.706
C-16-1	861	6.30	1079	0.704	1551	1701	1556	150	5	16.7	0.27	2.9	0.706
D-2-1	861	6.30	905	0.700	1551	1675	1559	124	8	20.5	1.13	2.9	0.706
D-3-1	712	5.21	803	0.703	1551	1640	1559	89	8	16.8	0.84	2.9	0.706
D-4-1	861	6.30	763	0.699	1550	1691	1559	141	9	16.3	-	2.9	0.706
D-5-1	458	3.35	844	0.730	1558	1642	1565	84	7	12.5	0.80	2.9	0.730
D-5-2	458	3.35	-	0.739	1560	1631	1568	71	8	14.9	1.15	2.9	0.730
D-5-3	458	3.35	-	0.751	1563	1635	1569	72	6	13.9	0.57	2.9	0.730
D-5-4	458	3.35	-	0.763	1566	1639	1570	73	4	14.7	1.47	2.9	0.730
D-5-5	458	3.35	-	0.766	1567	1640	1572	73	5	16.0	0.37	2.9	0.730
D-5-6	458	3.35	-	0.771	1568	1649	1573	81	5	15.3	0.89	2.9	0.730
D-5-7	458	3.35	-	0.776	1569	1648	1574	79	5	13.4	0.37	2.9	0.730
D-5-8	458	3.35	-	0.783	1571	1630	1575	59	4	15.6	0.20	2.9	0.730
D-5-9	458	3.35	-	0.789	1573	1648	-	75	-	17.1	0.09	2.9	0.730
D-5-10	458	3.35	-	0.790	1573	1643	1574	70	4	14.7	1.16	2.9	0.730
D-5-11	458	3.35	-	0.790	1573	1648	1579	75	6	19.1	-	2.9	0.730
E-1-1	861	6.30	600	0.693	1548	1679	1564	131	16	15.1	0.34	2.9	0.730
E-2-1	712	5.21	858	0.709	1553	1686	1570	133	17	14.6	0.38	2.9	0.730
E-3-1	525	3.84	839	0.726	1557	1660	1568	103	11	15.7	0.43	2.9	0.730
E-4-1	458	3.35	936	0.738	1560	1641	1571	81	11	13.4	0.28	2.9	0.738
E-4-2	458	3.35	-	0.752	1564	1649	1579	85	15	14.0	0.64	2.9	0.738
E-4-3	458	3.35	-	0.763	1566	1649	1580	83	14	14.0	0.83	2.9	0.738
E-4-4	457	3.35	-	0.772	1569	1660	1583	91	14	14.1	0.68	2.9	0.738
E-4-5	458	3.35	-	0.782	1571	1670	1586	99	15	14.0	-	2.9	0.738
E-4-6	458	3.35	-	0.796	1574	1671	1588	97	14	-	-	2.9	0.738
E-5-1	861	6.30	931	0.729	1558	1699	1570	141	12	16.2	0.32	2.9	0.729
E-6-1	861	6.30	1242	0.783	1571	1729	1581	158	10	17.3	0.34	2.9	0.783
E-7-1	572	4.19	579	0.739	1560	1664	1580	104	20	16.0	0.21	2.9	0.783
E-8-1	861	6.30	805	0.753	1564	1699	1585	135	21	18.5	0.33	2.9	0.783

Run No.	Heat Input, W	Heat Flux, W/cm ²	Initial Sodium Temp, °F	System Pressure, atm	Saturation Temp, °F	Max Sodium Temp, °F	SS Boiling Temp, °F	T _L -T _{sat} Incipient Boiling, °F	T _L -T _{sat} SS Boiling, °F	Max Vapor-collapse Pressure, psia	Time Delay between Nucleation and Max Pressure Pulse, sec	Height of Sodium above Heater, cm	Max Pressure Experienced by System with Liquid Subcooled, atm
E-9-1	712	5.21	872	0.739	1560	1684	1579	124	19	13.5	0.30	2.9	0.783
E-10-1	458	3.35	802	0.746	1562	1653	1576	91	14	20.0	0.62	2.9	0.783
E-10-2	458	3.35	-	0.766	1567	1650	1582	87	15	15.3	-	2.9	0.783
E-10-3	458	3.35	-	0.783	1571	1651	1583	80	12	13.5	-	2.9	0.783
E-10-4	458	3.35	-	0.795	1574	1662	1588	88	14	23.2	-	2.9	0.783
E-10-5	458	3.35	-	0.813	1578	1685	-	93	-	14.7	-	2.9	0.783
E-11-1	861	6.30	1005	0.773	1569	1711	1587	142	18	17.9	0.17	2.9	0.783
E-12-1	579	4.24	419	0.731	1558	1661	1574	103	16	13.5	0.63	2.9	0.783
E-13-1	712	5.21	840	0.729	1558	1689	1671	131	13	17.2	0.36	2.9	0.783
E-14-1	579	4.24	790	0.739	1561	1680	1578	119	17	13.7	0.85	2.9	0.783
E-15-1	712	5.21	978	0.756	1565	1702	1580	137	15	18.0	0.32	2.9	0.783
E-16-1	712	5.21	1010	0.763	1567	1705	1581	138	14	16.9	0.49	2.9	0.783
F-1-1	861	6.30	963	0.794	1574	1736	1590	162	16	18.8	0.50	2.9	0.794
F-2-1	712	5.21	957	0.793	1574	1702	1590	128	16	17.0	0.46	2.9	0.794
F-3-1	861	6.30	565	0.839	1584	1715	1594	131	10	21.3	0.38	2.9	0.839
F-4-1	861	6.30	940	0.876	1592	1738	1599	146	7	18.9	-	2.9	0.876
F-5-1	712	5.21	932	0.863	1590	1707	1595	117	5	17.7	0.37	2.9	0.876
F-6-1	525	3.84	905	0.866	1590	1682	1595	92	4	15.1	0.76	2.9	0.876
F-7-1	462	3.38	889	0.867	1590	1676	-	86	-	14.1	-	2.9	0.876
F-7-2	462	3.38	-	0.874	1592	1681	1600	89	8	17.8	-	2.9	0.876
F-7-3	462	3.38	-	0.901	1597	1683	1601	86	3	14.6	-	2.9	0.876
F-8-1	525	3.84	327	0.827	1581	1679	1585	98	2	16.2	0.45	2.9	0.876
F-9-1	712	5.21	907	0.869	1591	1687	1596	96	2	17.9	-	2.9	0.876
F-10-1	865	6.33	962	0.836	1583	1707	1593	124	10	17.6	0.45	2.9	0.876
F-11-1	462	3.38	1047	0.869	1591	1557	1593	76	2	14.8	0.07	2.9	0.876
F-11-2	462	3.38	-	0.876	1592	1664	1594	72	2	14.9	0.11	2.9	0.876
F-11-3	462	3.38	1047	0.889	1595	1670	1600	75	5	18.1	0.18	2.9	0.876
F-11-4	462	3.38	-	0.902	1598	1667	1604	69	6	17.3	0.25	2.9	0.876
F-11-5	462	3.38	-	0.916	1601	1675	1606	74	5	15.5	-	2.9	0.876
F-11-6	462	3.38	-	0.926	1603	1680	1607	77	4	17.6	0.27	2.9	0.876
F-12-1	579	4.24	918	0.826	1589	1701	1599	112	10	16.1	0.58	2.9	0.876
G-1-1	843	6.17	824	0.016	1041	1132	-	91	-	3.9	-	2.9	0.876
G-2-1	860	6.29	560	0.016	1041	1180	-	139	-	2.1	-	2.9	0.876
G-3-1	712	5.21	820	0.039	1133	1207	-	74	-	-	-	2.9	0.876
G-3-2	712	5.21	-	0.039	1133	1180	-	47	-	1.7	-	2.9	0.876
G-3-3	712	5.21	-	0.039	1133	1190	-	57	-	1.7	-	2.9	0.876
G-3-4	712	5.21	-	0.039	1133	1199	-	66	-	3.9	-	2.9	0.876
G-3-5	712	5.21	-	0.039	1133	1189	-	56	-	5.3	-	2.9	0.876
G-3-6	712	5.21	-	0.039	1133	1189	-	56	-	3.8	-	2.9	0.876
G-3-7	712	5.21	-	0.039	1133	1192	-	59	-	12.9	-	2.9	0.876
G-3-8	712	5.21	-	0.039	1133	1204	-	71	-	6.3	-	2.9	0.876
G-3-9	712	5.21	-	0.039	1133	1203	-	70	-	5.2	-	2.9	0.876
G-3-10	712	5.21	-	0.039	1133	1222	-	87	-	6.7	-	2.9	0.876
G-3-11	712	5.21	-	0.039	1133	1227	-	93	-	8.8	-	2.9	0.876
G-3-12	712	5.21	-	0.039	1133	1194	-	59	-	8.0	-	2.9	0.876
G-4-1	579	4.24	764	0.046	1152	1282	-	130	-	1.8	-	2.9	0.876
G-4-2	579	4.24	-	0.046	1152	1253	-	101	-	2.5	-	2.9	0.876
G-4-3	579	4.24	-	0.046	1152	1234	-	82	-	2.4	-	2.9	0.876
G-4-4	579	4.24	-	0.046	1152	1209	-	55	-	3.2	-	2.9	0.876
G-4-5	579	4.24	-	0.046	1152	1213	-	61	-	3.0	-	2.9	0.876
G-4-6	579	4.24	764	0.046	1152	1217	1599	65	10	3.1	0.58	2.9	0.876
G-4-7	579	4.24	-	0.046	1152	1212	-	60	-	9.0	-	2.9	0.876
G-4-8	579	4.24	-	0.046	1152	1209	-	57	-	3.1	-	2.9	0.876
G-4-9	579	4.24	-	0.046	1152	1211	-	59	-	3.5	-	2.9	0.876
G-4-10	579	4.24	-	0.046	1152	1229	-	77	-	6.8	-	2.9	0.876
G-5-1	462	3.38	802	0.056	1175	1275	-	100	-	25.8	-	2.9	0.876
G-6-1	352	2.58	935	0.064	1192	1276	-	84	-	4.3	-	2.9	0.876
G-6-2	352	2.58	-	0.064	1192	1261	-	69	-	4.3	-	2.9	0.876
G-6-3	352	2.58	-	0.064	1192	1254	-	62	-	4.3	-	2.9	0.876
H-1-1	352	2.58	754	0.017	1042	1149	-	107	-	5.2	-	2.9	0.876
H-1-2	352	2.58	-	0.017	1042	1125	-	83	-	1.2	-	2.9	0.876
H-1-3	352	2.58	-	0.017	1042	1149	-	107	-	-	-	2.9	0.876
H-1-4	352	2.58	-	0.017	1042	1152	-	110	-	-	-	2.9	0.876
H-2-1	847	6.20	599	0.018	1048	1166	-	118	-	3.8	0.90	2.9	0.876
H-3-1	712	5.21	555	0.015	1034	1181	-	147	-	2.6	-	2.9	0.876
H-3-2	712	5.21	-	0.015	1034	1152	-	118	-	1.8	-	2.9	0.876
H-3-3	712	5.21	-	0.015	1034	1145	-	111	-	3.0	-	2.9	0.876
H-3-4	712	5.21	-	0.015	1034	1159	-	125	-	2.5	-	2.9	0.876
H-3-5	712	5.21	-	0.015	1034	1147	-	113	-	3.7	-	2.9	0.876
H-3-6	712	5.21	-	0.015	1034	1142	-	103	-	2.1	-	2.9	0.876
H-3-7	712	5.21	-	0.015	1034	1149	-	115	-	-	-	2.9	0.876
H-3-8	712	5.21	-	0.015	1034	1151	-	117	-	1.9	-	2.9	0.876
H-3-9	712	5.21	-	0.015	1034	1147	-	113	-	-	-	2.9	0.876
H-3-10	712	5.21	-	0.015	1034	1153	-	119	-	-	-	2.9	0.876
H-3-11	712	5.21	555	0.015	1034	1161	1599	127	10	3.3	0.90	2.9	0.876
H-3-12	712	5.21	-	0.015	1034	1152	-	118	-	2.2	-	2.9	0.876
H-3-12	712	5.21	-	0.015	1034	1165	-	131	-	2.5	-	2.9	0.876
H-3-14	712	5.21	-	0.015	1034	1158	-	124	-	3.4	-	2.9	0.876
H-4-1	579	4.24	617	0.015	1034	1164	-	130	-	2.2	-	2.9	0.876

Run No.	Heat Input, W	Heat Flux, W/cm ²	Initial Sodium Temp, °F	System Pressure, atm	Saturation Temp, °F	Max Sodium Temp, °F	SS Boiling Temp, °F	T _L -T _{sat} Incipient Boiling, °F	T _L -T _{sat} SS Boiling, °F	Max Vapor-collapse Pressure, psia	Time Delay between Nucleation and Max Pressure, Pulse, sec	Height of Sodium above Heater, cm	Max Pressure Experienced by System with Liquid Subcooled, atm
H-4-2	579	4.24	-	0.015	1034	1152	-	118	-	2.2	-	2.9	0.876
H-4-3	579	4.24	-	0.015	1034	1142	-	108	-	2.2	-	2.9	0.876
H-4-4	579	4.24	-	0.015	1034	1143	-	109	-	2.2	-	2.9	0.876
H-4-5	579	4.24	-	0.015	1034	1146	-	112	-	4.2	-	2.9	0.876
H-4-6	579	4.24	-	0.015	1034	1149	-	115	-	7.3	-	2.9	0.876
H-4-7	579	4.24	-	0.015	1034	1150	-	116	-	1.1	-	2.9	0.876
H-4-8	579	4.24	-	0.015	1034	1151	-	117	-	1.9	-	2.9	0.876
H-4-9	579	4.24	-	0.015	1034	1157	-	123	-	2.3	-	2.9	0.876
H-4-10	579	4.24	-	0.015	1034	1176	-	142	-	2.1	-	2.9	0.876
H-4-11	579	4.24	-	0.015	1034	1158	-	124	-	12.1	-	2.9	0.876
I-1-1	352	2.58	534	0.188	1335	1398	-	63	-	6.0	-	2.9	0.876
I-1-2	352	2.58	-	0.188	1335	1396	-	61	-	5.4	-	2.9	0.876
I-2-1	455	3.33	918	0.182	1331	1418	1339	87	8	7.9	-	2.9	0.876
I-3-1	576	4.22	732	0.183	1332	1435	1340	103	5	17.9	-	2.9	0.876
I-4-1	704	5.15	940	0.182	1331	1463	1345	132	14	8.4	-	2.9	0.876
I-5-1	860	6.29	459	0.175	1325	1463	1338	138	13	6.6	1.32	2.9	0.876
J-1-1	847	6.20	707	0.340	1426	1498	1430	72	4	6.7	-	2.9	0.876
J-2-1	325	2.38	865	0.3476	1430	1496	1442	66	14	8.0	-	2.9	0.876
J-3-1	462	3.38	924	0.3506	1431	1527	1440	96	9	7.2	-	2.9	0.876
J-4-1	722	5.28	451	0.328	1421	1536	1430	115	9	10.9	0.64	2.9	0.876
J-5-1	579	4.24	862	0.334	1424	1525	1430	101	6	6.3	0.55	2.9	0.876
K-1-1	856	6.27	640	0.508	1493	1608	1500	115	7	11.2	0.12	2.9	0.876
K-2-1	352	2.58	970	0.523	1499	1555	-	56	-	11.1	-	2.9	0.876
K-2-2	352	2.58	-	0.530	1501	1565	-	64	-	-	-	2.9	0.876
K-3-1	455	3.33	780	0.524	1499	1568	-	69	-	10.5	0.28	2.9	0.876
K-4-1	705	5.16	964	0.519	1497	1592	-	95	-	10.8	0.47	2.9	0.876
K-5-1	584	4.27	445	0.4986	1490	1559	1500	69	10	62.7	0.29	2.9	0.876
L-1-1	856	6.27	730	0.677	1544	1655	1551	111	7	36.0	-	2.9	0.876
L-2-1	354	2.59	971	0.703	1551	1608	1558	57	7	135.3	-	2.9	0.876
L-2-2	354	2.59	-	0.709	1553	1592	-	39	-	113.4	-	2.9	0.876
L-2-3	354	2.59	-	0.711	1553	1579	-	26	-	12.3	-	2.9	0.876
L-2-4	354	2.59	-	0.717	1555	1619	1562	64	7	-	-	2.9	0.876
L-3-1	462	3.38	822	0.701	1551	1620	1560	69	9	47.9	-	2.9	0.876
L-3-2	462	3.38	-	0.705	1552	1618	1560	66	8	180.4	-	2.9	0.876
L-4-1	572	4.19	434	0.690	1548	1632	1552	84	7	12.6	0.48	2.9	0.876
L-5-1	709	5.19	791	0.685	1542	1647	1560	105	18	19.2	0.45	2.9	0.876
L-6-1	352	2.58	873	0.672	1543	1608	-	65	-	11.9	1.61	2.9	0.876
L-6-2	352	2.58	-	0.683	1546	1620	-	74	-	12.9	1.53	2.9	0.876
L-7-1	458	3.35	852	0.699	1550	1629	1561	79	11	14.9	0.31	2.9	0.876
L-7-2	458	3.35	-	0.712	1553	1629	1563	76	10	12.0	-	2.9	0.876
L-7-3	458	3.35	-	0.723	1556	1635	1565	79	9	12.5	0.69	2.9	0.876
L-8-1	572	4.19	529	0.671	1543	1611	-	68	-	13.3	-	2.9	0.876
L-8-2	572	4.19	-	0.680	1545	1628	1552	83	7	-	-	2.9	0.876
L-9-1	712	5.21	873	0.708	1552	1650	1558	98	6	17.3	0.65	2.9	0.876
L-10-1	861	6.30	898	0.666	1541	1600	-	59	-	26.9	-	2.9	0.876
L-10-2	861	6.30	-	0.679	1545	1656	1553	111	8	-	-	2.9	0.876
L-11-1	576	4.22	995	0.667	1542	1633	1550	91	8	17.9	0.79	2.9	0.876
L-12-1	357	2.61	581	0.684	1546	1597	-	51	-	11.9	-	2.9	0.876
L-12-2	357	2.61	-	0.694	1549	1600	-	51	-	12.5	0.85	2.9	0.876
L-12-3	357	2.61	-	0.708	1552	1618	-	66	-	12.1	-	2.9	0.876
L-13-1	861	6.30	762	0.670	1542	1681	1559	139	17	15.7	0.28	2.9	0.876
M-1-1	357	2.61	839	0.894	1596	1622	-	26	-	17.1	-	2.9	0.894
M-1-2	357	2.61	-	0.902	1598	1650	-	52	-	15.0	-	2.9	0.894
M-1-3	357	2.61	-	0.906	1599	1653	-	54	-	16.4	-	2.9	0.894
M-1-4	357	2.61	-	0.912	1600	1660	-	60	-	-	-	2.9	0.894
M-2-1	712	5.21	979	0.895	1596	1703	1601	107	5	18.1	0.43	2.9	0.895
M-3-1	357	2.61	690	0.9057	1599	1635	-	36	-	14.2	-	2.9	0.9057
M-3-2	357	2.61	-	0.9091	1599	1654	-	55	-	-	-	2.9	0.9057
M-4-1	580	4.25	656	0.896	1597	1675	1602	78	5	14.9	-	2.9	0.9057
M-5-1	465	3.40	539	0.892	1596	1665	1599	69	3	15.5	-	2.9	0.9057
M-6-1	861	6.30	646	0.873	1591	1702	1599	111	8	21.9	0.95	2.9	0.9057
N-1-1	861	6.30	553	1.0431	1627	1747	1638	120	11	20.0	0.31	2.9	1.0431
N-2-1	472	3.45	773	1.0846	1635	1694	1638	59	3	18.6	1.39	2.9	1.0846
N-2-2	472	3.45	773	1.0906	1636	1702	-	66	-	16.9	-	2.9	1.0846
N-2-3	472	3.45	773	1.0973	1637	1691	-	54	-	17.8	-	2.9	1.0846
N-2-4	472	3.45	773	1.1123	1640	1703	-	63	-	18.2	-	2.9	1.0846
N-3-1	579	4.24	568	1.045	1627	1699	1635	72	8	-	-	2.9	1.0846
P-1-1	861	6.30	759	0.482	1484	1550	1635	66	8	11.1	1.39	2.9	2.8
P-2-1	386	2.83	725	0.476	1482	1526	1492	44	10	9.1	-	2.9	2.8
P-3-1	533	3.90	787	0.527	1499	1559	1500	60	1	26.6	0.11	2.9	2.8
P-4-1	861	6.30	818	0.505	1492	1608	1501	116	9	11.1	0.30	2.9	2.8
P-5-1	704	5.15	556	0.499	1490	1543	-	53	-	100.5	0.20	2.9	2.8
Q-6-1	838	6.13	1150	0.611	1526	1660	1530	134	4	22.1	-	31.1	2.8
Q-7-1	692	5.06	731	0.602	1523	1596	1524	73	1	12.8	-	31.1	2.8
Q-8-1	842	6.16	1038	0.614	1527	1707	1531	180	4	38.6	-	31.1	2.8
Q-9-1	838	6.13	1009	0.619	1528	1716	1541	188	13	28.5	-	31.1	2.8
Q-10-1	842	6.16	1183	0.625	1530	1675	-	145	-	27.6	-	31.1	2.8
R-3-1	555	4.06	722	0.598	1521	1657	1528	136	7	21.9	-	31.1	2.8
R-4-1	688	5.04	1246	0.609	1525	1720	1530	195	5	47.9	-	31.1	2.8
R-5-1	856	6.27	420	0.570	1514	1551	-	37	-	16.4	-	31.1	2.8
R-7-1	856	6.27	300	0.308	1409	1484	1420	75	11	11.6	-	31.1	2.8
S-1-1	448	3.28	510	0.933	1605	1680	1601	75	15	30.8	-	31.1	2.8
S-2-1	885	6.48	1119	0.931	1604	1797	1620	193	16	63.9	-	31.1	2.8
S-3-1	885	6.48	1133	0.943	1607	1754	1626	147	19	40.1	-	31.1	2.8
S-4-1	885	6.48	501	0.895	1596	1765	1615	169	19	72.5	-	31.1	2.8
S-5-1	728	5.33	1025	0.916	1601	1707	1613	106	12	26.0	-	31.1	2.8
S-6-1	725	5.31	1053	0.933	1605	1736	1620	131	15	37.6	-	31.1	2.8

ACKNOWLEDGMENTS

We wish to acknowledge the assistance of H. J. Haupt, R. R. Macheel, W. A. Mele, and J. J. Reed for their contributions during the construction and operation stages of this experiment.

REFERENCES

1. H. W. Hoffman and A. J. Krakoviak, *Studies in Boiling with Liquid Potassium*, ORNL-P-35 (1963).
2. K. H. Spiller et al., *Überhitzung und Einzelblasenejektion bei der Verdampfung von stagnierenden Flussigmetallen*, Atomkernenergie 12, No. 3/4 (1967), 111-114.
3. Personal communication, K. Spiller, Centro Coumne di Ricerca (Euratom), Ispra, Italy.
4. Personal communication, L. Bernath, Atomics International, Canoga Park, California.
5. R. E. Holtz, *The Effect of the Pressure-Temperature History upon Incipient-boiling Superheats in Liquid Metals*, ANL-7184 (June 1966).
6. R. M. Singer, *The Expulsion of Liquid from a Rapidly Heated Channel*, ANL-7337 (May 1967).
7. I. Shai, *The Mechanism of Nucleate Pool Boiling Heat Transfer to Sodium and the Criterion for Stable Boiling*, Mass. Inst. of Tech. Report DSR-76303-45 (Jan 1967).
8. J. W. Westwater, *Boiling of Liquids*, Advances in Chemical Engineering, Vol. 2 (1958), Academic Press, N. Y., p. 29.
9. LeGonidec et al., *Etudes Experimentales sur l'Ebullition du Sodium*, Presented at the International Conference on the Safety of Fast Reactors, Aix-en-Provence, France (Sept.19-22, 1967).
10. B. S. Petukhov et al., *Study of Sodium Boiling Heat Transfer*, Proc. Third Intl. Heat Transf. Conf. (Chicago), pp. 80-91 (Aug.12, 1966).
11. G. C. Pinchera et al., *Liquid Sodium Superheat and Water Ejection Experiments*, Presented at the Symposium on Two-Phase Flow Dynamics, Eindhoven, The Netherlands (Sept.4-9, 1967).
12. P. J. Marto and W. M. Rohsenow, *The Effect of Surface Conditions on Nucleate Pool Boiling Heat Transfer to Sodium*, M.I.T. Tech. Report 5219-33 (Jan 1965).
13. J. B. Heineman, "Forced Convection Boiling Sodium Studies at Low Pressure," *Proceedings of the Conference on Application of High Temperature Instrumentation to Liquid-Metal Experiments*, September 28-29, 1965, ANL-7100, pp. 189-194.
14. J. A. Edwards and H. W. Hoffman, "Superheat with Boiling Alkali Metals," *Proceedings of the Conference on Application of High Temperature Instrumentation to Liquid-Metal Experiments*, September 28-29, 1965, ANL-7100, pp. 515-534.