Phil
210
12/20/67
ANL-7337

ANL-7337

MASTER

Argonne National Laboratory

THE EXPULSION OF LIQUID FROM A RAPIDLY HEATED CHANNEL

by

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

ANL-7337
Engineering and
Equipment (TID-4500)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

THE EXPULSION OF LIQUID FROM
A RAPIDLY HEATED CHANNEL

by

Ralph M. Singer

Reactor Engineering Division

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.

May 1967

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

TABLE OF CONTENTS

	<u>Page</u>
NOMENCLATURE	6
ABSTRACT	7
I. INTRODUCTION	7
II. EXPERIMENTAL DESIGN	11
III. EXPERIMENTAL RESULTS	16
A. Tests with Initially Stagnant Liquid	19
1. Pressure Transients	19
2. Coolant Motion	26
B. Tests with Initially Flowing Water	37
C. Flow Structure from Film Analysis	40
IV. DISCUSSION AND SUMMARY	41
V. CONCLUSIONS	43
APPENDIXES	
A. Transient Temperature of a Rapidly Heated Body with Conduction Losses	45
B. A Simplified Analytical Expulsion Model	50
C. Tabulated Data	56
ACKNOWLEDGMENTS	64
REFERENCES	65

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Transient Power Circuit	12
2.	Cross Section of Expulsion Tube	13
3.	View of Heated Tube	14
4.	General View of Experimental Apparatus	14
5.	Typical Experimental Measurements for Subcooled Liquid.	16
6.	Typical Experimental Measurements for Saturated Liquid :	17
7.	Effect of Initial Temperature on Transient Pressure	18
8.	Variation of Initial Pressure Pulse with Subcooling; Energy-generation Rate as a Parameter	20
9.	Variation of Initial Pressure Pulse with Energy-generation Rate; Subcooling as a Parameter.	20
10.	Variation of Maximum Secondary Pressure Pulse	21
11.	Effect of Column Height on Initial Pressure Pulse	22
12.	Effect of Annular Gap and Subcooling on Initial Pressure Pulse	23
13.	Effect of Type of Liquid on Initial Pressure Pulses.	23
14.	Effect of Subcooling and Energy-generation Rate on Initial Pressure Pulses for Ethylene Bromide	24
15.	Effect of Subcooling and Energy-generation Rate on Initial Pressure Pulses for Methanol	25
16.	Effect of Subcooling on Column Displacement and Void Fraction for Water with Heater Temperature Rise Rate of 5.95×10^3 °C/sec	26
17.	Effect of Subcooling on Water-expulsion Velocity with Heater Temperature Rise Rate of 5.95×10^3 °C/sec	27
18.	Effect of Subcooling on Column Displacement and Void Fraction for Water with Heater Temperature Rise Rate of 12.86×10^3 °C/sec.	27
19.	Effect of Subcooling on Water-expulsion Velocity with Heater Temperature Rise Rate of 12.86×10^3 °C/sec	28
20.	Qualitative Coolant Behavior	29

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
21.	Column Displacement and Void Fraction for Water in a 1.27-mm Annulus	29
22.	Expulsion Velocity for Water in a 1.27-mm Annulus	30
23.	Column Displacement and Void Fraction for Methanol.	31
24.	Variation in Expulsion Velocity with Subcooling of Methanol. . .	31
25.	Column Displacement and Void Fraction for Ethylene Bromide. . .	32
26.	Expulsion Velocity of Ethylene Bromide	33
27.	Effect of Subcooling and Heating Rate on Maximum Expulsion Velocity of Water	34
28.	Effect of Subcooling and Heating Rate on Maximum Expulsion Velocity of Methanol.	35
29.	Effect of Subcooling and Heating Rate on Conversion of Input to Water Kinetic Energy	36
30.	Effect of Subcooling and Heating Rate on Conversion of Input to Methanol Kinetic Energy	36
31.	Schematic Diagram of Overflow Loop.	37
32.	Schematic Diagram of Fixed-volume Loop	38
33.	Effect of Coolant Velocity on Initial Pressure Pulse in the Two Loops	38
34.	Effect of Coolant Velocity on Maximum Secondary Pressure Pulse in the Two Loops	39
35.	Effect of Initial Coolant Velocity on Expulsion Velocity for Water.	40
A1.	Simplified System Geometry.	45
A2.	Effect of Heat-capacity Ratio on Ratio of Transient Wall Temperature with Conduction Losses to That with No Losses. .	48
B1.	Expulsion Model Geometry.	50
B2.	Theoretical Transient Column Displacements	53
B3.	Theoretical Transient Expulsion Velocities.	54
B4.	Comparison of Theoretical and Experimental Results for Water.	55

NOMENCLATURE

English Letters

A, B, C	Positive constants in vapor-pressure equation
a	Wall thickness
b	Channel gap
c	Specific heat
erfc(x)	Complimentary error function, defined in Eq. 16
g	Gravitational acceleration
g _c	Units conversion factor
h	Heat wall height
h _{fg}	Latent heat of vaporization
k	Thermal conductivity
ℓ _i , i = 1, 2, 3	Interface heights, defined in Fig. B1
M	Vaporized mass
P	Pressure
Q ₀	Reference volumetric energy-generation rate
Q, Q(t)	Volumetric energy-generation rate
q(τ)	Dimensionless volumetric energy-generation rate, Q(τ)/Q ₀
q	Heat flux
R	Volumetric heat-capacity ratio, ρ _L c _L /ρ _w c _w
T	Temperature
t	Time
u	Velocity
x	Cartesian coordinate

Greek Letters

α	Dimensionless parameter, defined in Eq. 32
β	Dimensionless parameter, defined in Eq. 33
γ	Dimensionless parameter, defined in Eq. 34
ξ	Dimensionless time, Q ₀ t/ρ _w c _w B
η	Dimensionless coordinate, x/a
θ	Dimensionless temperature difference, (T _L - T ₀)/(Q ₀ a ² /k _L)
λ, λ(ξ)	Dimensionless interface height, defined in Eq. 30
ρ	Mass density
τ	Dimensionless time, k _L t/a ² ρ _L c _L

Subscripts

atm	Atmospheric conditions
L	Liquid
maw	Mean adiabatic wall conditions
mw	Mean wall conditions
o	Initial conditions
v	Vapor
w	Wall conditions

THE EXPULSION OF LIQUID FROM A RAPIDLY HEATED CHANNEL

by

Ralph M. Singer

ABSTRACT

To determine the dynamic behavior of a partially confined liquid in contact with a rapidly heated surface, experiments were conducted using water, methanol, ethylene bromide, and acetone. The inner wall of an annulus was rapidly heated by a rectangular power pulse; the pressure, temperature, and motion of the fluid in the annulus were measured. The wall was heated at rates up to about 1.4×10^4 °C/sec, the liquids were subcooled from 0 to 110°C, the liquid head varied from 0 to 1.5 m above the heated section, the annular spacing was either 1.27 or 3.18 mm, the initial liquid velocity varied from 0 to 9 m/sec, and the initial system pressure was always 1 atm.

Transient pressures up to about 16 atm and expulsion velocities up to about 16 m/sec were measured. Only slightly subcooled liquids could be expelled, although the largest pressures were generated when the liquid was highly subcooled. The results of over 400 experiments are summarized.

I. INTRODUCTION

A major problem in evaluating the safety of a fast reactor is the determination of the time history of coolant density during nonsteady reactor operation. This time history must be precisely determined in order to calculate net effects by coupling with other reactivity contributors. Without a qualitative and quantitative understanding of the mechanism(s) of coolant density changes, the detailed transient behavior of a reactor system cannot be predicted.* In fact, it may not be possible to predict with confidence the extent of damage caused by certain hypothesized accidents.

*If the reactivity insertion rate is so rapid that negligible energy is transferred to the coolant during the accident, coolant behavior would not be of paramount importance. However, in many cases the probability of such an accident is quite small relative to the case in which significant energy is transferred to the coolant.

This problem is especially acute when sudden phase changes occur in the coolant because of reactor power excursions. Rapid fuel heating can cause coolant vaporization, which may result in destructive pressure transients and/or core voiding. The latter can result in fuel and/or cladding melting due to decreased heat-transfer rates, or, if the void coefficient of reactivity is positive, an additional amount of reactivity is added to the system.

The problem of thermally generated pressure transients has been studied.¹ Several mechanisms of severe pressure transients have been proposed to explain the destructive power excursions that occurred in the BORAX-I, SL-1, and SPERT-ID reactors. At present, the proposed mechanisms do not predict sufficiently large pressures to explain the reactor results; however, these mechanisms are still of interest in reactor safety analyses.

The first mechanism considered the possible pressure generation caused by the sudden thermal expansion of a thin layer of water (several microns thick), which is in contact with a rapidly heated surface. The analysis¹ found that the following conditions are necessary for the thermal generation of pressure in excess of the critical pressure of water (3200 psi):

- a. The fuel-plate temperature must pass through the water critical temperature with a sufficiently large rate.
- b. The ratio of effective heated fuel surface to area available for pressure relief must be sufficiently large.
- c. A sufficient inertial head of water must be present.

Based on in-pile² and out-of-pile³⁻⁵ experiments, pressures no greater than about half the critical pressure of water were measured. These experiments involved both fixed-volume tests (closed system) and open-system tests. The temperature of the simulated fuel element increased as rapidly as 700°C in 150 μ sec.

The second mechanism of severe pressure generation studied was the impact of water upon the surface of molten aluminum. Experiments⁵ showed that the water impact produced violent disruption and dispersal of the molten aluminum, and pressures up to 2900 psia were measured. This mechanism is still under study.⁶

To calculate the pressure generated during transient boiling, the vapor growth rate must be determined. Many analyses of the growth rate of single bubbles in nonmetallic fluids have been made, several of which are in Refs. 7-10. Analyses of the growth rate of sodium vapor in a fast

reactor transient have recently been presented.¹¹⁻¹³ The first analysis¹¹ was based on a model of essentially complete phase segregation, with the vapor phase growing by pushing subcooled liquid out of the channel. It was postulated that the void growth rate could be limited either by heat transfer to the coolant and/or by the rate of generation of vapor pressure. Although numerical instability problems limited the scope of this study, several interesting conclusions were reached:

- a. Voiding in a reactor channel starts near the upper boundary of the core and grows axially along the fuel channel.
- b. Vapor production is so rapid that transient self-pressurization of the fuel channel occurs.
- c. The resulting two-phase flow is strongly unstable hydrodynamically.

These results have not yet been experimentally confirmed, although work is proceeding in this direction.

The second analysis¹² included the effect of superheat on the vapor growth rate. Only preliminary results are now available, but it is indicated that in sodium-cooled fast reactors:

- a. The superheat requirement is an important parameter in the formulation and growth of vapor.
- b. The coolant temperature distribution within the channel at the time of vapor formation can strongly affect the growth and pressure of vapor.
- c. The design of the reactor primary coolant system can greatly affect the rate of vapor growth by varying the mass of coolant that must be accelerated during expulsion.

However, one must be cautioned since the quantitative results are strongly dependent upon the assumption of "an effective vaporization heat-transfer coefficient." Apparently experimental data are not available for estimating this quantity.

Transient forced-convection boiling of sodium has been studied analytically.¹³ In this work, the conservation equations for two-phase flow were numerically solved for two types of transients: (1) mild over-power transients, and (2) coolant-flow coast-down. Again, the rate of vapor growth was quite sensitive to the coolant temperature profile, the inlet flow rapidly decayed to zero, and the pressure buildup was not excessively

large, typically less than 15 atm. However, the possibility of superheating the sodium before boiling was not considered, and steady-state friction factors and heat-transfer coefficients were used.

All three of these recent analyses of transient sodium-vapor growth did not consider the possible effects of the markedly reduced sonic velocity in two-phase mixtures. Without inclusion of this phenomenon, the dynamics of the coolant after boiling can be open to question. In addition, considerable uncertainty still remains as to the precise conditions under which the sodium boils.

These last two questions can probably be resolved by experimental work now underway at Argonne National Laboratory and several other nuclear laboratories.

The mechanism of coolant expulsion is directly tied to the mechanisms of pressure generation and transient two-phase flow. To predict the conditions under which coolant will be expelled from a reactor core as well as the expulsion velocity, the pressure history in the core must be known. Coolant expulsion and rapid transient boiling were studied at Argonne National Laboratory.¹⁴ In this study, a vertical copper tube filled with water and open at the top was rapidly heated with single voltage pulses ranging from 2 to 8 msec. Peak energy-input rates were approximately 1000 kW (40,000 Amps at 25 volts) and resulted in temperature rises of about 500°C in 6 msec. Pressures of the order of 50 to 150 psig were measured. Unfortunately, although the expelled water was observed photographically, no velocity data were reported. However, the expulsion velocity from one run was available in unpublished form.¹⁵ Initially stagnant, 90°C water was contained in a 9.5-mm-ID x 0.38-mm-wall, 152-mm-long copper tube; a power pulse of 460 kW (average) was put into the tube for 6.4 msec. A pressure pulse of 156 psig resulted 2 msec after the start of the power pulse, and the liquid started moving upward approximately 2.8 msec after the power pulse. The liquid quickly accelerated to the constant velocity of 6.7 m/sec.

Water expulsion was studied more recently at Ispra (Italy), the results being presented at a fast reactor conference at Argonne.¹⁶ In this experiment, water was pressurized up to 3.5 atm and then heated up to 125°C; a diaphragm was then suddenly ruptured to reduce the water pressure to 1 atm. As the rarefaction wave passed through the water, the water became superheated (i.e., 125°C at 1 atm) and started to boil. The two-phase system was then expelled from the tube with velocities ranging from 1 to 2.5 m/sec. Only photographic transient measurements were made (at about 3000 frames/sec). An analysis of the films revealed that a shock front appeared in the moving two-phase mixture; this front was interpreted to be associated with the critical ("choke") flow phenomenon. A simple

analysis, which assumed that the expulsion velocity was equal to the critical velocity, was presented and reasonably matched the experimental results.

In summary, we do not yet understand the mechanism(s) of severe pressure generation and of coolant expulsion; experimental data for these phenomena are extremely sparse for water and nonexistent for liquid metals. Therefore, a research program has been initiated by the Reactor Engineering Division of Argonne National Laboratory to thoroughly study pressure generation and coolant expulsion using experimental and analytical tools.

This report summarizes an extensive series of experiments in which various liquids (water, methanol, acetone, and ethylene bromide) were rapidly heated; the essential measurements of the transient pressure and expulsion velocity were made. The effects of initial subcooling, rate of energy input, height of liquid column, initial liquid velocity, system geometry, and fluid thermophysical properties were studied parametrically.

II. EXPERIMENTAL DESIGN

The experimental equipment was designed with the following goals in mind:

- a. To rapidly heat a solid surface in contact with liquid.
- b. To measure the transient pressure in the liquid.
- c. To measure motion induced in the liquid.
- d. To visually observe (with high-speed photography) the entire system.

To achieve the first goal, a method of storing and suddenly discharging a large amount of energy must be determined. Two techniques were studied, the first involving the discharge of a bank of condensers, the second using storage batteries. Because of its inherent simplicity and low cost, the latter method was chosen over the former. The power circuit, shown in Fig. 1, consisted of a bank of heavy-duty diesel truck batteries (Hester brand, 12 volts, 204 Amp-hr, 162 plates), a circuit breaker (General Electric type AK-2-15, overcurrent tripping device), a precision current shunt, and the resistive load. This type power circuit yielded excellent rectangular-wave energy-input rates with a rise time of approximately 1 msec. The maximum input rate used was about 115 kW; this corresponded to a volumetric energy-generation rate of about 14 kcal/sec-cm³ in the heated test section. The duration of the rectangular wave was controlled by the circuit breaker; the larger the current, the shorter the duration. The measured times varied from about 60 to 150 msec.

112-8099

Fig. 1. Transient Power Circuit

To measure rapidly changing pressures in the liquid, a suitably fast-response pressure transducer is required. Several unbonded strain-gauge transducers (Statham model number PA285TC), which were rated at about 16 to 20 kHz natural frequency, were purchased. To obtain some confidence in the dynamic performance of these transducers, several tests were conducted in which known pressure transients were imposed and the transducer response recorded. The first series of tests consisted of mounting the transducer in the wall of a small-volume (170 ml) steel container; this container was equipped with a pressurizing gas line and a thin (0.076 mm) copper diaphragm mounted in a flange. The system was pressurized until the diaphragm burst and the transducer output recorded. With a variety of discharge hole diameters in the flange (12.7 to 38.1 mm), the pressure dropped from 20 to 1 atm in 1.5 to 37.5 msec. The transducer recorded these transients with no sign of "ringing"; in fact, the rarefaction waves resulting from the diaphragm rupture were recorded with no apparent distortion. It was calculated that the rarefaction wave should reach the transducer diaphragm in 0.42 msec following the burst; the measured time was 0.43 msec. The frequency of the rarefaction wave was approximately 4 kHz.

A second test of the transducer involved the use of a shock tube. The principle of the shock tube is similar to that of the system described previously, except that the pressure transducer "sees" a compression wave rather than a rarefaction wave. In this shock tube, the transducer was mounted in a side wall, 90° off line from the high-pressure source (held by a copper diaphragm). Thus, the shock wave passes across the face of the transducer, and the rise time of the pressure is approximately the diameter of the transducer diaphragm divided by the speed of sound. For the system used, this resulted in a 57 μ sec rise time, corresponding to a frequency of about 18 kHz. When the transducer was subjected to this test, the diaphragm "rang," but still reproduced the general rise in pressure

with good accuracy (using the mean value of the output of the "ringing" transducer at each instant of time).

Based on the results of these tests, we felt that the transducer should accurately respond to pressure pulses with a frequency at least as large as 4 kHz, and is usable for frequencies up to about 10 kHz.

The third and fourth goals of the experimental design essentially required that the system be contained in a transparent structure; however, this structure must withstand anticipated transient pressure of 20 to 30 atm. Clear quartz was chosen for its good mechanical strength and fine optical qualities.

The geometry was chosen to be annular, the heated surface being interior, the quartz pipe exterior. This allowed visual studies of the liquid in contact with the heated surface and simulated a reactor fuel pin surrounded by coolant. A schematic drawing of the system is shown in Fig. 2 and photographs in Figs. 3 and 4.

112-8102

Fig. 2. Cross Section of Expulsion Tube

112-5428

Fig. 3. View of Heated Tube

112-5427

Fig. 4. General View of Experimental Apparatus

The heated section was made of seamless stainless steel Type 316 tubing, 19.05-mm OD and 0.127-mm wall. The effective heated length was 254 mm. To give this thin-walled tube structural strength and to thermally insulate its inner surface, a sleeve of Lavite was inserted inside the tube; a "tight fit" was maintained between the Lavite and the tube, a "loose fit" between the Lavite and the inner electrode. A nylon rod of identical diameter as the heated section continued the annular geometry away from the heated section.

The pressure transducer was mounted in a flanged port in the quartz pipe, its centerline at the midpoint of the heated tube. The annular gap between the tube and the quartz pipe was varied from 1.27 to 3.18 mm by changing the diameter of the quartz pipe. The height of the liquid column could be extended to about 1.5 m by adding 60-cm sections of glass pipe to the top of the original quartz pipe. Finally, as the temperature of the heated tube increased, the tube was allowed to fully expand upward by the use of a liquid-metal (62.5% Ga, 21.5% In, 16% Sn) contact between the inner electrode and the bottom bus bar.

During a typical experiment the following quantities were measured:

- a. Voltage drop across the heated tube.
- b. Current flow through the tube.
- c. Transient temperature in the coolant.
- d. Transient pressure in the coolant.
- e. Initial height of the coolant column.
- f. High-speed photographic measurements of the liquid-column interface and heated surface (using a Fastax camera and associated synchronization equipment).

From measurements a and b, the energy generation rate in the tube can be calculated; measurements f of the liquid-column interface yield expulsion heights, expulsion velocities, and liquid accelerations.

The measurement of the temperature of the heated tube was also attempted; however, because of the thinness of the wall and the severe heating transients, a method could not be found for satisfactorily attaching a thermocouple to the tube. Spot welding, silver soldering, and similar techniques invariably weakened the tube locally and resulted in a useful life of no more than one or two runs. Attempts to hold the thermocouple bead physically to the tube surface (either inner or outer) by means of compression, glass-fiber tape, or other techniques resulted in poor response. The measured temperature of the tube had hardly started to increase by the time the heating transient had ended.

Similarly, resistance thermometry was of no avail because of the relatively small change in electrical resistance of stainless steel over the temperature range studied. Thus, measurement of the tube surface temperature was abandoned and reliance placed on analytical calculations.

III. EXPERIMENTAL RESULTS

A total of 407 expulsion experiments were conducted to determine the parametric effects of several variables upon the expulsion process. The primary dependent quantities measured were the transient pressure and the coolant motion (displacement, velocity, and acceleration). The independent variables were the energy generation rate, initial liquid subcooling, liquid-column height, inlet coolant velocity in "fixed-volume" and "overflow" systems, annular spacing, and fluid physical properties.

Typical results from two experiments are shown in Figs. 5 and 6. Each figure shows a tracing of the oscillographic record indicating the voltage drop across the heated tube, the current flow, the liquid temperature, and the liquid pressure. The displacement and velocity curves were obtained from an analysis of the motion-picture film taken of the liquid-vapor interface.

112-8077

Fig. 5. Typical Experimental Measurements for Subcooled Liquid

112-8086

Fig. 6. Typical Experimental Measurements for Saturated Liquid

Figure 5, where highly subcooled water was used (initial temperature of 47°C), shows the typical rectangular energy-input pulse. Approximately 18 msec after the start of the heating, a small (1.26 atm) pressure pulse is noted; immediately following this pulse, the liquid is displaced upward. As the liquid moves upward, the pressure falls slightly below 1 atm and the liquid reverses direction and falls back down. A second, larger pressure pulse (about 2.8 atm) occurs approximately at the minimum displacement, and the liquid again moves upward. After reaching a peak displacement, the liquid again drops back, and more severe pressure pulses occur (about 8 atm). These larger pulses repeat with a period of approximately 20 msec.

Curves similar to those in Fig. 5 are shown in Fig. 6; this time slightly subcooled (4.5°C below saturation) acetone* was used. A similar rectangular pulse of energy input is shown; the pressure starts to increase

* The use of various fluids did not alter the qualitative aspects of expulsion; only the quantitative aspects were affected.

almost coincidentally with the start of the heating. The pressure transient consists merely of a single peak with a fall back to ambient pressure. Also, the liquid is displaced upward and does not fall back, i.e., is completely expelled from the tube. A relatively short period (~ 9 msec) is required to accelerate the liquid from a stationary condition to its final velocity of 5.10 m/sec.

Figure 7 shows the results of a sequence of experiments in which only the initial temperature of the liquid (water, in this case) was varied. For the 18°C water case, a small initial pressure pulse (1.59 atm) is shown, followed by larger (~ 5 atm) pulses, which repeat with a period of about 10 to 15 msec. As the temperature of the water is increased to 36°C, the pressure transient is qualitatively unchanged; however, the initial pulse is slightly larger (1.75 atm) and occurs somewhat sooner than the 18°C transient. The secondary pulses are also larger (up to 12.9 atm) and repeat with a somewhat longer period.

Fig. 7

Effect of Initial Temperature
on Transient Pressure

112-6607 Rev. 1

At 60°C, the initial pressure pulse has increased to 1.89 atm and the secondary pulses are only 3.4 atm, with a period of approximately 50 msec. When 99°C water is used, the initial pulse is 2.99 atm and no secondary pulses occur.

An analysis of these pressure transients in conjunction with the synchronized motion-picture films allows a physical interpretation of the data. The initial small pressure pulse corresponds to the sudden growth of vapor bubbles, which accelerate the liquid away from the heated surface. For highly subcooled liquid, the vapor recondenses,* causing a partial vacuum, and pulls the liquid back into contact with the hot test section after an upward motion of approximately 1 cm. Upon contact, the liquid suddenly revaporizes, causing another pressure pulse; the liquid again is accelerated

*The recondensation is caused by energy loss from the vapor to the subcooled liquid, as well as the increase in the system pressure.

upward and the vapor recondenses, creating a partial vacuum and pulling back the liquid. This cycle repeats until the heated surface has sufficiently cooled so as not to vaporize additional liquid.

As the initial temperature of the liquid is increased, a larger fraction of the input energy goes into latent heat as opposed to sensible heat, resulting in more vapor formation and a larger initial pressure pulse. However, the bulk of the liquid is still subcooled, and the vapor recondenses, creating a partial vacuum and pulling back the liquid; in this case, the liquid may have moved as much as 2 cm before falling. The same cycle of pressure pulses and rising and falling liquid is repeated as with the previous case.

When the liquid is initially close to saturation, almost all the input energy is utilized for vaporization, creating a larger and broader initial pressure pulse. The vapor does not recondense, but is continually formed, and the liquid is completely expelled from the heated section.

Since the initial pressure pulse initially accelerates the liquid, it would be wise to determine the factors that affect its magnitude and duration to aid in an understanding of the expulsion process. Also, the secondary pulses must be studied since their magnitudes can be sufficiently large to cause some core damage.

A. Tests with Initially Stagnant Liquid

1. Pressure Transients

Figures 8 and 9 show the effects of the initial liquid temperature and energy-generation rate upon the magnitude of the initial pressure pulse for water. In Fig. 8, energy-generation rate is shown as a parameter (this is the way the experiments were conducted); Fig. 9 is a cross-plot of Fig. 8, showing the initial temperature as a parameter.

The initial pressure pulse increases with an increase in the energy-generation rate and with an increase in the initial liquid temperature. The curves labeled 20, 60, and 80°C in Fig. 9 indicate that the initial pulse is zero until some particular value of the energy generation rate is reached; this is not quite correct. The sensitivity of the recording system was such that pressures could be read from the chart with an accuracy of ± 0.01 atm at best (because of the thickness of the trace and the chart scale). Thus, since the liquid did move upward on these low energy-generation rate runs at times that corresponded to no apparent pressure increase (the upward motion was only of the order of 0.1 to 0.3 cm), the initial accelerating pressure pulses must have been less than the thickness of the trace on the chart paper, i.e., less than 1.01 atm.

112-8093

Fig. 8. Variation of Initial Pressure Pulse with Subcooling; Energy-generation Rate as a Parameter.

112-8090

Fig. 9

Variation of Initial Pressure Pulse with Energy-generation Rate; Subcooling as a Parameter.

Figure 10 shows typical variation of the peak secondary pressure pulses with energy-generation rate and initial water temperature. A spread in the data of about ± 30 to $\pm 60\%$ consistently occurred for the secondary pulses, so for clarity, only a fared curve is shown. The magnitude of the secondary pulses generally increases with increasing water temperature; however, a maximum is reached, and the pressures quickly fall off as near-saturation conditions are approached. In fact, for nearly saturated liquid, no secondary pulses occur.

112-8097

Fig. 10. Variation of Maximum Secondary Pressure Pulse

formed. As the liquid starts to fall back, the upward motion of the vapor inhibits the downward liquid motion and the secondary pulse is reduced. Finally, at temperatures sufficiently close to saturation, the initial pressure pulse is large enough to expel the liquid completely out of the tube; or, if the tube is sufficiently high so that no liquid actually leaves it, the return time of the liquid is of the order of seconds, during which the heated tube has had time to cool.

To determine the effect of the height of the water column upon the magnitude of the initial pressure pulse, experiments were conducted in which the height was varied up to about 1.6 m above the heated section. The results of these experiments are summarized in Fig. 11. The pressures increase with increased column height up to a maximum; further increases in column height tend to depress the pressure pulses slightly. The interpretation of this result is not quite clear; two factors could possibly cause the maximum. One is the slight increase in static pressure at the heated surface due to the large water column; at a head of 1 m of water, the saturation temperature is increased to about 102°C. Thus, the liquid is subcooled two additional degrees; the upper two curves in Fig. 8 indicate a steep rise in the initial pressure as saturation is reached. For the curve indicated by the solid circles (which closely simulates the conditions found in the center curve in Fig. 11), a drop in temperature from 99 to 97°C reduces the initial pressure from 2.5 to 2.35 atm. This drop is not quite sufficient to explain the observations in Fig. 11.

A second factor that could affect the initial pressure pulses is the heat losses from the high column of water and a lowering of the temperature. Precautions were taken to avoid axial temperature gradients; however, temperatures did vary 1 to 3°C from the top to the bottom of the

This behavior is related closely to the initial pressure pulse and vapor growth rate. For highly subcooled water, the initial pressure pulse is small, only a small amount of vapor is formed, and the liquid moves upward less than 1 cm before the vapor recondenses and pulls back the liquid. As the liquid temperature is increased, the initial pressure pulse becomes larger, the liquid rises higher (still only 1 to 3 cm), and a larger impact or secondary pulse results. But as the liquid temperature is increased further, the initial pressure pulse is sufficiently large to drive the liquid up 5 to 15 cm, and relatively large amounts of vapor are

column. As the column height was increased, this temperature variation increased to the 3°C figure. Thus, a combination of this axial temperature gradient and the increased saturation temperature at the heated surface could account for the leveling off of the pressure-versus-height curve.

112-8087

Fig. 11. Effect of Column Height on Initial Pressure Pulse

Noting this behavior of the system under a varying inertial water head, we conducted several experiments in which we attempted to completely fill and close the tube. Conditions identical to the center curve in Fig. 11 were used, with a height of 35.2 cm. Pressure of 10 to 13 atm resulted; larger pressures would have resulted had not the seal at the top of the column leaked in all three runs. Thus, the system was not truly closed, but a major reduction in the pressure-relief area was effected. Therefore, another parameter in addition to those listed at the start of this section, which is of importance in the magnitude of the pressure pulse, is the relative area available for pressure relief.

Since the initial pressure pulses are caused by the sudden formation of vapor under an inertial head of liquid, the annular spacing should affect these pulses. Therefore, essentially identical experiments were conducted using two different outer cylinders; annular gaps of 3.18 and 1.27 mm were compared. The results are shown in Fig. 12. The lower two curves are for water, the upper curve for the ethylene bromide ($C_2H_4Br_2$). The results are plotted against liquid subcooling to compare

the two liquids more directly. The reduction of the annular gap increases the initial pressure pulse, but the increase diminishes as the subcooling increases (i.e., as the liquid temperature decreases). This is apparently due to the fact that the size of the vapor bubbles formed in highly subcooled liquid were small, relative to the annulus size; as the liquid temperature increased, the bubble size also increased and became comparable to the annular gap. Thus, the effect of the spacing upon the pressure pulse should become more pronounced as the liquid temperature is increased.

In addition, Fig. 12 indicates that ethylene bromide experiences somewhat larger pressure pulses than the water. These two liquids, as well as methanol, are compared more directly in Fig. 13. Three series of experiments were conducted using each of the aforementioned liquids at various liquid subcoolings, all other parameters being essentially held constant. The largest initial pressures occurred in the ethylene bromide, followed by the methanol, and use of water resulted in the smallest pulses. A comparison of the densities and latent heats of vaporization of these three liquids, as illustrated in Table I, reveals some insight into the differences in the pressure pulses.

112-8084

Fig. 12. Effect of Annular Gap and Subcooling on Initial Pressure Pulse

Fig. 13
 Effect of Type of Liquid
 on Initial Pressure Pulses

112-8088

TABLE I. Liquid Physical Properties

Liquid	Density, gm/ml	Latent Heat of Vaporization, cal/gm
Water	1.00	585
Methanol	0.79	263
Ethylene bromide	2.17	46.2

It is physically intuitive that as the density of liquids increases and their latent heat of vaporization decreases, the initial pressure pulse should increase. This is explained by noting that the inertia of a liquid column increases as its density increases, and for a given energy input, the amount of vapor generated increases as the latent heat decreases. This pressure behavior is precisely that observed in Fig. 13. Methanol is slightly less dense than water, but has a latent heat only half that of water; its initial pressure pulses are larger than those for water for the entire range of initial subcooling. Also, ethylene bromide is much denser than either methanol or water, and its latent heat is only one-twelfth that of water and one-fifth that of methanol; accordingly, its initial pressure pulses are significantly larger than those for either liquid.

Figures 14 and 15 summarize in more detail the effects of subcooling and energy-generation rate upon the initial pressure pulses in methanol and ethylene bromide.

112-8078

Fig. 14. Effect of Subcooling and Energy-generation Rate on Initial Pressure Pulses for Ethylene Bromide

112-8089

Fig. 15. Effect of Subcooling and Energy-generation Rate on Initial Pressure Pulses for Methanol

2. Coolant Motion

High-speed motion pictures (up to 7500 frames/sec) were taken of the liquid-vapor interface during several runs. These pictures were used to determine the transient motion of the coolant following boiling. From the measured displacement-versus-time results, the velocity and acceleration of the expelled two-phase mixture could be computed as well as an approximation to the transient void fraction in the heated zone.

Since the displacement of the liquid was caused solely by vapor growth in the heated zone, the void fraction in this zone could be approximated using the following relation:

$$\text{Void fraction} = \frac{\text{Vertical displacement of liquid}}{\text{Heated zone height}}.$$

Thus, the transient void-fraction curves will be of the identical form as the transient displacement curves with the scale changed by the factor of the height of the heated zone (which was 25.4 cm in all runs).

Figures 16-26 show the transient liquid column displacement, void fraction, and expulsion velocity for various initial subcoolings and heater-temperature rise rates for water, methanol, and ethylene bromide.

The displacement and void fraction for two different heating rates with various initial subcoolings are shown in Figs. 16 and 18; the corresponding expulsion velocities are shown in Figs 17 and 19. In general,

112-7828 Rev. 1

Fig. 16. Effect of Subcooling on Column Displacement and Void Fraction for Water with Heater Temperature Rise Rate of 5.95×10^3 °C/sec

112-7829 Rev. 1

Fig. 17. Effect of Subcooling on Water-expulsion Velocity with Heater Temperature Rise Rate of 5.95×10^3 °C/sec

112-8081

Fig. 18. Effect of Subcooling on Column Displacement and Void Fraction for Water with Heater Temperature Rise Rate of 12.86×10^3 °C/sec

112-8076

Fig. 19. Effect of Subcooling on Water-expulsion Velocity with Heater Temperature Rise Rate of 12.86×10^3 °C/sec

the void fraction, displacement, and velocity increase with decreased subcooling. This is in agreement with the transient-pressure results. However, Figs. 16 and 17 indicate that larger displacements and velocities result when the water is subcooled 3°C as compared to that at 1°C subcooling. This effect was observed at other heating rates and represents typical behavior of the liquids used.

For highly subcooled water, expulsion does not occur; rather the liquid oscillates as the vapor alternately grows and collapses. This behavior is most apparent in Fig. 16. For a much larger heating rate than is shown in Fig. 16, highly subcooled liquid is displaced more. However, it still falls back in contact with the heated section to be revaporized.

Figure 20 summarizes the conditions necessary to completely expel water from an annulus with a 19.05-mm ID and a 25.40-mm OD (the same size as used for Figs. 16-19). The water must be close to its saturation temperature (slightly subcooled) for complete expulsion to result. For highly subcooled water (i.e., temperatures less than about 50-60°C), expulsion could not be caused with heating rates as high as 1.2×10^4 °C/sec.

Fig. 20
Qualitative Coolant Behavior

112-8098

Figures 21 and 22 show transient void fractions, displacements, and velocities for water in an annulus considerably smaller than that used

112-8085

Fig. 21. Column Displacement and Void Fraction for Water in a 1.27-mm Annulus

112-8101

Fig. 22. Expulsion Velocity for Water in a 1.27-mm Annulus

in the previous several figures. Interestingly, larger expulsion velocities resulted in the larger annulus, although it has previously been demonstrated that larger pressures occur in the smaller annulus.

Similarly, Figs 23-26 show results for methanol and ethylene bromide. The dynamic behavior of these two fluids is qualitatively identical to that of water, although their latent heats and densities differ markedly. The large negative expulsion velocities indicate the returning of the liquid to the heated zone, which results in secondary vaporizations. These secondary vaporizations give rise to the large secondary pressure pulses as illustrated for example in Fig. 5.

The maximum expulsion velocities of water and methanol are summarized in Figs. 27 and 28. The velocities remain less than about 12 m/sec for water and 16 m/sec for methanol, an increased heating rate and decreased subcooling resulting in an increased velocity. However, the maximum expulsion velocity does not occur at the minimum subcooling (for the smaller heating rates), as might be expected. This behavior is apparent for both water and methanol. As the heating rate is increased, this effect vanishes and the expulsion velocity varies monotonically with the subcooling.

112-8083

Fig. 23. Column Displacement and Void Fraction for Methanol

112-8082

Fig. 24. Variation in Expulsion Velocity with Subcooling of Methanol

112-8080

Fig. 25. Column Displacement and Void Fraction for Ethylene Bromide

112-8079

Fig. 26. Expulsion Velocity of Ethylene Bromide

112-8104

Fig. 27. Effect of Subcooling and Heating Rate on Maximum Expulsion Velocity of Water

112-8100

Fig. 28. Effect of Subcooling and Heating Rate on Maximum Expulsion Velocity of Methanol

A quantity of considerable interest to reactor safety analysts is the fraction of input energy converted to coolant kinetic energy. The maximum percent conversion is shown in Figs. 29 and 30 for water and

112-8094

Fig. 29. Effect of Subcooling and Heating Rate on Conversion of Input to Water Kinetic Energy

112-8105

Fig. 30. Effect of Subcooling and Heating Rate on Conversion of Input to Methanol Kinetic Energy

methanol, respectively. Since the maximum conversion observed was less than 0.14%, this process is quite inefficient. Essentially all the input energy is consumed by increasing the heater temperature and supplying the latent heat of vaporization. The conversion efficiency, although small, does increase markedly as the subcooling is decreased. We must use care, however, in extrapolating these results to specific reactor designs; a typical reactor-fuel assembly will have considerably more fuel mass relative to coolant mass than in this experiment. The affect of this mass ratio was not studied in this work.

B. Tests with Initially Flowing Water

The previously described tests are all concerned with the rapid heating of initially stagnant liquid. Although this study is directed primarily toward a fundamental understanding of the expulsion process and the generation of pressure in reactor coolants, a secondary goal is the provision of useful data for reactor designers. Thus, the situation of rapidly heating a stagnant liquid corresponds to a reactor situation of loss of flow suddenly followed by a power excursion. This accident may or may not be credible; thus, we conducted a series of experiments which simulated a power excursion without a loss of flow, which probably is more credible.

The system sketched in Fig. 2 was modified to permit through-flow; liquid entered at the bottom via a manifold and exited at the top. Two types of flow loops were used: the first was essentially a fixed-volume system,* the second was an "overflow" type. Schematic diagram of these loops are shown in Figs. 31 and 32. In both systems, water was pumped from a large (about 40 liters) reservoir and entered at the bottom of the heated section.

112-8096

Fig. 31. Schematic Diagram of Overflow Loop

*This system, although referred to as a "fixed-volume" loop, is not of constant volume. As can be seen from Figs. 31 and 32, the essential difference between the loops is that the fixed-volume loop has a much smaller area available for pressure relief than the overflow loop.

Fig. 32. Schematic Diagram of Fixed-volume Loop

A special inlet manifold introduced the water in a symmetric manner. The inlet temperature of the water was varied from 35 to 97°C, and inlet velocities ranged up to about 9 m/sec. Figure 33 summarizes the results for both flow systems.

112-8091

Fig. 33. Effect of Coolant Velocity on Initial Pressure Pulse in the Two Loops

It is immediately evident the initial pressure pulses in a flowing-water system are essentially unchanged from the values measured in stagnant water (zero velocity). There also were few significant qualitative differences in the pressure histories obtained with flowing or stagnant water. However, a significant difference in the initial and secondary pressure transients arose between the two types of flow systems.

The fixed-volume flow loop consistently yielded larger initial pressure pulses than the overflow loop. The initial pulses in the former loop were almost 50% larger than those in the latter. This undoubtedly was due to the reduced area for pressure relief in the fixed-volume loop (pressure was relieved into the water reservoir). In addition, as shown in Fig. 34, the secondary pressure pulses in the overflow system were two to four times larger than those in the fixed-volume loop.

112-8095

Fig. 34. Effect of Coolant Velocity on Maximum Secondary Pressure Pulse in the Two Loops

Figure 35 shows the expulsion velocities measured in the overflow type loop. As would be expected from the pressure transients, very little effect is evident in these transient velocities.

112-8103

Fig. 35. Effect of Initial Coolant Velocity on Expulsion Velocity for Water

C. Flow Structure from Film Analysis

High-speed motion pictures were taken of the expelled liquid using a Wollensak Fastax camera at film speeds up to 7500 frames/sec. A total of 173 films were analyzed for expulsion displacement, velocity, and acceleration, as well as for flow structure. As a result of these films, the following qualitative statements can be made concerning expulsion dynamics.

1. The four liquids used* showed no observable differences in their dynamic behavior.

2. Highly subcooled liquid initially moved up a short distance, fell back, and rose again, its interface usually remaining intact during the first

*Water, methanol, acetone, and ethylene bromide.

oscillation. However, during subsequent oscillations, the interface shattered, partially due to Taylor-Helmholtz instability.*

3. Slightly subcooled liquid is usually expelled completely from the tube. If a column of water exists above the heated section, it flows upward as a single phase; it is followed by region of two-phase flow (vapor-liquid). The region of two-phase flow adjacent to the liquid slug is merely a few dispersed bubbles in a continuous liquid phase. The void fraction gradually increases in the following regions until it becomes 100%, i.e., all vapor. Annular (i.e., film) flow and local slip are observed.

4. The behavior of moderately subcooled liquid is intermediate to the behavior of the highly subcooled and saturated case. The liquid is expelled upward 5 to 15 cm and falls back due to gravity. As the liquid recontacts the heated section (which is still hot), it is suddenly vaporized and the remaining liquid is expelled as a spray. This second displacement usually is as large as the first.

These observations lead to the conclusion that a general analysis of the expulsion process that would be valid for all ranges of subcooling would be exceedingly complex, if at all possible. However, restricted analyses of the limiting cases of highly subcooled and highly saturated liquid should be possible. The assumptions of some authors (e.g., Ref. 11) on the mechanism of expulsion in liquid sodium does not correspond to the behavior of non-metallic fluids. The hydrodynamic behavior of sodium and water is likely to be quite similar because of their comparable dynamic properties. The major difference will probably arise because of the large thermal conductivity and superheating of sodium; however, if and how this property would affect expulsion dynamics is not presently known.

In any case, an analysis of the expulsion of saturated liquid should take into account the two-phase region that separates the two single-phase regions of liquid and vapor.

IV. DISCUSSION AND SUMMARY

The experimental results discussed in this report have shed considerable light on the mechanism of expulsion of nonmetallic fluids from simulated reactor channels. In the range of conditions investigated, highly subcooled liquids could not be expelled, but large secondary pressure pulses were observed. Highly saturated liquids were expelled with relatively small energy inputs; however, only small pressure pulses resulted.

*A liquid-vapor interface is highly unstable when acceleration is in the direction of the vapor phase.

Two types of pressure pulses were observed during the transient expulsion process. The first pulse, with a rise time of the order of 1 to 10 μsec , was caused by the sudden growth of vapor bubbles following the transient heating of the inner wall and provided the initial liquid acceleration. These pulses were relatively small (less than 5 atm) and displayed excellent repeatability. Large secondary pulses were caused by the collapse of vapor (by condensation) and the subsequent impact of cold liquid upon the hot surface followed by a violent revaporization. These secondary pulses were as large as 20 atm, with rise times of the order of 100 μsec .

To determine the effects of these two types of pressure pulses on a system, it is necessary to determine first if the system behaves inertially or acoustically. The system is inertial if the rise time of the pressure pulse is significantly longer than the time required for the pressure to be transmitted to, and return from, the system boundaries. The pressure is transmitted at the sonic velocity. The system is acoustic if the rise time of the pressure pulse is significantly less than the time for the pressure to be transmitted to, and return from, the system boundaries.

In an inertial system, any pressure disturbance is effectively instantaneously transmitted throughout the fluid; thus all the system boundaries can interact with the pressure-generating source and perhaps alter it. However, in an acoustic system, the pressure at the source essentially rises instantaneously and is slowly transmitted through the fluid. Thus, during the initial stages of the transient, there is no dynamic communication between the system boundaries, and the pressure source is initially unaffected by the system boundaries and behaves as though it were surrounded by an infinite body of fluid.

In the system used in this work, the closest boundary to the pressure source was the wall of the quartz pipe. The distance was 1.27 or 3.18 mm, depending upon the quartz pipe used. Thus, using the velocity of sound in liquid water of 1500 m/sec, the pressure is transmitted across the annular gap and returns in, at most, 4.24 μsec . Therefore, during the initial pressure pulse with its rise time of 1 to 10 msec and pressure transmission through liquid water, the system is unquestionably inertial.

However, when the secondary pressure pulses occur, they may have to be transmitted through a two-phase region. As has been shown analytically by Fauske¹⁷ and Fisher and Häfele,¹⁸ the sonic velocity is drastically reduced in two-phase mixtures (for both metallic and nonmetallic fluids). Depending upon the model used (phases unaffected by passage of pressure waves, i.e., "frozen" system, or differentially small condensations and vaporizations in the pressure wave, i.e., equilibrium system), the sonic velocity can be as low as 5 to 30 m/sec. If the larger velocity (which corresponds to the "frozen" model) is used, the pressure wave takes about 200 μsec to travel 3.18 mm to the quartz pipe and return. Coincidentally,

this is also the approximate rise time of the secondary pressure pulse; thus, the system behaves intermediate to the inertial and acoustic cases. This observation may provide an additional explanation as to why the secondary pressure pulses are much larger than the initial pulses. The primary means of pressure relief in this experimental system is the motion of the liquid away from the pressure source. However, if the liquid-vapor interface is several centimeters above the top of the heated section, the secondary pressure pulses will take approximately 12 msec to be transmitted to this interface and returned. Thus, since the rise of time of the pulse is about 100-200 μ sec, the pressure will not be relieved until after the peak has been reached. For initial pulses, pressure is transmitted instantaneously throughout the system (relative to the pressure rise time), so that the pressure is relieved almost as fast as it is generated; the only way the pressure increases is due to the inertia of the liquid column.

Therefore, any analytical model that attempts to explain the secondary pressure pulses will probably have to consider compressibility effects. However, to include these effects in a working model, the acoustic velocity in two-phase mixtures must be available; at present, experimental data is almost nonexistent.* However, analytical and experimental programs are now under way at several laboratories.^{17,18}

V. CONCLUSIONS

As a result of the experiments discussed in this report, experimental information is now available on vapor growth rates, expulsion velocities, and pressure pulses for several nonmetallic fluids. Also, a considerable insight into the mechanism of the rapid transient boiling of partially confined liquids has been obtained.

The general conclusions of this report can be summarized as follows:

1. Within the range of heating rates used (up to 10^4 °C/sec), highly subcooled liquids cannot be expelled.
2. Slightly subcooled liquids can be expelled with relatively modest heating rates.
3. The expulsion velocity increases directly with increasing heating rates, but exhibits a maximum at a particular subcooling (i.e., the minimum subcooling does not necessarily result in the maximum expulsion velocity).

*Some data are available in Ref. 19 for water-steam mixtures.

4. During the transient boiling of slightly subcooled liquid, the void growth monotonically increases, resulting in a single, relatively small but sustained pressure pulse (normally less than about 5 atm in these tests).

5. During the transient boiling of highly subcooled liquid, the void growth oscillates as the fluid alternately vaporizes and condenses. The secondary vaporizations result in pressure pulses considerably larger than those caused by the initial vaporization. (Pulses up to 15 to 20 atm occur with frequencies up to 100 per second.)

6. Initial coolant velocities up to about 9 m/sec had little effect on the boiling dynamics.

7. The essential mechanisms that occurred during the transient process were not qualitatively affected by the type of fluid used.

A final word of caution must be issued to those who might wish to extrapolate the results presented herein to sodium-cooled fast reactors. Since little, if anything, is now known about the transient boiling of sodium,* the use of water data to indicate sodium behavior is fraught with pitfalls.

*A program now under way at the Argonne National Laboratory conducted by the author and his associates is concerned with this problem.

APPENDIX A

Transient Temperature of a Rapidly Heated
Body with Conduction Losses

To estimate the transient temperature of the rapidly heated stainless steel tube used experimentally, a thermal analysis will be conducted. Since the annular gap is quite small relative to the tube radius (gap/radius ≈ 0.13), and the following analysis will neglect any phase changes, the annular geometry will be simplified to a slab in contact with a semi-infinite fluid. This geometry is shown in Fig. A1.

Fig. A1. Simplified System Geometry

The energy-conservation equation in the wall is

$$\rho_w c_w \frac{\partial T_w}{\partial t} = k_w \frac{\partial^2 T_w}{\partial x^2} + Q(t), \quad (1)$$

where one-dimensional transient heat transfer is assumed, subscript w refers to the wall, and $Q(t)$ is an arbitrary internal energy-generation rate.

Since the dimension a is quite small (0.127 mm) and the conductivity of the wall is large relative to the liquid ($k_w/k_{\text{water}} \approx 30$), we will assume that the temperature gradient in the wall is much smaller than that in the liquid. Thus, a mean wall temperature will be used with the definition

$$T_{mw} = \frac{1}{a} \int_{-a}^0 T_w(x,t) dx. \quad (2)$$

Integration of Eq. 1 with respect to x over $(-a, 0)$ results in

$$\rho_w c_w \frac{dT_{mw}}{dt} = Q(t) + \frac{k_w}{a} \left[\left(\frac{\partial T_w}{\partial x} \right)_{x=0} - \left(\frac{\partial T_w}{\partial x} \right)_{x=-a} \right]. \quad (3)$$

Assume that the surface $x = -a$ is perfectly thermally insulated, so that $(\partial T_w / \partial x)_{x=-a} = 0$. Also, the heat flux at $x = 0$ must be continuous; i.e.,

$$k_w \left(\frac{\partial T_w}{\partial x} \right)_{x=0} = k_L \left(\frac{\partial T_L}{\partial x} \right)_{x=0}, \quad (4)$$

where the subscript L refers to liquid. Thus, Eq. 3 becomes

$$\rho_w c_w \frac{dT_{mw}}{dt} = Q(t) + \frac{k_L}{a} \left(\frac{\partial T_L}{\partial x} \right)_{x=0} \quad (5)$$

The conduction equation for the liquid is

$$\rho_L c_L \frac{\partial T_L}{\partial t} = k_L \frac{\partial^2 T_L}{\partial x^2} \quad (6)$$

The initial and boundary conditions to be used in conjunction with Eqs. 5 and 6 are

$$T_{mw} = T_0 \quad \text{at } t = 0, \quad -a < x < 0; \quad (7a)$$

$$T_L = T_0 \quad \text{at } t = 0, \quad x > 0; \quad (7b)$$

$$T_L = T_{mw} \quad \text{at } x = 0, \quad t > 0; \quad (7c)$$

$$T_L \text{ finite as } x \rightarrow \infty, \quad t \geq 0. \quad (7d)$$

To uncouple this system, Eq. 5 is integrated with respect to t , yielding

$$T_{mw} - T_0 = \frac{1}{\rho_w c_w} \int_0^t Q(t') dt' + \frac{k_L}{a \rho_w c_w} \int_0^t \left(\frac{\partial T_L}{\partial x} \right)_{x=0} dt', \quad (8)$$

so that the interface condition (7c) becomes

$$T_L = T_0 + \frac{1}{\rho_w c_w} \int_0^t Q(t') dt' + \frac{k_L}{a \rho_w c_w} \int_0^t \left(\frac{\partial T_L}{\partial x} \right)_{x=0} dt' \quad \text{at } x = 0. \quad (9)$$

Equation 6 with conditions 7b, 7d, and 9 can now be solved explicitly. For convenience, the following dimensionless quantities are defined:

$$\eta = x/a, \quad \tau = k_L t / a^2 \rho_L c_L, \quad R = \rho_L c_L / \rho_w c_w, \quad (10)$$

$$q(\tau) = Q(t)/Q_0, \quad \theta_L(\eta, \tau) = [T_L(x, t) - T_0] / (Q_0 a^2 / k_L),$$

when Q_0 is a reference value of $Q(t)$. This reduces the differential system defining the liquid temperature to

$$\frac{\partial \theta_L}{\partial \tau} = \frac{\partial^2 \theta_L}{\partial \eta^2}, \quad \eta > 0, \quad \tau > 0; \quad (11)$$

$$\theta_L(\eta, 0) = 0, \quad \eta > 0; \quad (11a)$$

$$\theta_L(\infty, \tau) \text{ finite}, \quad \tau \geq 0; \quad (11b)$$

$$\theta_L(0, \tau) = R \int_0^\tau \left[q(\tau') + \left(\frac{\partial \theta_L}{\partial \eta} \right)_{\eta=0} \right] d\tau', \quad \tau > 0. \quad (11c)$$

This system can now be solved using the LaPlace transformation in a straightforward manner, resulting in

$$\theta_L(\eta, \tau) = R e^{R\eta} \int_0^\tau q(t - \tau) e^{R^2 t} \operatorname{erfc} \left(R\sqrt{t} + \frac{\eta}{2\sqrt{t}} \right) dt, \quad (12)$$

and, using Eq. 7c,

$$\theta_{mw}(\tau) = \frac{T_{mw}(t) - T_0}{Q_0 a^2 / k_w} = R \int_0^\tau q(t - \tau) e^{R^2 t} \operatorname{erfc}(R\sqrt{t}) dt. \quad (13)$$

It is of interest to compare the above wall temperature with the temperature obtained with no conduction losses at $x = 0$, i.e., if $(\partial T_w / \partial x)_{x=0} = 0$. From Eq. 3, this adiabatic temperature is

$$\rho_w c_w \frac{dT_{maw}}{dt} = Q(t), \quad T_{maw} = T_0 \text{ at } t = 0, \quad (3a)$$

so that

$$\theta_{maw}(\tau) = \frac{T_{maw}(t) - T_0}{Q_0 a^2 / k_w} = R q(\tau) \tau. \quad (14)$$

In the experiments discussed in this report, only nominally rectangular energy-generation rates were used; i.e.,

$$\begin{aligned} q(\tau) &= 0, & \tau < 0; \\ q(\tau) &= 1, & 0 < \tau < \tau_0; \\ q(\tau) &= 0, & \tau > \tau_0; \end{aligned} \quad (15)$$

so that Eqs. 13 and 14 reduce to

$$\theta_{mw}(\tau) = R \int_0^\tau e^{R^2 t} \operatorname{erfc}(R\sqrt{t}) dt \quad (13a)$$

and

$$\theta_{maw}(\tau) = R\tau. \quad (14a)$$

Note that $\operatorname{erfc}(R\sqrt{t})$ is defined as

$$\operatorname{erfc}(R\sqrt{t}) = \frac{2}{\sqrt{\pi}} \int_{R\sqrt{t}}^\infty e^{-u^2} du, \quad (16)$$

so that Eq. 13a can be explicitly evaluated by interchanging the order of integration to yield

$$\theta_{mw}(\tau) = \frac{1}{R} \left[e^{R^2 \tau} \operatorname{erfc}(R\sqrt{\tau}) - 1 + 2R\sqrt{\tau/\pi} \right]. \quad (17)$$

The ratio of $\theta_{mw}(\tau)$ to $\theta_{maw}(\tau)$ is shown in Fig. A2, which shows the effects of τ and R . As R increases, the ratio θ_{mw}/θ_{maw} decreases;

112-8092

Fig. A2. Effect of Heat-capacity Ratio on Ratio of Transient Wall Temperature with Conduction Losses to That with No Losses

i.e., heat is lost from the wall at a faster rate. The values of $R = 0.31$ and 1.16 correspond to a stainless steel wall and liquid sodium and water, respectively. The time range shown varies from approximately $4 \mu\text{sec}$ to 10 msec for sodium and 1 msec to 10 sec for water, measured from the start of the heating transient.

Apparently, significant energy is transferred from the wall to the liquid in the time range by pure conduction; since boiling also occurs during the heating transient, the wall temperature is lowered still further.

APPENDIX B

A Simplified Analytical Expulsion Model

To understand the transient behavior of a rapidly heated, partially confined liquid, it would be helpful if we could postulate a physical model, describe the model mathematically, and solve the resulting equation(s). Based on the experimental data presented in this report, a model that describes fluid behavior over the full range of subcoolings appears to be

Fig. B1. Expulsion Model Geometry

quite complex. Thus, to gain an initial thrust at this problem, a model that is limited to slightly subcooled liquids appears most promising. In this situation, a reasonable assumption might be that all the heat input to the liquid is used as latent heat of vaporization and condensation of the vapor is not possible. This premise considerably simplifies the analysis, primarily since the cyclic vaporization-condensation phenomenon that invariably occurs in subcooled liquids is avoided. The coordinate system and physical dimensions are shown in Fig. B1, which represents the limiting case of a thin annulus.

If energy is generated in a section of the wall at a rate of Q

calories per unit volume per unit time, and heat is transferred to the fluid at a rate of q_w calories per unit area per unit time, then the wall temperature, T_w , increases at the rate

$$\rho_w c_w \frac{dT_w}{dt} = Q - \frac{q_w}{a}. \quad (18)$$

If the liquid is initially at its boiling temperature, we can assume that all the heat loss from the wall is used as latent heat of vaporization; i.e.,

$$h q_w = h_{fg} \frac{dM}{dt}, \quad (19)$$

where M is the mass of vapor formed. But,

$$M = \rho_v b l_1 \quad (20)$$

so that Eqs. 18-20 may be combined to yield

$$\rho_w c_w \frac{dT_w}{dt} = Q - \left(\frac{\rho_v h_{fg} b}{ah} \right) \frac{d\ell_1}{dt} \quad (21)$$

Noting that $T_w(0) = T_{w0}$ and $\ell_1(0) = 0$, Eq. 21 can be directly integrated to yield

$$T_w(t) = T_{w0} + \frac{1}{\rho_w c_w} \int_0^t Q(t') dt' - \left(\frac{\rho_v h_{fg} b}{ah \rho_w c_w} \right) \ell_1(t). \quad (22)$$

To determine the pressure in the vapor, the mean temperature of the vapor must be known. The mean temperature that will be used is the arithmetic average of the wall temperature, $T_w(t)$, and the liquid-vapor interfacial temperature, T_{w0} . To relate the vapor pressure with its temperature, the standard relation

$$\log P = A - \frac{B}{T}, \text{ or } P = C \exp \left(-\frac{B}{T} \right), \quad (23)$$

will be used. Combining Eq. 23 with Eq. 22 gives the maximum pressure in the growing vapor space as

$$P(t) = C \exp \left\{ -2B \left[2T_{w0} + \frac{1}{\rho_w c_w} \int_0^t Q(t') dt' - \left(\frac{\rho_v h_{fg} b}{ah \rho_w c_w} \right) \ell_1(t) \right] \right\}. \quad (24)$$

When this pressure exceeds the ambient pressure plus the liquid head, the liquid is accelerated upward. The motion of the liquid can be approximated by the unsteady form of Bernoulli's energy equation,

$$\frac{u^2}{2} + \frac{P}{\rho} + gx + \int_0^x \frac{\partial u}{\partial t} dx' = \text{constant}. \quad (25)$$

Application of Eq. 25 between $x = \ell_1(t)$ and $x = \ell_3(t)$ results in

$$[\ell_3(t) - \ell_1(t)] \frac{du}{dt} = \frac{P(t) - P_{atm}}{\rho_L} + g[\ell_1(t) - \ell_3(t)], \quad (26)$$

where the assumption of incompressible liquid has required that u be a function of t only.

A mass balance on the system shows that

$$l_3(t) = l_{30} + \left(1 - \frac{\rho_v}{\rho_L}\right) l_1(t). \quad (27)$$

However, $\rho_v/\rho_L \ll 1$ in most cases, so that

$$l_3(t) - l_1(t) = l_{30} = \text{constant}. \quad (28)$$

Furthermore, it is observed that $u = dl_1/dt$, so that Eq. 26 finally may be written as

$$\frac{d^2 l_1}{dt^2} = \frac{P(t) - P_{\text{atm}}}{\rho_L l_{30}} - g, \quad (29)$$

where $P(t)$ is given by Eq 24.

For ease in representation and computation, the following nondimensional quantities are defined

$$\Lambda(\xi) = \frac{1}{B} \left[\left(\frac{\rho_v h_{fg} b}{2\rho_w c_w a h} \right) l_1(t) - T_{w0} \right], \quad (30)$$

$$\xi = \frac{Q_0 t}{2\rho_w c_w B}, \quad (31)$$

$$\alpha = Q_0 \left(\frac{\rho_L l_{30} a h}{2CB\rho_v b h_{fg} \rho_w c_w g_c} \right)^{1/2}, \quad (32)$$

$$\beta = \frac{1}{C} \left(P_{\text{atm}} + g\rho_L l_{30}/g_c \right), \quad (33)$$

and

$$\gamma = T_{w0}/B, \quad (34)$$

and Eqs. 29 and 24 become

$$\alpha^2 \frac{d^2 \Lambda}{d\xi^2} = -\beta + \exp\left(\frac{1}{\Lambda - \xi}\right) \quad (35)*$$

*This form is valid only for the special case of

$$Q(t) = \begin{cases} 0, & t < 0; \\ Q_0, & t \geq 0. \end{cases}$$

with the initial conditions

$$\Lambda(0) = -\gamma \quad (36a)$$

$$\frac{d\Lambda(0)}{d\xi} = 0, \quad (36b)$$

which specify a zero initial displacement and velocity.

An analytic solution could not be found to this system; thus, a numerical solution using a fourth-order Runge-Kutta technique on an IBM-360/50 digital computer was obtained. Inspection of the values of the parameters indicates that γ is fixed for a given fluid (assuming T_{w0} is the normal boiling temperature) and β varies only slightly. Thus, α is the only parameter that can reasonably vary over a considerable range, and the solutions should depend primarily on α .

The results of some computations of the transient displacement and velocity for the case of initially saturated water at 1 atm are shown in Figs. B2 and B3. These results compare well qualitatively with the

112-8198

Fig. B2. Theoretical Transient Column Displacements

112-8197

Fig. B3. Theoretical Transient Expulsion Velocities

experimental results presented in the body of this report. The rapid acceleration to a maximum, relatively constant velocity is clearly evident. However, as shown in Fig. B4, where the results of the model are compared to the experiment results of Run 6-Q, a quantitative discrepancy is apparent. The initial part of the transient is predicted reasonably, but the latter part poorly. Although it is not shown in Fig. B4, the theoretical pressure reaches a maximum, and its shape is quite similar to that of the experimental pressure; however, the peak is overpredicted by approximately a factor of 5. The results in Fig. B4 are quite typical of all the runs.

The weakest point in this model appears to be the prediction of the pressure in the vapor. Obviously, the experimental pressure does not rise as fast or as high as would be expected by the heated wall temperature. If this model is to be extended or corrected, a new criterion of pressure prediction must be postulated. It is somewhat gratifying, however, that such a simple model illustrated the qualitative features of expulsion for an initially saturated liquid.

112-8196

Fig. B4. Comparison of Theoretical and Experimental Results for Water

APPENDIX C

Tabulated Data

This appendix presents the experimental data from all runs, including all measurements. The detailed pressure and coolant-motion transients are not shown because of the excess space that would be required; these results are presented in summarized form.

The maximum liquid kinetic energy was calculated using the standard relationship, $KE = \frac{1}{2}(\text{mass})(\text{velocity})^2$; the total initial mass of liquid was used (neglecting the loss due to vaporization), and the maximum liquid velocity yielded the maximum kinetic energy. The initial liquid displacement, velocity, and acceleration were calculated numerically from the smoothed displacement-time data.

Explanation of Abbreviations

S.P.	Only a single <u>secondary</u> <u>pulse</u> occurred
-	No secondary pulses
N.M.	Not measurable
C.E.	Complete expulsion
N.P.	No pictures taken during this run

The initial liquid height was measured from the top of the heated test section; to determine the total liquid height, add 25.4 cm to the tabulated values. The time at which the first pressure pulse occurs is measured from the start of heating.

Date	Run No.	No. of Batteries	Voltage	Amperage	Power Duration, msec	Energy Input Rate		Total Energy Input		Test Liquid	Initial Liquid Temp, °C	Initial Liquid Height, cm	Annular Gap, mm	Total Liquid Mass, gm	Max Heater Temp (calc), °C		Heater Temp Rise Rate (calc), 10 ³ °C/sec		Time of First Pressure Pulse, msec	Peak Initial Pressure Pulse		Peak Secondary Pressure Pulse, atm	Frequency of Secondary Pulses, cps	Max Initial Liquid Displacement, cm	Max Initial Liquid Velocity, m/sec	Max Initial Liquid Acceleration, m/sec ²	Max Liquid Kinetic Energy, W	Ratio, Kinetic to Input Energy, %
						kW	($\frac{\text{kcal}}{\text{sec-cm}^2}$)	kW-sec	kcal						Adiabatic	With Conduction Losses	Adiabatic	With Conduction Losses		psia	atm							
9-1-65	1	1	8.23	365	148	3.00	0.374	0.445	0.106	H ₂ O	23	0	3.18	65.5	66	45	0.44	0.23	-	14.7	1.00	-	-	0	0	0		
9-1	2	2	15.00	655	112	9.83	1.225	1.100	0.263	H ₂ O	24	0	3.18	65.5	165	97	1.45	0.76	-	14.7	1.00	-	-	0	0	0		
9-2	3-A	3	20.83	890	98	18.54	2.310	1.817	0.434	H ₂ O	23	0	3.18	65.5	291	163	2.73	1.43	-	14.7	1.00	1.82	100	N.P.				
9-2	3-Aa	3	21.08	890	94	18.76	2.337	1.764	0.421	H ₂ O	23	0	3.18	65.5	283	160	2.76	1.46	-	14.7	1.00	3.58	143	N.P.				
9-2	3-B	3	21.08	890	92	18.76	2.337	1.726	0.412	H ₂ O	22	0	3.18	65.5	276	157	2.76	1.46	-	14.7	1.00	2.97	111	N.P.				
9-2	3-C	3	21.08	890	93	18.76	2.337	1.745	0.417	H ₂ O	22	0	3.18	65.5	279	158	2.77	1.46	-	14.7	1.00	2.43	100	N.P.				
9-2	3-D	3	21.08	890	95	18.76	2.337	1.782	0.426	H ₂ O	23	2.5	3.18	71.5	286	161	2.77	1.45	-	14.7	1.00	3.86	100	N.P.				
9-3	3-E	3	21.00	885	99	18.59	2.316	1.840	0.440	H ₂ O	24	5.1	3.18	77.4	295	165	2.74	1.43	-	14.7	1.00	2.90	100	N.P.				
9-3	3-Ea	3	21.00	885	98	18.59	2.316	1.821	0.435	H ₂ O	22	5.1	3.18	77.4	290	162	2.74	1.43	-	14.7	1.00	2.84	125	N.P.				
9-3	3-F	3	20.50	875	96	17.94	2.235	1.722	0.411	H ₂ O	23	7.6	3.18	83.3	287	156	2.64	1.39	-	14.7	1.00	2.84	100	N.P.				
9-3	3-G	3	20.75	885	104	18.36	2.288	1.910	0.456	H ₂ O	25	10.2	3.18	89.2	306	170	2.71	1.39	-	14.7	1.00	2.90	100	N.P.				
9-3	3-Ga	3	20.83	885	95	18.43	2.296	1.751	0.418	H ₂ O	21	12.7	3.18	95.1	279	157	2.72	1.43	-	14.7	1.00	2.43	100	N.P.				
9-3	3-H	3	20.92	885	97	18.51	2.306	1.796	0.429	H ₂ O	24	15.2	3.18	101.1	288	162	2.73	1.43	-	14.7	1.00	2.70	100	N.P.				
9-3	3-Ha	3	20.92	875	96	18.31	2.281	1.757	0.420	H ₂ O	23	15.2	3.18	101.1	282	159	2.70	1.42	-	14.7	1.00	1.48	100	N.P.				
9-3	3-Hb	3	20.83	875	95	18.23	2.281	1.731	0.414	H ₂ O	23	15.2	3.18	101.1	278	157	2.69	1.41	-	14.7	1.00	1.75	100	N.P.				
9-3	3-Hc	3	20.92	875	107	18.31	2.281	1.959	0.468	H ₂ O	22	15.2	3.18	101.1	300	159	2.69	1.38	-	14.7	1.00	3.11	100	N.P.				
9-3	3-J	3	21.00	885	93	18.59	2.316	1.728	0.413	H ₂ O	22	17.8	3.18	106.8	276	157	2.74	1.45	-	14.7	1.00	3.86	100	N.P.				
9-3	3-K	3	20.92	880	96	18.41	2.294	1.767	0.422	H ₂ O	22	20.3	3.18	102.8	282	159	2.71	1.42	-	14.7	1.00	2.97	100	N.P.				
9-3	3-L	3	21.00	885	95	18.59	2.316	1.766	0.422	H ₂ O	23	22.9	3.18	118.6	283	160	2.74	1.44	-	14.7	1.00	4.67	100	N.P.				
9-3	3-M	3	21.00	885	95	18.59	2.316	1.766	0.422	H ₂ O	23	20.3	3.18	102.8	283	160	2.74	1.44	-	14.7	1.00	2.90	100	N.P.				
9-3	3-N	3	21.00	890	95	18.69	2.329	1.776	0.424	H ₂ O	23	17.8	3.18	106.8	285	161	2.76	1.45	-	14.7	1.00	2.77	100	N.P.				
9-3	3-P	3	20.83	885	101	18.43	2.296	1.862	0.445	H ₂ O	24	15.2	3.18	101.1	298	166	2.72	1.41	-	14.7	1.00	2.97	100	N.P.				
9-3	3-Q	3	21.00	885	102	18.59	2.316	1.896	0.453	H ₂ O	21	12.7	3.18	95.1	300	165	2.74	1.42	-	14.7	1.00	2.77	100	N.P.				
9-3	3-R	3	20.92	885	102	18.51	2.306	1.888	0.451	H ₂ O	21	10.2	3.18	89.2	299	165	2.73	1.41	-	14.7	1.00	2.77	100	N.P.				
9-3	3-S	3	20.92	885	95	18.51	2.306	1.759	0.420	H ₂ O	25	22.9	3.18	118.6	284	161	2.73	1.44	-	14.7	1.00	3.65	100	N.P.				
9-3	3-T	3	21.00	890	95	18.69	2.329	1.776	0.424	H ₂ O	22	7.6	3.18	83.3	283	160	2.76	1.45	-	14.7	1.00	2.90	100	N.P.				
9-3	3-U	3	20.92	885	105	18.51	2.306	1.944	0.464	H ₂ O	23	5.1	3.18	77.4	309	170	2.72	1.40	-	14.7	1.00	3.18	125	N.P.				
9-3	3-V	3	20.83	880	102	18.33	2.284	1.870	0.447	H ₂ O	21	2.5	3.18	71.5	296	163	2.70	1.40	-	14.7	1.00	2.50	100	N.P.				
9-3	3-W	3	20.92	880	109	18.41	2.294	2.007	0.479	H ₂ O	24	0	3.18	65.5	319	174	2.71	1.38	-	14.7	1.00	2.16	143	N.P.				
9-3	3-X	3	21.08	890	97	18.76	2.337	1.820	0.435	H ₂ O	23	0	3.18	65.5	291	163	2.76	1.45	-	14.7	1.00	3.04	125	N.P.				
9-3	4-A	4	26.0	1200	95	31.20	3.888	2.964	0.708	H ₂ O	23	0	3.18	65.5	460	253	4.84	2.66	-	14.7	1.00	3.65	143	N.P.				
9-3	4-B	4	24.5	1065	98	26.09	3.251	2.557	0.611	H ₂ O	23	0	3.18	65.5	400	220	4.08	2.24	-	14.7	1.00	5.22	143	N.P.				
9-3	4-C	4	26.3	1075	90	28.27	3.522	2.545	0.608	H ₂ O	25	0	3.18	65.5	400	225	4.44	2.50	-	14.7	1.00	3.18	111	N.P.				
9-3	4-D	4	26.2	1075	104	28.17	3.510	2.929	0.700	H ₂ O	24	0	3.18	65.5	456	246	4.38	2.37	-	14.7	1.00	2.90	125	N.P.				
9-3	4-E	4	26.2	1070	85	28.03	3.493	2.383	0.569	H ₂ O	25	5.1	3.18	77.4	376	215	4.42	2.53	-	14.7	1.00	3.04	100	N.P.				
9-3	4-Ea	4	26.3	1070	89	28.14	3.506	2.505	0.598	H ₂ O	22	5.1	3.18	77.4	391	219	4.39	2.46	-	14.7	1.00	2.77	83	N.P.				
9-3	4-Eb	4	26.3	1070	91	28.14	3.506	2.561	0.612	H ₂ O	23	5.1	3.18	77.4	400	223	4.40	2.45	-	14.7	1.00	3.45	100	N.P.				
9-3	4-F	4	26.2	1065	88	27.90	3.476	2.455	0.586	H ₂ O	23	12.7	3.18	95.1	330	189	3.75	2.15	-	14.7	1.00	4.47	63	N.P.				
9-3	4-Fa	4	26.3	1065	96	28.01	3.490	2.689	0.642	H ₂ O	23	12.7	3.18	95.1	419	231	4.36	2.41	-	14.7	1.00	3.52	63	N.P.				
9-3	4-G	4	26.3	1070	93	28.14	3.506	2.617	0.625	H ₂ O	24	17.8	3.18	106.8	420	228	4.52	2.45	-	14.7	1.00	4.54	63	N.P.				
9-3	4-Ga	4	24.5	1070	86	26.22	3.267	2.254	0.538	H ₂ O	25	17.8	3.18	106.8	357	204	4.15	2.37	-	14.7	1.00	3.72	100	N.P.				
9-7	4-H	4	23.3	1055	89	24.58	3.063	2.188	0.523	H ₂ O	21	2.5	3.18	71.5	343	193	3.85	2.17	-	14.7	1.00	4.33	83	N.P.				
9-7	4-Ha																											

Date	Run No.	No. of Batteries	Voltage	Amperage	Power Duration, msec	Energy Input Rate		Total Energy Input		Test Liquid	Initial Liquid Temp, °C	Initial Liquid Height, cm	Annular Gap, mm	Total Liquid Mass, gm	Max Heater Temp (calc), °C		Heater Temp Rise Rate (calc), 10 ³ °C/sec		Time of First Pressure Pulse, msec	Peak Initial Pressure Pulse		Peak Secondary Pressure Pulse, atm	Frequency of Secondary Pulses, cps	Max Initial Liquid Displacement, cm	Max Initial Liquid Velocity, m/sec	Max Initial Liquid Acceleration, m/sec ²	Max Liquid Kinetic Energy, W	Ratio, Kinetic to Input Energy, %
						kW	(kcal/sec-cm ³)	kW-sec	kcal						Adiabatic	With Conduction Losses	Adiabatic	With Conduction Losses		psia	atm							
9-8-65	4-Lc	4	22.8	1050	92	23.94	2.983	2.202	0.526	H ₂ O	20	10.2	3.18	89.2	344	192	3.52	1.87	-	14.7	1.00	2.63	50	N.P.				
	4-M	4	23.3	1055	91	24.58	3.063	2.237	0.534	H ₂ O	25	12.7	3.18	95.1	355	200	3.63	1.92	-	14.7	1.00	2.77	56	N.P.				
	4-Ma	4	22.2	1050	91	23.31	2.904	2.121	0.507	H ₂ O	24	12.7	3.18	95.1	337	190	3.44	1.82	-	14.7	1.00	2.50	48	N.P.				
	4-Mb	4	23.7	1055	90	25.00	3.115	2.250	0.538	H ₂ O	21	12.7	3.18	95.1	352	198	3.68	1.97	-	14.7	1.00	3.59	48	N.P.				
	4-Mc	4	24.2	1055	90	25.53	3.181	2.298	0.549	H ₂ O	23	12.7	3.18	95.1	361	203	3.76	2.00	-	14.7	1.00	2.84	48	N.P.				
	4-N	4	23.3	1055	90	24.58	3.063	2.212	0.528	H ₂ O	23	15.2	3.18	101.1	359	197	3.62	1.93	-	14.7	1.00	2.70	45	N.P.				
	4-Na	4	24.3	1055	92	25.64	3.195	2.359	0.564	H ₂ O	22	15.2	3.18	101.1	369	206	3.77	2.00	-	14.7	1.00	2.56	45	N.P.				
	4-Nb	4	24.3	1055	89	25.64	3.195	2.282	0.545	H ₂ O	23	15.2	3.18	101.1	359	203	3.78	2.02	-	14.7	1.00	2.84	43	N.P.				
	4-Nc	4	24.3	1050	90	25.52	3.180	2.296	0.549	H ₂ O	23	15.2	3.18	101.1	361	203	3.76	2.00	-	14.7	1.00	4.13	42	N.P.				
	4-Nd	4	24.3	1050	90	25.52	3.180	2.296	0.549	H ₂ O	23	15.2	3.18	101.1	361	203	3.76	2.00	-	14.7	1.00	3.72	42	N.P.				
	4-P	4	23.3	1050	91	24.47	3.049	2.226	0.532	H ₂ O	22	17.8	3.18	106.8	350	196	3.60	1.91	-	14.7	1.00	2.77	53	N.P.				
	4-Pa	4	24.8	1050	89	26.04	3.245	2.318	0.554	H ₂ O	22	17.8	3.18	106.8	363	204	3.83	2.04	-	14.7	1.00	3.31	50	N.P.				
	4-Pb	4	24.5	1050	90	25.73	3.206	2.315	0.553	H ₂ O	22	17.8	3.18	106.8	363	204	3.79	2.02	-	14.7	1.00	2.70	53	N.P.				
	4-Pc	4	24.7	1050	89	25.93	3.231	2.308	0.551	H ₂ O	23	17.8	3.18	106.8	363	205	3.82	2.04	-	14.7	1.00	2.70	48	N.P.				
	4-Q	4	24.7	1050	94	25.93	3.231	2.438	0.582	H ₂ O	22	20.3	3.18	112.7	381	211	3.82	2.01	-	14.7	1.00	3.31	45	N.P.				
	4-Qa	4	25.0	1050	81	26.25	3.271	2.126	0.508	H ₂ O	23	20.3	3.18	112.8	336	194	3.86	2.11	-	14.7	1.00	3.04	42	N.P.				
	4-Qb	4	24.5	1050	90	25.73	3.206	2.315	0.553	H ₂ O	22	20.3	3.18	112.6	363	204	3.79	2.02	-	14.7	1.00	2.90	45	N.P.				
	4-Qc	4	23.7	1050	92	24.88	3.100	2.289	0.547	H ₂ O	22	20.3	3.18	112.7	359	201	3.66	1.95	-	14.7	1.00	2.90	42	N.P.				
	4-R	4	25.0	1050	88	26.25	3.271	2.310	0.552	H ₂ O	24	27.9	3.18	130.2	364	206	3.86	2.07	-	14.7	1.00	2.90	36	N.P.				
11-5	4-a	4	25.5	1100	88.6	28.05	3.495	2.485	0.594	H ₂ O	22	0	3.18	65.6	388	218	4.13	2.21	-	14.7	1.00	3.72	95	0.59	0.61	85.1	0.012	0.0005
11-5	4-β	4	26.0	1105	92.7	28.73	3.580	2.663	0.636	H ₂ O	30	1	3.18	67.7	422	238	4.23	2.24	-	14.7	1.00	3.29	81	0.59	0.61	99.6	0.013	0.0005
11-5	4-γ	4	26.3	1105	92.7	29.06	3.621	2.694	0.644	H ₂ O	35	2	3.18	70.1	432	245	4.28	2.27	-	14.7	1.00	4.77	69	0.20	0.22	-	0.002	0.0001
11-10	4-δa	4	23.3	1150	88.7	26.79	3.338	2.377	0.568	H ₂ O	27	6	3.18	79.5	377	214	3.95	2.11	-	14.7	1.00	2.88	50	0.56	0.63	88.7	0.016	0.0007
11-10	4-δb	4	24.5	1155	87.2	28.30	3.526	2.830	0.676	H ₂ O	24	6	3.18	79.6	387	219	4.16	2.24	-	14.7	1.00	3.18	44	0.30	0.43	46.2	0.007	0.0002
11-10	4-ε	4	26.2	1105	85.4	28.95	3.607	2.472	0.591	H ₂ O	33	22	3.18	116.4	397	230	4.26	2.31	-	14.7	1.00	3.08	37	0.93	0.30	14.5	0.005	0.0002
11-10	4-ζ	4	25.2	1150	99.2	28.98	3.611	2.875	0.687	H ₂ O	19	3	3.18	72.6	441	243	4.26	2.26	-	14.7	1.00	2.38	50	0.20	0.23	-	0.002	0.0001
11-10	4-η	4	24.5	1155	87.7	28.30	3.526	2.482	0.593	H ₂ O	25	12	3.18	93.6	389	221	4.15	2.23	-	14.7	1.00	3.08	50	0.20	0.18	-	0.002	0.0001
11-11	4-θ	4	23.7	1150	92.6	27.25	3.395	2.524	0.603	H ₂ O	25	18	3.18	107.3	396	222	4.01	2.13	-	14.7	1.00	2.88	45	0.69	0.76	-	0.031	0.0012
11-11	4-i	4	25.5	1140	88.2	29.07	3.622	2.564	0.613	H ₂ O	22	15	3.18	100.4	398	224	4.26	2.29	-	14.7	1.00	2.99	48	0.77	0.42	41.4	0.009	0.0004
11-11	4-ia	4	25.0	1125	86.9	28.12	3.504	2.444	0.584	H ₂ O	27	15	3.18	100.3	354	221	3.76	2.23	-	14.7	1.00	2.68	50	0.39	0.41	14.2	0.008	0.0003
11-11	4-ka	4	25.2	1135	90.0	28.60	3.564	2.574	0.615	H ₂ O	27	8.0	3.18	84.1	406	229	4.21	2.24	-	14.7	1.00	3.08	50	0.52	0.54	68.4	0.012	0.0005
11-11	4-kb	4	25.2	1135	89.2	28.60	3.564	2.551	0.609	H ₂ O	43	8.0	3.18	83.6	419	244	4.22	2.25	-	14.7	1.00	3.08	36	0.68	0.34	20.2	0.005	0.0002
11-11	4-kc	4	25.5	1135	89.5	28.94	3.606	2.590	0.619	H ₂ O	45	8.0	3.18	83.6	426	249	4.26	2.28	-	14.7	1.00	2.88	36	0.58	0.45	56.1	0.009	0.0003
12-6	4-l	4	25.2	1035	87.5	28.60	3.564	2.282	0.545	H ₂ O	24	6.0	3.18	79.5	393	222	4.22	2.26	-	14.7	1.00	3.29	63	0.42	0.53	58.4	0.011	0.0005
12-6	4-la	4	25.2	1055	87.5	29.11	3.627	2.326	0.556	H ₂ O	34	6.2	3.18	79.8	409	235	4.29	2.30	-	14.7	1.00	2.69	63	0.45	0.54	21.6	0.012	0.0005
12-6	4-lb	4	25.2	1055	86.1	29.11	3.627	2.289	0.547	H ₂ O	44	6.3	3.18	79.7	413	243	4.17	2.31	-	14.7	1.00	3.18	45	0.56	0.38	26.2	0.006	0.0003
12-6	4-lc	4	25.0	1070	85.9	26.75	3.333	2.298	0.549	H ₂ O	54	6.0	3.18	78.6	385	237	3.85	2.13	-	14.7	1.00	3.48	76	0.85	0.62	61.4	0.015	0.0007
12-6	4-lc	4	25.3	1035	91.6	28.72	3.579	2.399	0.573	H ₂ O	68	6.0	3.18	78.0	455	274	4.22	2.25	33	19.7	1.34	5.37	71	N.P.				
12-6	4-le	4	25.2	1025	91.8	25.83	3.218	2.371	0.566	H ₂ O	78	6.0	3.18	77.6	417	263	3.80	2.02	33	20.7	1.41	1.30	S.P.	C.E.	2.30	169.9	0.205	0.0086
12-6	4-lf	4	25.0	1000	87.7	25.00	3.115	2.193	0.524	H ₂ O	81	6.0	3.18	77.4	404	254	3.68	1.97	-	17.7	1.20	1.00	-	C.E.	2.73	138.6	0.289	0.0132
12-10	4-li	4	25.8	1075	94.5	27.74	3.456	2.621	0.626	H ₂ O	30	6.0	3.18	79.4	416	253	4.08	2.15	-	14.7	1.00	3.98	80	N.P.				
12-10	4-lg	4	25																									

Date	Run No.	No. of Batteries	Voltage	Amperage	Power Duration, msec	Energy Input Rate		Total Energy Input	Test Liquid	Initial Liquid Temp, °C	Initial Liquid Height, cm	Annular Gap, mm	Total Liquid Mass, gm	Max Heater Temp (calc), °C		Heater Temp Rise Rate (calc), 10 ³ °C/sec		Time of First Pressure Pulse, msec	Peak Initial Pressure Pulse		Peak Secondary Pressure Pulse, atm	Frequency of Secondary Pulses, cps	Max Initial Liquid Displacement, cm	Max Initial Liquid Velocity, m/sec	Max Initial Liquid Acceleration, m/sec ²	Max Liquid Kinetic Energy, W	Ratio, Kinetic to Input Energy, %	
						kW	(kcal/sec-cm ³)							Adiabatic	With Conduction Losses	Adiabatic	With Conduction Losses		psia	atm								
								kW-sec																				kcal
12-16-65	6-B	6	31.17	1360	83.0	42.39	5.282	3.518	0.602	H ₂ O	32	6.2	3.18	79.9	540	314	6.24	3.40	23.1	37.8	1.18	5.37	81	N.P.				
12-16	6-C	6	31.84	1313	79.7	41.81	5.210	3.332	0.796	H ₂ O	42	6.4	3.18	80.0	532	312	6.15	3.39	22.9	37.6	1.20	5.37	74	N.P.				
12-16	6-D	6	31.67	1313	82.6	41.58	5.185	3.435	0.821	H ₂ O	53	6.0	3.18	78.8	558	329	6.11	3.34	20.6	35.3	1.30	6.46	78	N.P.				
12-16	6-E	6	31.84	1307	76.6	41.61	5.185	3.188	0.762	H ₂ O	62	6.2	3.18	78.9	531	322	6.12	3.39	19.0	33.7	1.39	10.33	62	N.P.				
12-16	6-Fa	6	31.84	1287	85.9	40.98	5.106	3.520	0.841	H ₂ O	72	6.2	3.18	78.4	590	352	6.03	3.26	18.8	33.5	1.45	12.82	S.P.	N.P.				
12-16	6-G	6	32.34	1287	79.7	41.62	5.186	3.317	0.792	H ₂ O	79	6.2	3.18	78.1	567	347	6.12	3.36	14.4	29.1	1.60	4.48	S.P.	N.P.				
12-16	6-H	6	32.51	1280	84.5	41.61	5.185	3.518	0.840	H ₂ O	75	6.0	3.18	77.9	593	355	6.13	3.31	16.9	31.6	1.41	7.85	S.P.	N.P.				
12-16	6-I	6	32.34	1267	82.6	40.97	5.105	3.385	0.809	H ₂ O	76	5.9	3.18	77.5	574	348	6.03	3.29	16.7	31.4	1.44	11.43	S.P.	N.P.				
12-16	6-J	6	32.17	1287	80.8	41.40	5.158	3.345	0.799	H ₂ O	79	6.0	3.18	77.7	571	349	6.09	3.34	15.4	30.1	1.56	1.00	-	N.P.				
12-16	6-L	6	32.17	1273	85.2	40.95	5.102	3.489	0.834	H ₂ O	88	5.7	3.18	76.4	602	366	6.03	3.26	15.7	30.4	1.87	1.00	-	N.P.				
12-16	6-N	6	32.17	1273	85.4	40.95	5.102	3.497	0.835	H ₂ O	93	6.0	3.18	76.9	608	371	6.03	3.26	14.0	28.7	1.80	1.00	-	N.P.				
12-16	6-O	6	31.84	1260	90.8	40.12	4.999	3.643	0.870	H ₂ O	89	6.6	3.18	78.3	652	374	6.20	3.14	15.1	29.8	1.75	1.00	-	C.E.	4.81	243.0	0.906	0.0249
12-16	6-P	6	32.01	1260	84.5	40.33	5.025	3.408	0.814	H ₂ O	86	6.0	3.18	77.3	588	358	5.94	3.22	13.2	27.9	1.65	5.67	S.P.	N.M.	4.06	229.1	0.637	0.0187
12-16	6-Q	6	32.17	1267	82.0	40.76	5.079	3.342	0.798	H ₂ O	97	6.0	3.18	77.4	589	366	6.00	3.28	12.4	27.1	2.10	1.00	-	C.E.	9.38	483.7	3.406	0.1019
12-17	6-R	6	34.67	1240	82.8	42.99	5.357	3.560	0.850	H ₂ O	100	6.2	3.18	78.2	624	385	6.33	3.44	20.4	35.1	1.80	1.00	-	C.E.	5.59	397.8	1.222	0.0343
12-17	6-S	6	32.17	1253	83.1	40.31	5.023	3.350	0.800	H ₂ O	99	6.2	3.18	76.9	592	367	5.93	3.23	13.2	27.9	2.10	1.00	-	C.E.	6.11	407.4	1.436	0.0429
12-17	6-T	6	32.51	1267	79.2	41.19	5.132	3.262	0.779	H ₂ O	95	6.1	3.18	77.7	575	359	6.06	3.33	13.7	28.4	2.04	1.00	-	C.E.	7.20	522.0	2.015	0.0618
12-17	6-U	6	32.84	1260	79.1	41.38	5.156	3.273	0.782	H ₂ O	95	6.5	3.18	77.9	577	360	6.09	3.35	14.1	28.8	2.00	1.00	-	C.E.	5.90	340.1	1.356	0.0414
12-17	6-V	6	32.67	1267	84.9	41.39	5.157	3.514	0.839	H ₂ O	84	6.4	3.18	78.1	601	364	6.09	3.30	12.6	27.3	1.46	1.00	-	C.E.	2.40	210.1	0.225	0.0064
12-17	6-W	6	32.84	1267	82.8	41.61	5.185	3.445	0.823	H ₂ O	89	6.2	3.18	77.1	596	365	6.12	3.33	14.9	29.6	1.67	1.00	-	C.E.	4.62	241.1	0.823	0.0239
12-17	6-X	6	32.17	1260	81.2	40.53	5.050	3.291	0.786	H ₂ O	94	6.2	3.18	77.2	576	359	5.97	3.26	14.7	29.4	1.59	1.00	-	C.E.	5.24	322.6	1.060	0.0322
12-17	6-Y	6	32.51	1260	84.7	40.96	5.104	3.470	0.829	H ₂ O	91	5.9	3.18	76.7	602	368	6.03	3.27	13.0	27.7	1.80	1.00	-	C.E.	4.57	340.7	0.801	0.0231
12-17	6-AA	6	32.67	1240	91.7	40.51	5.048	3.715	0.888	H ₂ O	99	6.4	3.18	77.3	646	389	5.97	3.16	13.5	28.2	1.90	1.00	-	C.E.	6.03	328.6	1.406	0.0378
12-17	6-BB	6	32.34	1253	85.8	40.52	5.049	3.477	0.831	H ₂ O	91	5.7	3.18	76.2	603	368	5.97	3.23	13.9	28.6	1.83	1.00	-	C.E.	3.92	262.0	0.586	0.0169
12-17	6-CC	6	32.17	1260	80.5	40.53	5.050	3.263	0.780	H ₂ O	84	6.0	3.18	77.4	564	347	5.96	3.27	12.2	26.9	1.80	5.37	19	6.49	237	282.9	0.217	0.0067
12-17	6-DD	6	31.84	1260	78.6	40.12	4.999	3.153	0.753	H ₂ O	82	5.9	3.18	77.2	546	338	5.90	3.26	12.8	27.5	1.55	6.27	21	5.40	229	263.2	0.203	0.0064
12-17	6-FF	6	31.67	1280	80.6	40.54	5.051	3.267	0.780	H ₂ O	75	5.7	3.18	77.0	556	339	5.97	3.28	14.7	29.4	1.54	5.71	25	2.30	173	221.8	0.115	0.0035
12-17	6-GG	6	31.51	1273	85.4	40.11	4.998	3.426	0.818	H ₂ O	68	5.5	3.18	76.8	572	340	5.90	3.19	14.1	28.8	1.40	8.62	39	1.73	1.19	127.6	0.054	0.0016
12-28	8-A	8	35.17	1467	77.7	51.59	6.428	4.009	0.958	H ₂ O	24	6.2	3.18	80.0	614	350	7.59	4.20	25.1	17.3	1.18	7.1	100	0.71	0.68	64.1	0.018	0.0005
12-28	8-B	8	36.34	1467	75.3	53.31	6.642	4.014	0.959	H ₂ O	29	6.3	3.18	80.1	620	358	7.85	4.37	19.9	16.9	1.15	10.0	97	0.96	0.88	99.4	0.031	0.0008
12-28	8-C	8	35.17	1467	85.0	51.59	6.428	4.385	1.048	H ₂ O	37	6.5	3.18	80.4	682	376	7.59	4.11	18.8	19.1	1.30	10.1	100	0.88	0.89	119.9	0.032	0.0007
12-28	8-D	8	35.34	1460	77.4	51.60	6.429	3.994	0.954	H ₂ O	43	6.6	3.18	80.4	621	369	7.60	4.21	18.8	18.5	1.26	8.1	59	1.35	1.10	132.5	0.049	0.0011
12-28	8-E	8	37.34	1467	85.1	54.78	6.826	4.662	1.114	H ₂ O	48	6.8	3.18	80.7	734	419	8.06	4.36	17.4	19.4	1.32	7.0	74	0.84	0.57	63.6	0.013	0.0003
12-28	8-F	8	35.01	1447	81.5	50.66	6.312	4.129	0.986	H ₂ O	53	6.9	3.18	80.8	661	385	7.46	4.07	16.8	20.5	1.40	12.2	56	2.64	1.49	130.8	0.090	0.0019
12-28	8-G	8	35.34	1453	86.7	51.35	6.398	4.452	1.064	H ₂ O	56	6.9	3.18	80.7	712	409	7.57	4.07	15.9	21.3	1.45	8.8	33					
12-28	8-H	8	35.51	1460	77.8	51.84	6.459	4.033	0.963	H ₂ O	60	7.0	3.18	80.6	653	388	7.62	4.22	16.2	20.0	1.36	12.1	54	4.38	2.47	203.8	0.246	0.0061
12-28	8-I	8	36.34	1433	78.2	52.07	6.488	4.072	0.973	H ₂ O	69	7.1	3.18	80.5	668	400	7.66	4.23	15.7	23.5	1.60	14.8	27	N.M.	3.09	252.9	0.384	0.0094
12-28	8-J	8	35.51	1440	76.5	51.13	6.371	3.911	0.934	H ₂ O	44	6.5	3.18	80.1	620	364	7.53	4.18	18.3	19.1	1.30	12.9	115					
12-28	8-K	8	35.17	1453	75.7	51.10	6.367	3.868	0.924	H ₂ O	59	6.8	3.18	80.3	629	366	7.53	4.19	18.4	21.4	1.46	11.6	70</					

Date	Run No.	No. of Batteries	Volt-age	Amper-age	Power Duration, msec	Energy Input Rate		Total Energy Input		Test Liquid	Initial Liquid Temp, °C	Initial Liquid Height, cm	Annular Gap, mm	Total Liquid Mass, gm	Max Heater Temp (calc), °C		Heater Temp Rise Rate (calc), 10 ³ °C/sec		Time of First Pressure Pulse, msec	Peak Initial Pressure Pulse		Peak Secondary Pressure, atm	Frequency of Secondary Pulses, cps	Max Initial Liquid Displacement, cm	Max Initial Liquid Velocity, m/sec	Max Initial Liquid Acceleration, m/sec ²	Max Liquid Kinetic Energy, W	Ratio, Kinetic to Input Energy, %
						kW	(kcal sec-cm ³)	kW-sec	kcal						Adia-batic	With Con-duction Losses	Adia-batic	With Con-duction Losses		psia	atm							
12-29-65	10-H	10	40.00	1540	81.3	61.60	7.675	5.016	1.198	H ₂ O	70	6.7	3.18	79.5	807	473	9.07	4.96	12.6	23.8	1.62	17.3	28	N.P.				
12-29	10-I	10	41.67	1527	79.4	63.63	7.928	5.052	1.207	H ₂ O	74	6.9	3.18	79.8	817	483	9.36	5.15	14.1	25.7	1.75	12.1	26	3.10	2.33	362.8	0.217	0.0043
12-29	10-J	10	41.17	1520	76.4	62.58	7.797	4.781	1.142	H ₂ O	86	7.0	3.18	79.4	790	477	9.21	5.12	12.1	28.6	1.93	1.0	-	C.E.	7.23	509.1	2.076	0.0434
12-29	10-K	10	41.34	1520	76.7	62.84	7.830	4.820	1.151	H ₂ O	93	6.6	3.18	78.1	803	483	9.26	5.14	10.2	32.2	2.19	1.0	-	C.E.	10.89	575.0	4.633	0.0961
12-29	10-L	10	41.17	1513	82.0	62.29	7.761	5.170	1.235	H ₂ O	98	6.6	3.18	77.8	850	509	9.17	5.01	10.1	35.1	2.39	1.0	-	C.E.	9.15	478.7	3.258	0.0733
12-29	10-M	10	40.67	1520	71.8	61.82	7.703	4.445	1.062	H ₂ O	96	5.7	3.18	75.9	749	464	9.09	5.13	9.9	32.2	2.19	1.0	-	C.E.	6.06	425.2	1.394	0.0314
12-29	10-N	10	40.67	1513	72.6	61.53	7.667	4.467	1.067	H ₂ O	100	5.7	3.18	75.7	758	469	9.06	5.08	9.2	37.8	2.57	1.0	-	C.E.	8.04	913.8	2.448	0.0548
12-29	10-O	10	41.01	1520	75.4	62.34	7.768	4.700	1.123	H ₂ O	85	5.9	3.18	77.0	777	470	9.18	5.11	9.2	27.8	1.89	4.3	28	N.M.	4.03	963.2	0.626	0.0133
12-29	10-P	10	40.67	1513	73.7	61.53	7.667	4.535	1.083	H ₂ O	82	5.8	3.18	76.9	749	456	9.05	5.07	12.6	27.8	1.89	8.7	49	N.M.	6.60	830.4	1.676	0.0370
12-29	10-Q	10	41.17	1513	8.12	62.29	7.761	5.058	1.208	H ₂ O	79	5.7	3.18	76.8	824	486	9.17	5.01	13.6	26.4	1.80	9.0	43	N.M.	5.03	482.9	0.972	0.0192
2-3-66	12-A	12	45.18	1840	73.4	83.13	10.358	6.102	1.458	H ₂ O	20	7.8	3.18	83.9	919	523	12.25	6.85	16.4	19.1	1.30	13.8	S.P.	N.P.				
2-3	12-B	12	46.01	1860	78.0	85.58	10.663	6.675	1.595	H ₂ O	35	7.9	3.18	83.7	1017	578	12.59	6.96	14.0	20.8	1.41	10.3	S.P.	N.M.	3.23	75.4	0.438	0.0066
2-3	12-C	12	47.51	1833	74.1	87.09	10.851	6.453	1.542	H ₂ O	50	8.1	3.18	83.5	1000	581	12.82	7.17	12.4	22.0	1.50	14.7	S.P.	N.M.	3.80	254.0	0.603	0.0093
2-3	12-D	12	49.68	1793	74.3	89.08	11.099	6.619	1.581	H ₂ O	88	8.9	3.18	83.6	1074	632	13.27	7.32	11.5	36.6	2.49	1.0	-	C.E.	8.96	983.9	3.357	0.0507
2-3	12-E	12	48.84	1800	70.9	87.91	10.954	6.233	1.489	H ₂ O	94	8.8	3.18	83.0	1006	606	12.95	7.31	13.4	41.7	2.84	1.0	-	C.E.	10.85	1802.8	4.887	0.0784
2-3	12-F	12	50.18	1787	72.8	89.67	11.173	6.528	1.560	H ₂ O	100	9.3	3.18	83.8	1061	639	13.20	7.40	10.6	45.4	3.09	1.0	-	C.E.	11.15	1250.3	5.211	0.0798
2-3	12-G	12	46.51	1847	73.6	85.90	10.703	6.322	1.510	H ₂ O	42	7.2	3.18	81.8	973	563	12.65	7.08	12.3	23.5	1.60	8.2	N.M.	N.P.				
2-3	12-H	12	47.84	1760	72.9	84.20	10.491	6.138	1.466	H ₂ O	62	7.7	3.18	82.2	966	569	12.40	6.95	13.0	30.8	2.10	15.8	59	N.M.	6.08	314.7	1.520	0.0248
2-3	12-I	12	49.18	1793	72.4	88.18	10.987	6.384	1.525	H ₂ O	73	8.1	3.18	82.5	1014	601	13.00	7.29	8.4	30.8	2.10	8.2	50	C.E.	6.77	708.5	1.891	0.0296
2-3	12-J	12	49.18	1793	74.3	88.18	10.987	6.552	1.565	H ₂ O	82	8.7	3.18	82.3	1058	621	13.14	7.25	15.0	30.8	2.10	4.9	S.P.	N.M.	9.37	927.2	3.614	0.0552
2-17	8S1-A	8	44.84	1727	77.7	77.44	9.649	6.017	1.437	H ₂ O	19	12.4	3.18	84.9	904	509	11.39	6.31	17.3	22.0	1.50	5.8	57	N.P.				
2-17	8S1-B	8	45.18	1713	78.2	77.39	9.643	6.052	1.446	H ₂ O	45	12.7	3.18	84.9	936	537	11.39	6.29	14.5	26.4	1.80	9.8	50	1.35	1.73	402.8	0.127	0.0021
2-17	8S1-C	8	46.51	1653	78.4	76.88	9.579	6.027	1.440	H ₂ O	67	13.2	3.18	85.0	954	557	11.31	6.25	12.3	27.8	1.89	6.2	20	N.P.				
2-17	8S1-D	8	47.34	1620	73.7	76.69	9.556	5.652	1.350	H ₂ O	80	13.6	3.18	85.0	912	546	11.29	6.32	16.5	25.7	1.75	3.2	S.P.	8.10	4.47	308.3	0.850	0.0150
2-17	8S1-E	8	46.34	1653	73.4	76.60	9.544	5.622	1.343	H ₂ O	88	13.8	3.18	85.1	915	552	11.27	6.32	14.4	30.0	2.04	1.0	-	N.P.				
2-17	8S1-F	8	47.01	1620	68.8	76.16	9.490	5.240	1.252	H ₂ O	93	13.9	3.18	85.1	864	531	11.21	6.37	12.3	30.8	2.10	1.0	-	C.E.	4.65	448.6	0.920	0.0176
2-17	8S1-G	8	47.51	1607	72.8	76.35	9.513	5.558	1.328	H ₂ O	98	14.8	3.18	86.5	916	557	11.24	6.30	11.2	33.7	2.29	1.0	-	C.E.	4.50	345.8	0.876	0.0158
2-17	8S1-H	8	47.84	1600	78.8	76.54	9.537	6.031	1.441	H ₂ O	100	14.3	3.18	85.4	988	589	11.27	6.21	12.2	35.1	2.39	1.0	-	C.E.	5.46	716.9	1.273	0.0211
2-17	8S1-I	8	45.34	1707	74.4	77.40	9.644	5.759	1.376	H ₂ O	22	12.2	3.18	84.4	870	495	11.40	6.36	16.6	23.5	1.60	9.4	105	N.P.				
2-17	8S1-J	8	45.34	1707	79.5	77.40	9.644	6.153	1.470	H ₂ O	30	12.4	3.18	84.6	936	528	11.40	6.26	16.1	24.9	1.69	8.1	91	N.P.				
2-17	8S1-K	8	45.84	1687	77.0	77.33	9.635	5.954	1.422	H ₂ O	45	12.7	3.18	84.9	921	531	11.38	6.31	13.9	27.1	1.84	13.3	52	N.P.				
2-17	8S1-L	8	46.34	1660	81.2	76.92	9.584	6.246	1.492	H ₂ O	53	12.8	3.18	84.8	973	556	11.33	6.19	13.8	26.4	1.80	11.0	31	N.P.				
2-17	8S1-M	8	47.84	1640	72.9	78.46	9.776	5.720	1.367	H ₂ O	85	13.7	3.18	85.0	927	558	11.55	6.49	13.5	30.8	2.10	1.7	S.P.	N.P.				
2-17	8S1-N	8	47.84	1620	65.9	77.50	9.656	5.107	1.220	H ₂ O	93	14.0	3.18	85.2	845	524	11.41	6.54	-	34.4	2.34	1.0	-	N.P.				
2-17	8S1-O	8	46.68	1607	76.9	75.01	9.346	5.768	1.378	H ₂ O	97	14.4	3.18	85.9	946	568	11.04	6.12	14.4	39.5	2.69	1.0	-	N.P.				
2-18	14S1-A	14	46.34	1850	-	85.73	10.682	-	-	H ₂ O	19	12.3	3.18	84.6	-	-	-	-	-	20.5	1.39	5.5	119	N.P.				
2-18	14S1-B	14	47.84	1900	67.6	90.90	11.326	6.145	1.468	H ₂ O	25	12.4	3.18	84.8	924	535	13.39	7.63	13.5	23.5	1.60	6.9	85	N.P.				
2-18	14S1-C	14	44.34	1867	74.7	82.78	10.314	6.184	1.477	H ₂ O	18	12.3	3.18	84.6	935	533	12.18	6.80	15.3	23.4	1.59	5.8	105	N.P.				
2-18	14S1-D	14	45.01	1850	77.2	83.27	10.375	6.428	1.536	H ₂ O	36	12.6	3.18	84.8	963	542	12.24	6.79	13.2	25.7	1.75	12.9	70	N.P.				
2-18	14S1-E	14	46.01	1833	77.6	84.34	10.509	6.545	1.564	H ₂ O	44	12.8	3.18	8														

Date	Run No.	No. of Batteries	Voltage	Amperage	Power Duration, msec	Energy		Test Liquid	Initial Liquid Temp, °C	Initial Liquid Height, cm	Annular Gap, mm	Total Liquid Mass, gm	Max Heater Temp (calc), °C		Heater Temp Rise Rate (calc), 10 ³ °C/sec		Time of First Pressure Pulse, msec	Peak Initial Pressure Pulse		Peak Secondary Pressure, atm	Frequency of Secondary Pulses, cps	Max Initial Liquid Displacement, cm	Max Initial Liquid Velocity, m/sec	Max Initial Liquid Acceleration, m/sec ²	Max Liquid Kinetic Energy, W	Ratio, Kinetic to Input Energy, %		
						kW	kcal (sec-cm ³)						kW-sec	kcal	Adiabatic	With Conduction Losses		Adiabatic	With Conduction Losses								psia	atm
1-26-66	VIII-K	8	43.68	1633	79.7	71.33	8.888	5.685	1.358	H ₂ O	100	111	3.18	465.6	936	560	10.49	5.77	15.5	55.6	3.78	1.0	-	N.P.				
1-26	VIII-Ka	8	43.84	1647	74.0	72.20	8.996	5.343	1.276	H ₂ O	98	111	3.18	465.6	884	538	10.62	5.95	14.9	55.9	3.80	1.0	-	N.P.				
1-26	VIII-L	8	43.84	1673	72.0	73.34	9.138	5.280	1.261	H ₂ O	100	120	3.18	513.6	878	537	10.81	6.07	15.8	57.0	3.87	1.0	-	N.P.				
3-24	XIV-A	14	59.51	1927	71.7	114.68	14.289	8.223	1.964	H ₂ O	91	9.1	3.18	83.9	1301	772	16.87	9.50	10.4	42.4	2.88	1.0	-	N.P.				
3-24	XIV-B	14	57.01	1940	68.6	110.60	13.781	7.587	1.813	H ₂ O	96	21.5	3.18	111.2	1213	731	16.28	9.26	21.1	51.2	3.48	1.0	-	N.P.				
3-24	XIV-C	14	57.01	1947	68.5	111.00	13.831	7.604	1.817	H ₂ O	95	34.5	3.18	140.4	1214	732	16.34	9.30	22.6	61.4	4.18	1.0	-	N.P.				
3-24	XIV-D	14	56.68	1947	69.8	110.36	13.751	7.703	1.840	H ₂ O	96	46.1	3.18	166.3	1230	738	16.25	9.20	22.2	68.7	4.67	1.0	-	N.P.				
3-24	XIV-E	14	57.34	1953	69.4	111.99	13.954	7.772	1.857	H ₂ O	98	57.4	3.18	191.3	1242	747	16.48	9.35	24.8	78.9	5.37	1.0	-	N.P.				
3-24	XIV-F	14	56.68	1953	68.6	110.70	13.793	7.594	1.814	H ₂ O	99	66.0	3.18	210.3	1217	735	16.30	9.27	22.6	71.6	4.87	1.0	-	N.P.				
3-24	XIV-G	14	56.34	1947	72.4	109.69	13.667	7.942	1.897	H ₂ O	96	71.0	3.18	222.0	1266	753	16.16	9.07	20.0	68.7	4.67	1.0	-	N.P.				
4-11	XIII-A	13	45.01	1633	78.3	73.50	9.158	5.755	1.375	H ₂ O	86	6.7	3.18	78.8	933	553	10.82	5.96	12.7	37.7	2.56	1.0	-	N.P.				
4-11	XIII-B	13	43.84	1647	76.2	72.20	8.996	5.502	1.314	H ₂ O	88	14.4	3.18	95.0	893	538	10.56	5.91	20.6	37.8	2.56	1.0	-	N.P.				
4-11	XIII-C	13	44.01	1647	72.8	72.48	9.031	5.277	1.261	H ₂ O	89	28.2	3.18	126.0	866	525	10.67	5.99	25.2	39.6	2.70	1.0	-	N.P.				
4-11	XIII-D	13	43.68	1633	74.6	71.33	8.888	5.321	1.271	H ₂ O	87	60.6	3.18	199.9	871	524	10.51	5.86	27.5	42.7	2.90	1.0	-	N.P.				
4-11	XIII-E	13	43.84	1633	80.0	71.59	8.920	5.727	1.368	H ₂ O	89	98.4	3.18	282.9	931	552	10.53	5.79	28.4	51.5	3.52	1.0	-	N.P.				
4-11	XIII-F	13	44.01	1653	81.6	72.75	9.065	5.936	1.418	H ₂ O	86	156.2	3.18	415.5	960	564	10.71	5.86	31.6	46.7	3.18	1.0	-	N.P.				
4-11	XIII-G	13	41.68	1613	74.3	67.23	8.377	4.995	1.193	H ₂ O	82	35.2	3.18	143.3	817	493	9.89	5.53	71.4	178	12.1	1.0	-	N.P.				
4-11	XIII-H	13	42.34	1653	72.0	69.99	8.721	5.039	1.204	H ₂ O	84	35.2	3.18	143.1	826	501	10.31	5.79	72.6	161	10.9	1.0	-	N.P.				
4-11	XIII-I	13	42.34	1640	75.7	69.44	8.652	5.257	1.256	H ₂ O	78	35.2	3.18	143.6	852	508	10.22	5.68	63.3	181	12.3	1.0	-	N.P.				
1-7	M-4A	4	24.50	1090	87.6	26.71	3.328	2.340	0.559	CH ₃ OH	18	8.0	3.18	66.9	355	203	3.85	2.11	34.1	26.4	1.80	13.0	36	N.P.				
1-7	M-4B	4	24.50	1080	89.3	26.46	3.297	2.367	0.565	CH ₃ OH	31	8.6	3.18	68.0	379	217	3.90	2.08	34.5	26.4	1.80	13.9	30	5.41	2.82	207.2	0.270	0.0114
1-7	M-4C	4	24.50	1085	93.5	26.58	3.312	2.485	0.594	CH ₃ OH	22	8.2	3.18	67.6	388	215	3.91	2.06	36.7	27.1	1.84	13.9	36	N.P.				
1-7	M-4D	4	24.50	1085	91.3	26.58	3.312	2.427	0.580	CH ₃ OH	21	8.1	3.18	67.1	378	211	3.91	2.08	39.5	26.4	1.80	15.1	36	5.22	3.46	337.7	0.402	0.0166
1-7	M-4E	4	25.17	1080	90.7	27.18	3.387	2.465	0.589	CH ₃ OH	37	9.0	3.18	68.8	400	220	4.00	2.13	36.4	27.8	1.89	9.4	S.P.	5.91	3.07	397.6	0.324	0.0131
1-7	M-4F	4	27.17	1070	89.6	29.07	3.622	2.605	0.622	CH ₃ OH	50	9.3	3.18	69.3	433	255	4.27	2.29	34.0	29.3	1.99	1.0	-	N.P.				
1-7	M-4G	4	27.34	1065	84.0	29.12	3.628	2.446	0.584	CH ₃ OH	57	9.7	3.18	70.0	417	252	4.29	2.32	31.9	30.0	2.04	1.0	-	N.P.				
1-7	M-4H	4	25.51	1065	89.2	27.17	3.385	2.424	0.579	CH ₃ OH	61	9.8	3.18	70.2	418	252	4.00	2.14	30.5	30.2	2.05	1.0	-	C.E.	8.05	674.1	2.275	0.0939
1-7	M-4I	4	25.67	1065	88.9	27.34	3.407	2.431	0.581	CH ₃ OH	62	9.5	3.18	69.6	420	253	4.03	2.15	28.8	30.5	2.07	1.0	-	C.E.	6.53	507.7	1.484	0.0610
1-7	M-4J	4	27.17	1065	87.2	28.94	3.606	2.524	0.603	CH ₃ OH	60	8.3	3.18	67.4	431	260	4.25	2.29	29.6	31.5	2.14	1.0	-	N.P.				
1-7	M-4K	4	25.84	1070	90.8	27.65	3.445	2.511	0.600	CH ₃ OH	54	8.0	3.18	66.9	424	251	4.07	2.17	31.0	30.8	2.10	1.0	-	C.E.	6.19	395.4	1.282	0.0511
1-7	M-4L	4	26.67	1075	91.6	28.67	3.572	2.626	0.627	CH ₃ OH	47	8.0	3.18	66.9	434	252	4.22	2.24	32.3	29.3	1.99	6.2	S.P.	N.M.	4.00	322.0	0.555	0.0204
1-7	M-4M	4	27.51	1080	90.0	29.71	3.702	2.674	0.639	CH ₃ OH	43	8.0	3.18	66.9	437	253	4.38	2.33	32.0	29.3	1.99	9.6	34	8.80	4.26	322.7	0.607	0.0227
1-7	M-4N	4	26.51	1080	84.5	28.63	3.567	2.419	0.578	CH ₃ OH	42	7.8	3.18	66.5	398	235	4.21	2.28	35.0	27.8	1.89	12.0	32	7.11	3.71	399.3	0.458	0.0189
1-7	M-4O	4	26.84	1080	90.5	28.99	3.612	2.624	0.627	CH ₃ OH	35	7.6	3.18	66.2	421	241	4.26	2.28	35.5	27.4	1.86	11.3	38	5.47	2.86	189.9	0.271	0.0103
1-7	M-4P	4	27.01	1080	88.1	29.17	3.635	2.570	0.614	CH ₃ OH	36	7.6	3.18	66.2	414	239	4.29	2.30	36.0	25.7	1.75	10.3	38	N.P.				
1-17	M-8A	8	43.34	1600	75.3	69.34	8.640	5.221	1.247	CH ₃ OH	21	8.4	3.18	67.6	770	450	9.95	5.70	16.1	40.0	2.72	5.8	S.P.	4.62	3.03	312.8	0.310	0.0059
1-17	M-8B	8	42.34	1600	73.1	67.74	8.440	4.952	1.183	CH ₃ OH	33	9.0	3.18	68.8	762	442	9.97	5.60	14.4	33.7	2.29	6.2	S.P.	N.M.	3.00	306.2	0.310	0.0063
1-17	M-8C	8	35.01	1590	74.2	55.67	6.936	4.131	0.987	CH ₃ OH	42	9.3	3.18	69.3	650	382	8.19	4.58	13.6	38.1	2.59	1.4	S.P.	N.M.	4.10	542.4	0.583	0.0141
1-17	M-8D	8	38.51	1585	72.7	61.04	7.606	4.438	1.060	CH ₃ OH	48	9.4	3.18	69.5	701	415	8.98	5.05	13.2	42.4	2.89	1.0	-	C.E.	5.41	560.2	1.017	0.0229
1-17	M-8E	8	38.67	1595	70.7	61.68	7.685	4.361	1.042	CH ₃ OH	52	9.0	3.18	68.8	694	415	9.08	5.13	13.1	41.4	2.82	1.0	-	C.E.	5.77	591.4	1.145	0.0263
1-17	M-8F	8	36.67	1585	80.5	58.12	7.242	4.679	1.118	CH ₃ OH	5																	

Date	Run No.	No. of Batteries	Voltage	Amperage	Power Duration, msec	Energy		Test Liquid	Initial Liquid Temp, °C	Initial Liquid Height, cm	Annular Gap, mm	Total Liquid Mass, gm	Max Heater Temp (calc), °C		Heater Temp Rise Rate (calc), 10 ³ °C/sec		Time of First Pressure Pulse, msec	Peak Initial Pressure Pulse		Peak Secondary Pressure Pulse, atm	Frequency of Secondary Pulses, cps	Max Initial Liquid Displacement, cm	Max Initial Liquid Velocity, m/sec	Max Initial Liquid Acceleration, m/sec ²	Max Liquid Kinetic Energy, W	Ratio, Kinetic to Input Energy, %			
						kW	Total Energy Input (kcal/sec-cm ³)						Adiabatic	With Conduction Losses	Adiabatic	With Conduction Losses		psia	atm										
1-18-66	Ac-8A	8	41.84	1633	73.9	68.32	8.513	5.049	1.206	(CH ₃) ₂ CO	32	9.3	3.18	69.2	836	482	10.88	6.09	13.3	43.0	2.93	3.0	S.P.	4.62	3.32	445.8	0.382	0.0076	
1-18	Ac-8B	8	43.68	1633	72.2	71.33	8.888	5.150	1.230	(CH ₃) ₂ CO	45	10.0	3.18	70.5	814	471	10.51	5.90	12.4	42.4	2.88	1.0	-	C.E.	4.81	368.9	0.816	0.0158	
1-18	Ac-8C	8	44.68	1620	77.5	72.38	9.019	5.609	1.340	(CH ₃) ₂ CO	52	10.3	3.18	71.0	877	509	10.64	5.90	11.9	39.5	2.69	1.0	-	C.E.	5.46	648.5	1.059	0.0189	
1-18	Ac-8D	8	44.18	1627	75.3	71.88	8.956	5.413	1.293	(CH ₃) ₂ CO	57	10.5	3.18	71.4	854	501	10.58	5.90	11.4	40.3	2.74	1.0	-	C.E.	5.10	818.9	0.929	0.0172	
1-18	Ac-8E	8	38.34	1613	72.6	61.84	7.705	4.490	1.073	(CH ₃) ₂ CO	54	9.1	3.18	68.8	715	425	9.10	5.11	11.9	42.4	2.88	1.0	-	N.P.	-	-	-	-	
1-18	Ac-8F	8	38.84	1640	74.3	63.70	7.937	4.733	1.131	(CH ₃) ₂ CO	55	9.1	3.18	68.8	752	444	9.38	5.24	12.3	49.7	3.38	1.0	-	C.E.	7.59	740.2	1.982	0.0419	
1-18	Ac-8G	8	37.34	1633	74.3	60.98	7.598	4.531	1.082	(CH ₃) ₂ CO	29	8.0	3.18	66.8	698	402	8.98	5.02	13.0	39.5	2.69	8.1	S.P.	-	-	-	-	-	
1-18	EB-8A	8	36.67	1627	80.5	59.66	7.434	4.803	1.147	(CH ₂) ₂ Br ₂	30	9.0	3.18	188.1	737	418	8.78	4.82	22.9	43.9	2.99	8.3	28	2.80	2.08	247.1	0.407	0.0085	
1-18	EB-8B	8	36.84	1620	72.4	59.68	7.436	4.321	1.032	(CH ₂) ₂ Br ₂	43	9.8	3.18	192.0	680	400	8.80	4.93	21.5	41.7	2.84	9.1	29	2.22	1.89	277.9	0.343	0.0079	
1-18	EB-8C	8	37.01	1620	72.6	59.96	7.471	4.353	1.040	(CH ₂) ₂ Br ₂	56	9.9	3.18	192.7	697	416	8.83	4.96	21.1	41.7	2.84	9.2	24	2.73	2.07	267.7	0.413	0.0095	
1-18	EB-8D	8	37.01	1607	78.7	59.48	7.411	4.681	1.118	(CH ₂) ₂ Br ₂	79	10.7	3.18	196.8	767	458	8.74	4.82	19.4	48.3	3.29	3.3	S.P.	N.M.	4.85	360.0	2.316	0.0495	
1-18	EB-8E	8	37.17	1600	82.4	59.47	7.410	4.900	1.171	(CH ₂) ₂ Br ₂	95	11.1	3.18	198.8	816	488	8.75	4.77	19.1	51.9	3.53	1.0	-	C.E.	6.05	470.6	3.640	0.0743	
1-18	EB-8F	8	37.34	1593	82.1	59.48	7.411	4.883	1.167	(CH ₂) ₂ Br ₂	114	11.8	3.18	200.1	833	506	8.76	4.77	18.4	65.8	4.48	1.0	-	C.E.	7.92	611.0	6.278	0.1286	
2-8	EB-12A	12	49.01	1687	80.8	82.68	10.302	6.681	1.596	(CH ₂) ₂ Br ₂	34	8.4	3.18	185.1	1017	573	12.17	6.67	18.7	49.7	3.38	8.7	S.P.	N.P.	3.21	508.9	0.954	0.0143	
2-8	EB-12B	12	49.01	1700	82.2	83.32	10.382	6.849	1.636	(CH ₂) ₂ Br ₂	44	8.8	3.18	187.1	1051	594	12.25	6.69	16.9	48.3	3.29	4.5	S.P.	N.M.	-	-	-	-	-
2-8	EB-12C	12	49.34	1687	80.7	83.24	10.372	6.717	1.605	(CH ₂) ₂ Br ₂	55	9.0	3.18	188.1	1043	597	12.24	6.72	16.0	67.3	4.58	2.1	S.P.	N.P.	-	-	-	-	-
2-8	EB-12D	12	49.34	1687	74.2	83.24	10.372	6.176	1.475	(CH ₂) ₂ Br ₂	63	9.4	3.18	189.9	972	571	12.25	6.85	14.9	84.8	5.77	1.0	-	N.P.	-	-	-	-	-
2-8	EB-12E	12	49.34	1687	73.1	83.24	10.372	6.085	1.454	(CH ₂) ₂ Br ₂	81	9.7	3.18	190.7	977	591	12.26	6.87	13.6	84.8	5.77	1.0	-	N.P.	-	-	-	-	-
2-8	EB-12F	12	50.00	1687	73.6	84.35	10.510	6.208	1.483	(CH ₂) ₂ Br ₂	97	10.0	3.18	193.1	1013	604	12.42	6.89	13.0	77.5	5.27	1.0	-	N.P.	-	-	-	-	-
3-3	8S2-A	8	44.01	1667	72.8	73.36	9.141	5.341	1.276	H ₂ O	22	10.0	1.27	37.9	808	463	10.80	6.06	17.1	20.5	1.39	7.1	15	N.P.	-	-	-	-	-
3-3	8S2-B	8	43.68	1667	72.8	72.81	9.072	5.301	1.266	H ₂ O	35	10.1	1.27	37.9	815	473	10.71	6.02	17.2	27.8	1.89	8.0	23	N.P.	-	-	-	-	-
3-3	8S2-C	8	44.34	1633	74.0	72.41	9.022	5.358	1.280	H ₂ O	68	10.5	1.27	38.2	857	509	10.66	5.96	32.5	39.5	2.69	2.9	S.P.	N.P.	-	-	-	-	-
3-3	8S2-D	8	45.18	1640	75.5	74.10	9.233	5.595	1.337	H ₂ O	61	10.4	1.27	38.1	885	519	10.91	6.07	-	30.8	2.10	4.7	11	N.P.	-	-	-	-	-
3-3	8S2-E	8	45.01	1620	78.5	72.92	9.086	5.724	1.367	H ₂ O	80	10.6	1.27	38.1	922	545	10.73	5.92	21.5	43.9	2.99	1.0	-	N.P.	-	-	-	-	-
3-3	8S2-F	8	46.01	1613	74.0	74.21	9.247	5.492	1.312	H ₂ O	92	10.7	1.27	38.1	900	544	10.92	6.11	27.2	49.7	3.38	1.0	-	N.P.	-	-	-	-	-
3-3	8S2-G	8	46.18	1600	73.1	73.89	9.207	5.401	1.290	H ₂ O	98	10.9	1.27	38.4	893	544	10.88	6.10	27.7	56.3	3.83	1.0	-	N.P.	-	-	-	-	-
3-3	8S2-H	8	45.01	1660	-	74.72	9.310	-	-	H ₂ O	30	10.2	1.27	38.2	-	-	-	-	-	26.4	1.80	4.2	S.P.	N.P.	-	-	-	-	-
3-3	8S2-I	8	45.68	1633	78.0	74.60	9.295	5.819	1.390	H ₂ O	51	10.8	1.27	39.1	907	524	10.97	6.06	-	33.7	2.29	2.5	S.P.	N.P.	-	-	-	-	-
3-3	8S2-J	8	45.34	1633	75.1	74.04	9.226	5.560	1.328	H ₂ O	58	10.8	1.27	39.0	876	516	10.89	6.07	40.8	46.8	3.18	2.1	S.P.	N.P.	-	-	-	-	-
3-3	8S2-K	8	46.34	1620	78.3	75.07	9.354	5.878	1.404	H ₂ O	75	10.8	1.27	38.6	940	553	11.05	6.10	-	45.4	3.09	1.4	S.P.	N.P.	-	-	-	-	-
3-3	8S2-L	8	46.01	1613	79.7	74.21	9.247	5.915	1.413	H ₂ O	85	10.6	1.27	38.0	955	564	10.92	6.01	30.7	51.2	3.48	1.0	-	N.P.	-	-	-	-	-
3-3	8S2-M	8	47.18	1620	80.1	76.43	9.523	6.122	1.463	H ₂ O	96	10.1	1.27	36.6	997	591	11.25	6.18	-	-	-	-	-	N.P.	-	-	-	-	-
3-3	8S2-N	8	46.68	1607	76.1	75.01	9.346	5.708	1.364	H ₂ O	98	9.2	1.27	34.6	938	565	11.04	6.14	-	54.1	3.68	1.0	-	N.P.	-	-	-	-	-
3-3	8S2-O	8	46.18	1647	74.8	76.06	9.477	5.689	1.359	H ₂ O	89	9.4	1.27	35.5	926	556	11.19	6.24	16.9	43.9	2.99	1.0	-	N.P.	-	-	-	-	-
3-3	8S2-P	8	46.51	1607	73.5	74.74	9.313	5.493	1.312	H ₂ O	98	9.8	1.27	36.1	907	551	11.01	6.16	-	55.6	3.78	1.0	-	N.P.	-	-	-	-	-
2-22	14S2-A	14	50.67	1867	73.2	94.60	11.787	6.925	1.654	H ₂ O	84	12.9	1.27	42.8	1103	655	13.92	7.80	-	55.6	3.78	1.0	-	N.P.	-	-	-	-	-
2-22	14S2-B	14	50.67	1883	73.1	92.88	11.573	6.790	1.622	H ₂ O	85	12.1	1.27	41.0	1085	646	13.68	7.67	22.1	52.7	3.59	1.0	-	C.E.	7.59	463.3	1.181	0.0174	
2-22	14S2-C	14																											

Date	Run No.	No. of Batteries	Voltage	Amperage	Power Duration, msec	Energy Input Rate		Total Energy Input		Test Liquid	Initial Liquid Temp, °C	Initial Liquid Height, cm	Annular Gap, mm	Total Liquid Mass, gm	Max Heater Temp (calc), °C		Heater Temp Rise Rate (calc), 10 ³ °C/sec		Time of First Pressure Pulse, msec	Peak Initial Pressure Pulse		Peak Secondary Pressure Pulse, atm	Frequency of Secondary Pulses, cps	Max Initial Liquid Displacement, cm	Max Initial Liquid Velocity, m/sec	Max Initial Liquid Acceleration, m/sec ²	Max Liquid Kinetic Energy, W	Ratio, Kinetic to Input Energy, %
						kW	($\frac{\text{kcal}}{\text{sec-cm}^2}$)	kW-sec	kcal						Adiabatic	With Conduction Losses	Adiabatic	With Conduction Losses		psia	atm							
3-4-66	EB-8S2-J	8	48.18	1580	74.9	76.12	9.485	5.701	1.362	(CH ₂) ₂ Br ₂	122	9.7	1.27	81.2	951	590	11.20	6.25	18.0	76.0	5.17	1.0	-	N.P.				
3-4	EB-8S2-K	8	48.83	1553	79.4	75.83	9.448	6.021	1.438	(CH ₂) ₂ Br ₂	124	9.1	1.27	78.3	1010	613	11.16	6.16	-	-	-	-	-	N.P.				
3-4	EB-8S2-L	8	48.67	1533	82.2	74.61	9.296	6.133	1.465	(CH ₂) ₂ Br ₂	120	8.5	1.27	76.8	1022	613	10.97	6.00	18.7	70.2	4.78	1.0	-	N.P.				
2-23	EB-14S2-A	14	52.67	1733	71.3	91.28	11.373	6.508	1.555	(CH ₂) ₂ Br ₂	115	12.2	1.27	92.7	1074	655	13.45	7.57	13.4	70.2	4.78	2.1	S.P.	N.M.	2.56	225.2	0.304	0.0047
2-23	EB-14S2-B	14	52.33	1767	76.7	92.47	11.522	7.092	1.694	(CH ₂) ₂ Br ₂	117	12.3	1.27	92.9	1261	696	13.61	7.55	13.8	65.8	4.48	2.1	S.P.	N.M.	4.03	144.3	0.755	0.0106
2-23	EB-14S2-C	14	53.00	1750	72.3	92.75	11.557	6.706	1.602	(CH ₂) ₂ Br ₂	92	11.8	1.27	90.9	1080	647	13.67	7.68	13.2	58.5	3.98	1.9	S.P.	N.P.				
2-23	EB-14S2-D	14	53.00	1767	72.3	93.65	11.669	6.771	1.618	(CH ₂) ₂ Br ₂	89	10.0	1.27	82.5	1086	649	13.79	7.75	17.4	48.3	3.29	1.0	-	C.E.	5.25	576.4	1.137	0.0168
2-23	EB-14S2-E	14	52.67	1767	73.9	93.07	11.597	6.878	1.643	(CH ₂) ₂ Br ₂	74	9.8	1.27	81.6	1086	640	13.69	7.66	19.9	49.7	3.38	1.3	S.P.	N.M.	3.76	137.5	0.577	0.0084
2-23	EB-14S2-F	14	52.67	1767	74.2	93.07	11.597	6.906	1.650	(CH ₂) ₂ Br ₂	57	9.6	1.27	80.3	1074	625	13.71	7.65	18.3	45.4	3.09	1.3	S.P.	N.M.	2.95	208.4	0.350	0.0051
2-23	EB-14S2-G	14	52.33	1800	73.0	94.19	11.736	6.876	1.643	(CH ₂) ₂ Br ₂	31	9.2	1.27	78.8	1043	598	13.86	7.77	18.2	45.4	3.09	1.6	S.P.	N.M.	2.32	101.1	0.212	0.0031
2-23	EB-14S2-H	14	52.33	1733	77.1	90.69	11.300	6.992	1.670	(CH ₂) ₂ Br ₂	42	9.2	1.27	78.8	1070	612	13.33	7.39	-	-	-	-	-	N.M.	2.21	121.2	0.193	0.0028
2-23	EB-14S2-I	14	52.33	1750	72.3	91.58	11.411	6.621	1.582	(CH ₂) ₂ Br ₂	49	9.2	1.27	78.8	1024	597	13.49	7.58	16.8	51.2	3.48	1.4	S.P.	N.P.				
2-23	EB-14S2-J	14	52.67	1767	72.6	93.07	11.597	6.757	1.614	(CH ₂) ₂ Br ₂	62	9.3	1.27	79.4	1057	620	13.71	7.69	15.7	52.7	3.59	1.6	S.P.	N.M.	3.54	329.8	0.497	0.0074
2-23	EB-14S2-K	14	52.33	1750	71.1	93.33	11.629	6.636	1.585	(CH ₂) ₂ Br ₂	97	10.3	1.27	84.0	1074	648	13.74	7.75	18.3	58.5	3.98	1.0	-	C.E.	5.51	459.0	1.276	0.0192
2-23	EB-14S2-L	14	52.33	1733	77.9	92.42	11.516	7.200	1.720	(CH ₂) ₂ Br ₂	103	9.0	1.27	78.1	1156	689	13.59	7.52	17.3	55.6	3.78	2.1	S.P.	N.P.				
3-18	8(F)-A	8	43.84	1593	77.8	69.83	8.701	5.433	1.298	H ₂ O	98	2.52*	3.18	897	540	10.27	5.68	15.8	41.2	2.80	1.0	-	-	N.P.				
3-18	8(F)-B	8	43.51	1607	75.4	69.92	8.712	5.258	1.256	H ₂ O	97	1.18*	3.18	873	539	10.29	5.73	20.2	38.1	2.59	1.0	-	-	C.E.	9.16	1164.5		
3-18	8(F)-C	8	44.18	1613	72.2	71.26	8.879	5.145	1.229	H ₂ O	97	1.37*	3.18	855	523	10.50	5.90	20.3	36.6	2.49	1.0	-	-	C.E.	9.63	1246.0		
3-18	8(F)-D	8	43.68	1600	77.8	69.89	8.708	5.437	1.299	H ₂ O	97	1.84*	3.18	897	540	10.28	5.69	19.0	36.6	2.49	1.0	-	-	C.E.	10.51	1463.1		
3-18	8(F)-E	8	44.51	1600	78.8	71.22	8.874	5.612	1.341	H ₂ O	96	1.97*	3.18	922	551	10.48	5.77	19.7	38.1	2.59	1.0	-	-	C.E.	8.54	949.6		
3-18	8(F)-G	8	43.84	1607	80.2	70.45	8.778	5.650	1.350	H ₂ O	97	2.52*	3.18	929	553	10.37	5.69	21.7	41.2	2.80	1.0	-	-	C.E.	8.45	601.3		
3-18	8(F)-A1	8	43.01	1667	70.4	71.70	8.934	5.048	1.206	H ₂ O	40	0.57*	3.18	783	460	10.55	5.97	15.3	22.0	1.50	12.6	S.P.	N.M.	2.07	292.3			
3-18	8(F)-A2	8	42.84	1753	70.6	75.10	9.357	5.302	1.267	H ₂ O	42	1.00*	3.18	823	483	11.06	6.25	18.8	26.4	1.80	11.5	S.P.	1.13	1.09	179.7			
3-18	8(F)-A3	8	42.84	1660	78.9	71.11	8.860	5.611	1.340	H ₂ O	43	1.26*	3.18	869	498	10.47	5.77	18.1	26.4	1.80	13.9	66	1.47	0.92	106.1			
3-18	8(F)-A4	8	43.68	1673	80.1	73.08	9.106	5.854	1.399	H ₂ O	40	1.57*	3.18	902	513	10.76	5.91	18.6	26.4	1.80	11.8	S.P.	1.15	1.04	127.4			
3-18	8(F)-A5	8	43.51	1660	78.0	72.23	9.000	5.634	1.346	H ₂ O	42	1.91*	3.18	871	500	10.63	5.87	18.3	26.4	1.80	9.1	S.P.	1.40	1.11	146.7			
3-18	8(F)-A6	8	43.01	1653	77.2	71.10	8.859	5.489	1.311	H ₂ O	40	2.08*	3.18	847	488	10.45	5.80	17.9	26.4	1.80	16.7	S.P.	1.53	1.47	203.3			
3-18	8(F)-A7	8	42.18	1653	74.2	69.72	8.687	5.173	1.236	H ₂ O	38	2.28*	3.18	800	463	10.27	5.73	16.8	23.5	1.60	16.0	103	1.04	1.11	100.9			
3-18	8(F)-A8	8	42.18	1660	71.6	70.02	8.724	5.013	1.198	H ₂ O	40	2.51*	3.18	778	456	10.31	5.81	18.7	26.4	1.80	9.9	S.P.	1.80	0.85	63.0			
3-18	8(F)-A9	8	43.84	1647	79.2	72.20	8.996	5.718	1.366	H ₂ O	40	2.65*	3.18	882	504	10.63	5.86	18.6	27.8	1.89	11.8	63	1.71	1.14	115.3			
3-18	8(F)-A10	8	43.68	1673	77.8	73.08	9.106	5.686	1.358	H ₂ O	38	0*	3.18	874	501	10.74	5.95	18.3	24.9	1.69	15.7	95	1.32	1.06	117.5			
3-22	14(F)-A	14	43.34	1893	72.5	82.04	10.222	5.948	1.421	H ₂ O	90	0.79*	3.18	966	582	12.08	6.79	-	64.3	4.37	1.0	-	-					
3-22	14(F)-B	14	45.84	1720	78.2	78.84	9.823	6.165	1.473	H ₂ O	89	1.37*	3.18	996	590	11.60	6.41	-	77.5	5.27	1.0	-	-					
3-22	14(F)-C	14	47.01	1720	72.4	80.86	10.075	5.854	1.399	H ₂ O	89	1.77*	3.18	951	573	11.91	6.69	-	83.3	5.67	1.0	-	-					
3-22	14(F)-D	14	47.01	1720	71.6	80.86	10.075	5.790	1.383	H ₂ O	89	2.28*	3.18	941	569	11.90	6.70	-	70.2	4.78	1.0	-	-					
3-22	14(F)-E	14	47.01	1733	77.5	81.47	10.151	6.314	1.508	H ₂ O	90	2.54*	3.18	1019	604	11.99	6.63	-	65.8	4.48	1.0	-	-					
3-22	14(F)-F	14	47.01	1733	76.7	81.47	10.151	6.249	1.493	H ₂ O	91	0*	3.18	1009	601	11.99	6.65	-	71.6	4.87	1.0	-	-					
3-22	14(F)-G	14	47.01	1733	78.1	81.47	10.151	6.363	1.520	H ₂ O	89	2.91*	3.18	1025	606	11.98	6.62	-	61.4	4.18	1.0	-	-					
3-22	14(F)-H	14	47.01	1740	76.3	81.80	10.192	6.241	1.491	H ₂ O	91	3.42*	3.18	957	601	11.35	6.68	-	68.7	4.67	1.0	-	-					
3-22	14(F)-I	14	47.01	173																								

ACKNOWLEDGMENTS

I would like to take this opportunity to thank Dr. Paul A. Lottes of Argonne and Mr. S. A. Szawlewicz of the AEC for their interest and discussions of the work presented in this report. Also, the skilled assembly and operation of the experimental equipment by Mr. Angelo Mele and Mr. H. James Haupt made possible the collection of the data. The above two gentlemen, as well as Mr. Ray R. Macheel, gave extensive assistance in the reduction of the data, and their aid is appreciated.

Special acknowledgment is also due to Mr. J. J. Kaganove and Miss Sue Katilavas for their work in numerically smoothing and differentiating the displacement data.

REFERENCES

1. S. M. Zivi, *A Mechanism for Severe Pressure Transients in Heterogeneous Reactor Power Excursions*, STL Quarterly Progress Report 8977-6019-SY-000 (May 30, 1962).
2. L. B. Wentz and S. M. Zivi, *Preliminary Results of In-pile Capsule Experiments in the KEWB Reactor*, STL Quarterly Progress Report STL-6303 (April 15, 1963).
3. S. M. Zivi *et al.*, *Kinetic Studies of Heterogeneous Water Reactors*, STL Quarterly Progress Report 8977-6028-SU-000 (Oct. 11, 1962).
4. R. W. Wright, *Pressure Pulses in Rapid Transient Boiling*, CONF-187-111, presented at the 1963 Winter Meeting of the American Nuclear Society, New York, N.Y., Nov. 18-21, 1963.
5. R. W. Wright *et al.*, *Kinetic Studies of Heterogeneous Water Reactors*, TRW Systems Quarterly Progress Report STL-372-22 (July 30, 1965).
6. S. M. Zivi *et al.*, *Kinetic Studies of Heterogeneous Water Reactors*, TRW Systems Quarterly Progress Report STL-372-47 (Sept. 30, 1966).
7. H. K. Forster and N. Zuber, *Growth of a Vapor Bubble in a Superheated Liquid*, J. Appl. Phys., Vol. 25, No. 4, pp. 474-478 (April 1954).
8. M. S. Plessett and S. A. Zwick, *The Growth of Vapor Bubbles in Superheated Liquids*, J. Appl. Phys., Vol. 25, No. 4, pp. 493-500 (April 1954).
9. R. Darby, *The Dynamics of Vapour Bubbles in Nucleate Boiling*, Chem. Eng. Sci., Vol. 19, pp. 39-49 (1964).
10. L. A. Skinner and S. G. Bankoff, *Dynamics of Vapor Bubbles in General Temperature Fields*, Phys. Fluids, Vol. 8, No. 8, pp. 1417-1420 (Aug 1965).
11. R. C. Noyes *et al.*, "The Development and Growth of In-core Voids Due to Boiling during Fast Reactor Transients," *Proceedings of the Conference on Safety, Fuels, and Core Design in Large Fast Power Reactors*, Argonne National Laboratory, ANL-7120, Oct. 11-14, 1965.
12. W. G. Meinhardt, *Calculating Vapor Growth in a Superheated Liquid Metal Within a Heated Channel*, Trans. ANS, Vol. 9, No. 2 (Oct 1966), pp. 566-567.
13. D. R. MacFarlane, *An Analytical Study of the Transient Boiling of Sodium in Reactor Coolant Channels*, Ph.D. thesis, Purdue University (June 1966); also available as ANL-7222.
14. H. H. Hooker and R. J. Schiltz, *Time Delay Between Single-pulse Heating and Transient Boiling*, Reactor Eng. Div. Tech. Memo 9, Argonne National Laboratory (June 25, 1954).
15. P. A. Lottes and R. J. Schiltz, personal communication.
16. G. Friz, "Coolant-ejection Studies with Analogy Experiments," *Proceedings of the Conference on Safety, Fuels, and Core Design in Large Fast Power Reactors*, Argonne National Laboratory, ANL-7120, Oct. 11-14, 1965.

17. H. K. Fauske, *Propagation of Pressure Disturbances in Two-Phase Flow*, presented at the Symposium on Two-Phase Flow Dynamics, Eindhoven, The Netherlands, Sept. 4-9, 1967.
18. M. Fischer and W. Häfele, "Shock Front Conditions in Two-phase Flow Including the Case of Desuperheat," *Proceedings of the Conference on Safety, Fuels, and Core Design in Large Fast Power Reactors*, Argonne National Laboratory, ANL-7120, Oct. 11-14, 1965.
19. M. E. Deich *et al.*, *The Speed of Sound in Two-phase Media*, Thermal Engineering, No. 8 (March 1965), pp. 44-48.