UNITED STATES ATOMIC ENERGY COMMISSION

**FAST TRANSIENT HEATING AND EXPLOSION
OF METALS UNDER STAGNANT LIQUIDS**

By
A. J. Bendler
J. K. Roros
N. H. Wagner

February 12, 1958

**Engineering Research Laboratories
Columbia University
New York, New York**

Technical Information Service Extension, Oak Ridge, Tenn.

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.

Other issues of this report may bear the number CU-1-58-AT-187-Ch.E.

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, express 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 to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

This report has been reproduced directly from the best available copy.

Printed in USA. Price \$3.00. Available from the Office of Technical Services, Department of Commerce, Washington 25, D. C.

AECU-3623

UNCL.

58-1037

COLUMBIA UNIV., NEW YORK. ENGINEERING RESEARCH LABS.
FAST TRANSIENT HEATING AND EXPLOSION OF METALS UNDER
STAGNANT LIQUIDS. A. J. BENDLER, J. K. ROROS,
AND N. H. WAGNER. FEB. 12, 1958. 161P. CONTRACT
AT(30-3)-187. (CU-1-58-AT-187-CH.E)

2/19/58cf gar

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

COLUMBIA UNIVERSITY - DEPARTMENT OF CHEMICAL ENGINEERING
ENGINEERING RESEARCH LABORATORIES

AECU-3623

FAST TRANSIENT HEATING AND EXPLOSION
OF METALS UNDER STAGNANT LIQUIDS

By

A. J. Bendler

J. K. Roros

N. H. Wagner

Issued February 12, 1958

Prepared Under AEC
Contract AT(30-3)-187
Task II

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

TABLE OF CONTENTS

	<u>Page No.</u>
ABSTRACT	
I. INTRODUCTION	1
II. EXPERIMENTAL METHOD	3
III. DISCUSSION OF RESULTS	
A. Background Discussion	7
1. Burnout and Explosion	7
2. Transient Boiling	8
B. Results of Underwater Burnout Tests	10
1. Cu, Ag, Zn, Sn and Al	10
2. Zr and U	27
3. Pressures Resulting From Thermal Transients	29
C. Non-Burnout Tests	30
D. Burnout Tests Under Mineral Oil	35
E. General Burnout Correlation	39
F. Analysis of Errors	39
IV. SUMMARY OF CONCLUSIONS	45
REFERENCES	47
APPENDIX	49
Index to Section I - Figures and Graphs	49
Index to Section II - Rosenthal-Miller Equations	51
Index to Section III - Integration of Circuit Equation	51
Index to Section IV - Table of Nomenclature	51

ABSTRACT

Thermal transients with total pulse times of 3 to 28 milliseconds were simulated by direct current electrical heating in studies of the explosions of Ag, Al, Cu, Sn, U, Zn, and Zr specimens under water and under oil at an ambient temperature of 75°F and at atmospheric pressure. Motion pictures were taken of many of the explosions at film speeds of 7,500-14,500 frames/sec. A 600 foot composite reel was prepared which shows 7 representative explosions and views of the equipment. Data for 34 runs, photographs, and photomicrographs are presented and discussed with respect to burnout, heat transfer and metal-water reaction.

ACKNOWLEDGMENT

The contributions of W. E. Hovemeyer, A. J. Rothman, and J. J. Zimmerman in connection with experimental phases, calculations, editing of films, or data analysis are gratefully acknowledged.

I. INTRODUCTION

When power rises rapidly to high levels in water-cooled reactors built with large excess reactivity, severe explosions may occur. The Borax experiments^(1b) showed that destruction of such a reactor can result as a consequence of a sufficiently fast and high power transient. Knowledge of the mechanism of the explosions is essential in designing to minimize the destructive effects.

Analyses of the Borax explosions have been reported by Dietrich and Layman^(1a), by Dietrich^(1b) and by Ransohoff⁽²⁾. While it is somewhat an oversimplification of these reports it may be stated in brief that they show the energy release associated with the destruction may be explained by one or both of the following two possible effects:

- (1) Failure of the fuel element and rapid dispersion of very hot fuel element particles through the coolant leading to a severe steam explosion from the rapid local heat generation in the coolant;
- (2) Attainment of conditions for self-sustained, runaway chemical reaction of the fuel element with the coolant, leading to accelerated heating from rapid generation of the heat of reaction plus combustion of large volumes of hydrogen gas released locally.

It is uncertain, following study of the recorded data and of the debris from the Borax "accident", what the relative importance of each of these two effects was in producing the destruction.

This investigation has been limited to an experimental study of what happens to metals out-of-pile when they undergo thermal transients similar to those in a reactor explosion. Related studies on the kinetics of metal-water reactions have been conducted by Knolls Atomic Power Laboratory and by Aerojet-General Corporation which have been reported by Saltsberg⁽³⁾

and by Higgins and Schultz⁽⁴⁾ respectively.

In this investigation the nuclear thermal transient was simulated by direct current electrical heating. Reactor periods of the order of a few milliseconds were simulated and the metal samples were destroyed by "electrical explosion". The preliminary phases of this investigation were devoted to experiments to test the suitability of fast-transient direct current electrical heating as a means of simulating nuclear heating and to develop the necessary instruments and control devices. The work covered during the preliminary period, which extended from May 1955 through September 1956, was reported by Tick⁽⁵⁾, Stark⁽⁶⁾, and Markels and Stark⁽⁷⁾. The present report covers work done during the period October 1956 to October 1957.

Failure of a metal test specimen by "electrical explosion" refers to the phenomenon produced when a high current density (of the order of 10^5 amperes/cm²) vaporizes part or all of the metal. The gas which is emitted with great speed produces the impression of an explosion. The methods originally used by Tick and Stark for studying the thermal transients introduced certain difficulties in operation and interpretation. Their current pulses were not readily controllable because the rate of the current rise was a function of the operation of a circuit breaker. Furthermore, pulse transients could not readily be predicted since the circuit resistance external to the sample was changing. Finally, computation of total energy was uncertain because the point at which breaker arcing stopped could not be determined exactly. Further refinements were also required to be certain of instrument error caused by shunt-induced and test element-induced voltages. This report summarizes the results attained after these factors were improved.

II. EXPERIMENTAL METHOD

Metal specimens as shown in Figure 1 were prepared from Cu, Ag, Zn, Sn, Al, U and Zr. In making a run the specimen is inserted between electrodes and submerged in an open, transparent plastic (Plexiglas) tank containing undegassed, deionized water at room temperature (about 25°C). One electrode is attached to an adjustable, horizontal copper bar, which in turn is connected to parallel, vertical current leads. By positioning the vertically placed specimen equidistant from the pair of current leads, magnetic forces and deflection of the specimen at rupture are minimized. The arrangement of the apparatus, with the tank dropped below operating position, is shown in Figure 2.

The electrical circuitry for the tests is shown schematically in Figure 3. Electrical energy is supplied from either one of two DC generators each rated at 1575 KW. They are driven by a 5,000 HP synchronous motor (13.2 KV). High peak current values can be obtained (up to about 75,000 amperes) by operating both generators in parallel. A view of the MG set is given in Figure 4. Variable excitation for voltage control is obtained from an exciter having separate control circuits for voltage adjustment. The generator characteristics allow a minimum current pulse rise time of approximately 5 to 9 milliseconds with the present test section an integral part of the electrical circuit. With a fixed generator voltage, both rise time and peak value of current are determined by the overall circuit resistance and inductance. Pulse shaping was controlled by accurate timing of a high speed (ITE) DC circuit breaker, which, when tripped by its own self-tripping device, opens the circuit completely in a minimum of 8 milliseconds. A view of this breaker is shown in Figure 5. When the high speed circuit breaker is used as a switch, other breakers are utilized for back-up circuit protection. On closing the high speed breaker, the relation between current and voltage in the electrical circuit is given by:

$$V_G = Ri + L \frac{di}{dt}$$

where:

V_G = generator DC voltage

R = Total circuit resistance (shunt, load, bus, armature, compensating and interpole fields, and circuit breaker), ohms

L = total circuit inductance, henries

t = elapsed time after closing the circuit, seconds

i = instantaneous current, amperes.

Integration of this equation is discussed in the Appendix. Numerical solution is required. In practice it was not carried out because of the complexity of the calculation. In theory, the integration by numerical methods could yield predictions of current rise time, at least for the adiabatic case.

The value of "L" is determined from the slope of the recorded current trace at zero time, for which "i" is zero and V_G is known.

Thus:

$$\frac{di}{dt} = \frac{V_G}{L}$$

Analysis of the generator characteristics, checked by several tests, showed the value of "L" to be constant at 30 microhenries for generator output currents up to approximately 35,000 amperes. The experiments reported herein are within this range.

The current flow through the test specimen is measured by means of a co-axial shunt designed in accordance with Park's⁽⁸⁾ method. This shunt negates the effect of induced emfs by reversing the current on itself coaxially. The measured value of the shunt constant was 49.3 amperes per millivolt. The current trace is recorded on a moving coil oscillograph (Consolidated Electrodynamics) which measures the drop across the shunt. This unit is used

due to the presence of 2,000 cycle noise introduced into the circuit by tooth and commutator ripple from the generator. The frequency response of this oscillograph is essentially flat up to 350 cycles per second. The voltage drop across the test sample is also recorded on the moving coil oscillograph, with the leads soldered close to the enlarged ends of the sample. Deflection of the voltage galvanometer is made opposite to that of the current galvanometer in order to distinguish between the two traces more easily.

Since the average value of $\frac{di}{dt}$ in these experiments was high, viz. 500 amperes per millisecond, with initial value about double this amount, the possibility of spurious readings due to induced emfs in the voltage measuring loop had to be investigated. This was done by shaping one of the electrodes in the form of the test sample, but with a greater thickness, so that its IR drop was negligible compared to that for the test sample. The shaped electrode was then rotated to occupy the position of the test sample, and, with the voltage leads attached to it, a test run was performed to observe the induced emf in the voltage measuring loop. This emf was found to be nil. The voltage trace is also viewed on a cathode ray oscilloscope using a triggered sweep. Motion picture films of some of the experiments were taken at speeds up to 16,000 frames per second, using a Fastax camera.

The operating sequence for the instruments and apparatus is shown in Figure 6. The initiation of the event is accomplished by a control device which actuates a time cycle for camera startup. Through relays the moving coil oscillograph motor is started, a synchronizing pulse forms in the pulse-forming network, and a signal initiates to close the high speed breaker. The synchronizing pulse triggers the oscilloscope sweep, a delayed gate pulse triggers the 2D21 thyatron and lights a neon tube for time-indexing the camera. Approximately 250 milliseconds after the start of the oscilloscope sweep, the high speed circuit breaker

completely closes and the current transient begins.

A tourmaline crystal transducer mounted on the Plexiglas tank wall near the specimen, was used in some instances to measure the pressure pulse produced by the underwater electrical explosion. The voltage output of the crystal is measured by means of a standard capacitor and a cathode ray oscilloscope. The signal is recorded by a camera attached to the oscilloscope screen. Calibration of this unit was accomplished by means of a pulse generator producing a known pulse using the experimental test leads and oscilloscope, thereby accounting for their additional capacitance.

A typical oscillograph trace of current and voltage is shown in Figure 7. The upper frequency response limit of the galvanometers utilized in the oscillograph is 350 cycles per second. Therefore, any reading after the circuit has been broken is inaccurate and should be discarded. The peak value of power, immediately preceding the final power decay has been selected as the point at which the run actually ends. It should be noted that, once the sample becomes sufficiently plastic to be affected by the "pinch effect" forces, very close to the end of the run, heating becomes very inhomogenous. The forms of the earliest portions of the curves were confirmed by cathode ray oscilloscope traces, but the limited accuracy of measurement of these restrict their use for quantitative measurements.

Plots were made of the energy, $\int_0^t VI \, dt$, versus time on a semi-logarithmic scale. Knowledge of the specific heats then permitted the calculation of adiabatic temperature vs. time or energy. Furthermore, from records of instantaneous voltage and current, the sample resistance may be calculated. Knowledge of resistivity as a function of temperature permits calculation of temperature as a function of time. Thus the actual and adiabatic plots of temperature-time, and energy-resistance may be compared. The value of peak power generated (to burnout) is obtained by plotting the current multiplied by the sample voltage (VI) and selecting the maximum value of the product.

III. DISCUSSION OF RESULTS

A. Background Discussion

1. Burnout and Explosion

The electrical explosion of metal wires has been studied in some detail by others. In their investigations capacitors were discharged through the metal wires to produce "electrical explosions" with current pulse lengths of the order of microseconds. Anderson and Smith⁽⁹⁾ and Sobolev⁽¹⁰⁾ report temperatures in the explosions of about 30,000°K when the metals are exploded in air or in vacuum; and Kvartskhava et al.^(11a) estimate temperatures in excess of 10⁶ °K if the metal wires are exploded in a liquid or solid medium. Other investigators include Day⁽¹³⁾, Barrington⁽¹⁴⁾, and Northrup⁽¹⁵⁾. A mathematical analysis is presented in the latter reference.

In common in these very rapid transients, it is observed that as the wire is heated it becomes unduloidal in shape (Kvartskhava^(11a) and Kleen⁽¹²⁾). Later in the event the wire separates into beads and subsequently evaporates along strata perpendicular to the axis of the wire. Kvartskhava et al. explain these phenomena in terms of an axial compression of a constrained wire which, according to Euler, assumes a sinusoidal form. Because of the variation in compressive stress along the wire, the melting takes place non-uniformly. Also, according to Kvartskhava, the presence of the magnetic field interacting with the current produces a radial compression (pinch effect) of magnitude $F = \sigma j^2$ (σ = perimeter of a circular wire; j = current density). This force, inversely proportional to the cube of the radius, accentuates "necking" down of the already reduced cross-sections, especially where the metal is molten. The non-uniform section produces inhomogeneous electrical heating with the reduced sections evaporating sooner, and the consequent loss in matter there accelerates the difference in cross-sectional areas produced by the "pinch effect".

This inhomogeneous heating of the samples is characteristic of electrical heating. Furthermore, the pinch effect can produce large local forces on the conductors for high peak transients. These effects present differences which are not to be found in the thermal transients of a nuclear reactor. Both of these "electrical" effects tend to cause failure of the specimen prematurely in comparison with failure from a thermal transient. The electrical arc which occurs at rupture of the metal sample and the ejection of metal vapor due to the pinch effect contribute added destruction not to be found in a thermal failure. Finally, as the arc extinguishes, the decay in the magnetic fields of the test circuit produces added forces on the specimen which are absent in thermal failure. Because of these effects, care must be exercised in interpreting the results of a transient electrical experiment which is used to simulate the thermal transient in a reactor. These electrical "defects" all tend to accelerate the onset of burnout and increase the magnitude of an explosion, as contrasted with a purely thermal excursion. Consequently it would appear that, for a given pulse period, application of the present burnout results to a nuclear reactor would be conservative.

It should be noted that the lag in physical properties of metallic conductors, i.e. the time required to reach the steady state values, earlier suspected to be of importance, ⁽⁵⁾ has been calculated to be less than a microsecond, and thus appears to be insignificant in the present investigation.

2. Transient Boiling

The original objective of this research project was the study of metal explosions (burnout), and the experimental investigation was carried out primarily to this end. However, in writing this report it appeared to be of interest to attempt to analyze the data in terms of

transient heat transfer considerations, at least semi-quantitatively.

In this connection, reference is made to the work of Rosenthal and Miller⁽¹⁶⁾ in which they note that the times used in their work were too short for convection to have occurred during the initial portion of each test. Instead, they assert that simple transient conduction appears to describe the behavior of the system prior to the occurrence of boiling heat transfer. In their tests, the concept of pulse period is introduced. They started with an initial power level (P_0) and raised the power exponentially. The path of their power curve can be represented mathematically by the following equation: $P = P_0 e^{t/p}$, where p is the pulse period. The Columbia tests, starting at an initial zero power level, can be approximated, initially, by a curve of this form.

Rosenthal and Miller also introduced the concepts of temperature overshoot (the amount by which the sample temperature exceeded the coolant saturation temperature before boiling started) and of delay time (the time for the sample to pass through the temperature overshoot). These concepts were not utilized in analyzing the Columbia data, although certain aspects of their analysis were employed as given in Section B1 below. It is to be noted that the pulse periods used in the Columbia tests (0.5 to 2.5 milliseconds) were considerably less than those of Rosenthal and Miller (5 to 75 milliseconds). Consequently convection was undoubtedly absent in the Columbia tests before boiling began.

Another analysis of transient boiling in connection with rapid power rises is that of A. J. Ulrich⁽¹⁷⁾. In this report Ulrich applies heat transfer analysis to the case of power excursions in the Borax II reactor. It is interesting to note that these experiments were for periods of about 30 milliseconds which is considerably larger than the Columbia experiments reported herein.

B. Results of Underwater Burnout Tests

A summary of underwater burnout test data is presented in Table 1A. Plots of the derived data are presented in the Appendix.

As observed on fast motion pictures of the events, boiling was seen at the surface of the sample several milliseconds prior to burnout. Generally, soon after boiling initiated the intensity of boiling appeared to increase and the sample became unduloidal in shape. Very soon thereafter, the sample exploded in a flash of light which was extinguished very rapidly. The films do not show sufficient detail to define the mode of boiling or any changes in boiling mode which might have occurred during the run.

The data for copper (Cu), silver (Ag), zinc (Zn), tin (Sn), and aluminum (Al) fall into one group, and those for zirconium (Zr), and uranium (U), into a second group. The discussion below follows this division.

1. Group I - Cu, Ag, Zn, Sn and Al

The parallel pattern of results obtained with this group of metals may be noted from the similarity of the semi-logarithmic plots of energy vs. time and rectilinear plots of resistance vs. energy, as presented in Figures 8 to 17, showing the results for Runs 883 (Cu), 907 (Ag), 968 (Zn), 970 (Al), and 969 (Sn). Other similar plots for this group of metals are presented, either as part of the accompanying text or in the Appendix. The data for Sn (Figures 12, 17) are only fragmentary owing to the short duration of the power transient before destruction, but the trend of the data is similar to that for Ag, Al, Cu and Zn. Sn has therefore been included with this group of metals.

It should be noted that, in some cases, experimental values of resistance were found above those for the melting points of the metals. This effect was thought to be due either to the continuation of the passage of current through the arc or exploded particle cloud, to an error in measurement, or, to the inhomogeneity in heating which might be expected

Table 1A

SUMMARY OF BURNOUTS UNDERWATER

Oscillograph Run Number	Metal	Coolant	Film Speed Pict./Sec. $\times 10^3$	Pressure Test No.	Peak Pwr. Watts $\times 10^3$	Total Transient Time (M-Sec)	Total Energy Input (Gm-Cal)	Pressure Change in Coolant P.S.I.
970	AL	H ₂ O	-	9	27.2	7.0	11.1	15.3
883	CU	H ₂ O	-	None	18.2	21.0	26.8	-
887	CU	H ₂ O	-	None	23.0	14.0	20.2	-
892	CU	H ₂ O	-	None	33.5	11.0	20.5	-
895	CU	H ₂ O	-	None	37.4	11.0	22.1	-
898	CU	H ₂ O	-	None	31.0	10.0	18.2	-
901	CU	H ₂ O	-	None	38.9	10.0	21.2	-
929	CU	H ₂ O	-	None	36.6	10.0	21.0	-
930	CU	H ₂ O	-	None	53.3	7.0	17.5	-
951	CU	H ₂ O	-	None	40.1	11.0	24.8	-
903	AG	H ₂ O	-	None	28.6	9.0	14.9	-
907	AG	H ₂ O	-	None	28.4	9.5	15.1	-
910	AG	H ₂ O	-	None	43.0	6.5	13.7	-
967	AG	H ₂ O	-	6	31.7	10.8	18.0	13.1
918	SN	H ₂ O	-	None	10.7	4.0	2.6	-
920	SN	H ₂ O	-	None	18.1	3.0	3.0	-
969	SN	H ₂ O	-	8	18.5	3.5	4.2	Trace not clear
971	U	H ₂ O	-	10	16.8	9.0	23.1	Trace not clear
973	U	H ₂ O	-	12	16.8	9.0	24.0	Trace not clear
989	U	H ₂ O	7.5	None	16.3	10.0	25.7	-
913	ZN	H ₂ O	-	None	18.8	6.0	7.3	-
916	ZN	H ₂ O	-	None	14.4	5.0	5.2	-
968	ZN	H ₂ O	-	7	23.8	5.5	8.6	10.9
972	ZR	H ₂ O	-	11	30.6	22.0	121.8	21.8
987	ZR	H ₂ O	12.5	None	22.9	28.0	114.5	-
988	ZR	H ₂ O	7.5	None	26.5	26.0	112.4	-
990	ZR	H ₂ O	7.5*	None	24.9	24.0	114.6	-

*denotes estimated values

when the sample becomes sufficiently plastic to be affected by pinch effect forces. On the graphs, resistances higher than those for the melting points of the metals involved have usually been omitted.

An attempt was made to index the film and oscillograph traces together so as to determine the effect of the explosion on voltage (V) and current (I) oscillograph traces. However, the neon light utilized for film indexing appeared as a blur on several frames instead of a pip on a single frame. Therefore the film and traces could not be correlated exactly. For this reason, it was not possible to determine either whether power generation continued during the explosion (and thereafter), or whether average electrical resistances higher than those calculated for the melting points of the metals tested were to be found prior to explosion. Either of these possibilities would explain the excessively high values of resistance encountered. Further development of a more precise indexing system is therefore required for the benefit of future tests.

In general, it is to be noted from Figures 8-12 that the energy changes for the burnout runs with this group of metals may be represented fairly accurately by two straight lines on a semi-logarithmic plot of energy vs. time. The first line, covering the initial interval of the transient, has a slope about double that of the second line, which represents the final interval of the transient. The corresponding periods of these two parts of the transient are proportional to the reciprocals of the slopes of the straight lines. It is the period of the first line which is discussed below in this section of the report, in comparison with the Rosenthal-Miller periods noted in Section A-2 above.

As observed on Fastax motion pictures of the burnout runs with this group, the point of intersection of the two lines corresponds, within about $1\frac{1}{2}$ milliseconds, with the time of onset of boiling. However, the mode of boiling at its onset, and any change in mode thereafter in the course of the power transient, unfortunately, could not be ascertained from

close examination of the films.

In steady state heat transfer, as heat generated by the metal increases, nucleate boiling occurs first. Following attainment of the peak nucleate boiling heat flux with a slight increase in heat generation rate, the boiling mode then shifts and passes through a transition zone, generally described as unstable film boiling, to a stable film boiling zone. The metal temperature increases markedly during this interval. With high melting point metals, such as platinum, the metal temperature in the stable film boiling region is below the melting point at a value of heat flux corresponding to that for peak nucleate boiling, and burnout does not occur during the transition. For most metals, however, including those covered in this report, the melting point is reached in the stable film boiling zone before attaining peak nucleate heat flux, and burnout therefore occurs during the transition. To illustrate this discussion, a curve is presented in Figure 29, showing the relationship between steady state heat flux and heater surface temperature through the several boiling zones. The curve in Figure 29 is based on a similar curve for pool boiling which is discussed in detail by Bonilla⁽²¹⁾ and which has been approximated to reflect the subcooling of the tests under discussion. The melting points of the metals covered by this report, and of platinum, which was tested by Rosenthal and Miller, have been indicated on Figure 29 for reference.

The work of Rosenthal and Miller with fast transient heating of thin specimens of aluminum and platinum appears to develop the boiling sequence which would be expected from steady state considerations. Thus, it seemed reasonable to assume that the mode of initial boiling with Group I metals is nucleate, and that boiling starts at a time (within $1\frac{1}{2}$ milliseconds) corresponding to the point of intersection of the two straight lines on the log energy-time plots. Moreover, since the data in the latter plots actually show a curved transition section between the two straight lines, it

was further assumed that film boiling starts in the interval between initial nucleate boiling and the time where the data points and second straight line begin to coincide. These assumptions are examined in detail in the discussion below.

The data plots of electrical resistance vs. energy for the Group I metals are represented in Figures 13 to 17 covering typical runs. The dotted lines shown in these Figures are the adiabatic heating curves. In general, these Figures appear to show that for the range of power transients tested (periods of about 0.5 to 2.5 milliseconds), the initial interval up to the onset of boiling follows reasonably well the path taken by the adiabatic heating curves. Following onset of boiling the data points separate from the adiabatic curves throughout the subsequent interval up to burnout, during which heat is being transferred to the surroundings. As the transient period decreases (i.e. as the speed of the transient increases), the adherence of the data to the adiabatic curve increases - as shown by Figures 13, 18 and 19 for Runs 883, 887 and 930 with copper specimens at respective initial periods of 2.4, 1.3, and 0.8 milliseconds (and respective total pulse times of 21, 14 and 7 milliseconds).

It is interesting to contrast the foregoing generalizations with those derived from both faster and slower transients. The Rosenthal and Miller tests covered slower transients with periods from about 4 to 70 milliseconds. The initial interval of these were best represented by transient conduction, rather than adiabatic, curves.⁽¹⁶⁾ For very much faster transients, the work of Bondarenko et al.^(11b), covering transients in the microsecond range, may be cited. In these tests, the specimen temperatures through the entire transient were reported as following the adiabatic curves. Some further discussion on these references is presented later.

In order to check the hypotheses concerning the sequence of appearance of nucleate and film boiling Run 883 was selected as a typical burnout run, representative of the

Group I tests, for analysis and discussion. From the log energy-time plot for this run, shown in Figure 8 it is seen that one straight line fits the data approximately up to 8 milliseconds, and a second straight line of lesser slope fits the data from 14 milliseconds to the end of the transient. From the first line to the second the exponential period changes from 2.4 to 5.7 milliseconds.

The point of intersection of the two lines in Figure 8 occurs at $10\frac{1}{2}$ milliseconds. From the observations made with the Fastax films, noted above, the initiation of nucleate boiling would therefore be expected to occur at $10\frac{1}{2} \pm 1\frac{1}{2}$ milliseconds. Further on the data coincide with the second straight line at an elapsed time of 14 milliseconds. Therefore film boiling would be expected to start at some point between the time of initiation of nucleate boiling and 14 milliseconds. Analytical methods were employed to check the assumptions.

The initiation of nucleate boiling should be manifested by a sudden drop in the rate of rise in specimen temperature, or, by a sudden rise in rate of heat transferred to the surroundings. In turn, the initiation of film boiling should be manifested by a sudden increase in temperature, or, by an interval in which the heat transferred to the surroundings remains the same or decreases while the specimen temperature increases substantially at the same time.

The average specimen temperature was calculated by means of the measured resistance during the test, directly obtained from the voltage and current (V/I) oscillograph traces and from a plot of temperature vs. calculated resistance of a copper sample of average dimensions (Figure 20). The calculated resistance was based upon tabulated resistivities⁽¹⁸⁾. Temperatures of the sample thus derived are denoted in text and in Figures as the "calculated" temperature. The data for Run 883 are shown in Table 2.

The curve showing the relationship between time and

DATA FOR RUN 883
Taken From Oscillograph Traces

TIME (t) (Msec)	CURRENT ^(a) (Inches)	VOLTAGE ^(b) (Inches)	POWER (Inches ²)	INTEG. ENERGY (Inches ² - Msec)	INTEG. ENERGY (E) (Gm-Cal)	RESISTANCE (R) (Milliohms)	TEMPERATURE (T) (°C)
0.3	0	0	0	0	0	-	
1.0	0.24	0.04	0.01	-	-	0.825	155
2.0	0.48	0.06	0.03	0.02	0.02	0.631	55
3.0	0.74	0.10	0.07	0.11	0.14	0.679	81
4.0	0.96	0.14	0.13	0.16	0.20	0.728	107
5.0	1.18	0.18	0.21	0.38	0.47	0.728	107
6.0	1.24	0.20	0.25	0.58	0.71	0.776	132
7.0	1.54	0.26	0.40	0.84	1.03	0.825	117
8.0	1.68	0.28	0.47	1.35	1.66	0.825	157
9.0	1.80	0.36	0.65	1.92	2.36	0.970	230
10.0	1.92	0.38	0.73	2.50	3.08	0.970	230
11.0	2.00	0.44	0.88	3.46	4.26	1.067	280
12.0	2.08	0.46	0.96	4.34	5.34	1.067	280
13.0	2.16	0.52	1.12	5.45	6.70	1.164	321
14.0	2.24	0.56	1.25	6.60	8.12	1.213	345
15.0	2.28	0.62	1.41	7.94	9.77	1.310	390
16.0	2.34	0.70	1.64	9.47	11.65	1.460	455
17.0	2.36	0.80	1.89	11.22	13.80	1.650	535
18.0	2.38	0.94	2.24	13.33	16.40	1.892	635
19.0	2.34	1.12	2.62	15.66	19.26	2.328	801
20.0	2.30	1.30	2.99	18.48	22.73	2.765	962
21.0	2.24	1.58	3.54	21.76	26.76	3.444	> 1083 ^(c)

Calibrations for Run 883

(a) 1030 amperes per inch
(b) 5 volts per inch

(c) 1083° C is MP of Copper

calculated temperature is given in Figure 21. Because of the scattering of the data points on this Figure, no change in the rate of change of temperature with time can be defined before 13-14 milliseconds have elapsed. At this point, an abrupt increase in the rate of change of temperature is noted which corresponds to the change in slope associated with the start of film boiling.

Three other curves are shown on Figure 21 for Run 883: the time-temperature curve for adiabatic heating, and two transient-conduction curves based upon Rosenthal and Miller⁽¹⁶⁾ Equations 6 and 7 (presented in the Appendix). Equation 6 whose time-temperature curve followed closely the Rosenthal-Miller data points, assumes that heat is being transferred from the test specimen to the surrounding medium, considered as a semi-infinite solid, by the mechanism of conduction. Equation 7 is a simplified expression derived from Equation 6, assuming the heat capacity of the sample to be negligible. Since the initial exponential power rise approximates the data only for the first eight milliseconds, the transient conduction curves utilizing the equation approximating the true power increase, are valid only for this interval.

For the lower portion of the calculated time-temperature curve, it has been noted that the data points did not follow any easily discernible path until about 14 milliseconds. Therefore, both a straight line and a curved line were used to approximate them (see Figure 22) with the expectation that one might follow the true path. It appears, for both the approximating curve and line, that the rate of change of temperature with time, i.e. the slope of the curve, is greater for the calculated average sample temperature than for those calculated by use of the transient conduction equation (Equation 6) over the eight milliseconds in question. The calculated temperature also rises more rapidly than does the adiabatic temperature, for the first eight milliseconds. The temperature curve calculated by use of the simplified equation (Equation 7)

departs radically from the calculated temperature curve after four milliseconds. According to theory it is impossible for the true specimen temperature to rise faster than the adiabatic temperature, contrary to what the calculations indicate. In addition, the transient conduction temperature should increase at a slower rate than the true temperature.

In view of the foregoing, it appears that:

- (1) The use of the simplified equation (Equation 7) is not satisfactory since the calculated curve diverges rapidly from the actual, i.e. the heat capacity of the sample may not be neglected.
- (2) The calculated temperature curve is in question since it lies above the adiabatic curve and rises faster. Possible errors which might explain these discrepancies are discussed in Section F. Among them the following may be noted briefly:
 - (a) Errors in measurement of current and voltage,
 - (b) error in size of sample i.e. thickness, length, width, and/or weight,
 - (c) error in the use of average temperature (this should be more noticeable at higher rates of heat transfer.

Of these the one most likely to account for the discrepancies is (b); for if the thickness or width were less than expected, the resistance at the base temperature would be greater than that calculated and the calculated base temperature would be higher than the adiabatic. In addition, the energy generated would cause the sample temperature to rise more rapidly than would be calculated for the adiabatic temperature rise for an assumed larger sample. Thus, with a sample smaller than the assumed average size, the calculated temperature would be higher initially and would increase more rapidly than the adiabatic. This appears to be the case in Run 883.

After an elapsed time of eight milliseconds, however, the adiabatic temperature rise is continuously more rapid than

the calculated temperature, until sixteen milliseconds have elapsed. From this point until the end of the run the curves are approximately parallel. This, also, tends to corroborate the theory that the mode of heat transfer, for the latter part of the run, is film boiling with a rate of temperature rise closely approximating that of adiabatic heating.

To investigate further the initiation of boiling it was necessary to determine the relationship between the heat flux and both temperature and time. For this purpose as noted before, both a curved line and a straight line were fitted to the calculated time-temperature graph for Run 883 from the data points over an interval from the beginning of the run to an elapsed time of 14 milliseconds. The equation for the curve is:

$$T = 21.1 + 15.2t + 0.58t^2$$

$$\frac{dT}{dt} = 15.2 + 1.16t \text{ } ^\circ\text{C/msec}$$

and, for the line,

$$\frac{dT}{dt} = 24.8 \text{ } ^\circ\text{C/msec}$$

The following curve was fitted to the upper portion of the graph, beyond an elapsed time of 14 msec:

$$T = 134.7 - 16t^2 + 0.582t^3$$

$$\frac{dT}{dt} = 134.7 - 32t + 1.75t^2$$

From this the power stored in the metal was calculated (equal to $M_c \cdot p \cdot dT/dt$). In turn, the difference between this and the power generation rate (dE/dt) gave the rate of energy transferred to the surroundings, i.e. the heat flux.

The results are plotted against time and calculated temperature on rectilinear coordinates in Figures 23 and 24. Heat flux vs. temperature is also plotted on logarithmic coordinates in Figure 25. Note, in accordance with later discussion, that the values of heat flux in Figures 23 and 24 are considered to be relative rather than absolute; and they

were arbitrarily increased by adding 5×10^6 to each value in order to obtain positive values for plotting Figure 25. Discussion concerning these Figures should therefore regard the relative, rather than the plotted values of heat flux.

It should also be noted that, over the interval where the data of the log energy vs. time curve deviated from the straight lines (between 8 and 14 milliseconds), the actual data points were used in calculating the generated power, in lieu of the approximating straight lines. Three symbols appear in Figures 23 to 25: one indicates that the heat flux calculation included the use of dT/dt obtained from the curve fitted to the data on the time-temperature curve (Figure 22) up to 14 milliseconds; the second used dT/dt for the line fitted to the data to 14 milliseconds; and, the third symbol indicates the use of the time-temperature curve beyond 14 milliseconds.

It is observed from the Figures that all three curves reach a peak in the interval 13 to 14 milliseconds. Immediately thereafter there is a rapid decline in heat flux on all three curves and an increase in temperature, which corresponds to the change to be expected with the initiation of film boiling. This adds further proof to that obtained from the analysis of the time-temperature curve (Figure 21), namely that film boiling starts at an elapsed time of 13-14 milliseconds. This corresponds on the steady state curve of Figure 29 to unstable film boiling.

Examining the data of the three Figures point by point, a sudden increase in the positive slopes of the curves is found in the interval $9\frac{1}{2}$ to $10\frac{1}{2}$ milliseconds, which would be expected to correspond to the initiation of nucleate boiling. However, in the next interval between $10\frac{1}{2}$ and $11\frac{1}{2}$ milliseconds, there is a decrease in heat flux although the calculated specimen temperature continues to increase through this interval. There is no apparent reason for this flux decrease, except for errors in the data. The point of initiation of

nucleate boiling, therefore is not so well defined as that for film boiling. It is interesting to note, however, that the curves of Figures 24 and 25 generally follow the shape of the steady state curve of Figure 29 (which was adjusted for wall temperature and slope of the nucleate boiling zone from Bonilla's pool boiling curve⁽²¹⁾).

From previous analytical work on bubble growth⁽¹⁹⁾ based on data from the first phase of this investigation^(5,6), it is estimated that it would take $3\frac{1}{2}$ to 4 milliseconds for visible bubbles 0.003 to 0.007 inches in radius to mature after the metal surface reaches the boiling point of the coolant (100°C for water) at the initial heating rate of 250°C/msec observed for Run 883. A calculated sample temperature of 100°C was attained at 4.5-5.0 milliseconds, and 175-200°C at 8-8.5 milliseconds. However, the first bubbles in the Fastax films of the Group I tests did not appear until an elapsed time was reached within $1\frac{1}{2}$ milliseconds of the point of intersection of the two straight lines on the log energy-time plots. This corresponds for Run 883 to a time interval of 9 to 12 milliseconds and to calculated temperatures of 210°C to 275°C. Thus there appears to be a time delay of $5 \pm 1\frac{1}{2}$ msec and a temperature overshoot of 110°-175°C in Run 883 at the point where visible bubbles appear. This is generally consistent with the work of Rosenthal and Miller⁽¹⁶⁾ who report temperature overshoots of 40°-60°F and time delays of 4 ± 2 msec for aluminum immersed in 90°F water and with power transient following an exponential period of 10 milliseconds. Since the initial period in Run 883 was 2.4 milliseconds it would be expected that both the time delay and temperature overshoot would be greater, as found.

In light of the foregoing it seems plausible to theorize that bubbles did start to form in Run 883 at some point in the interval 9 to 12 milliseconds, but, at the extremely high heating rate which existed, their population grew so rapidly that film boiling conditions were attained within

the life cycle⁽¹⁶⁾ of the first bubbles which appeared (3-4 msec). The sample temperature therefore did not drop in this run because true local nucleate boiling apparently was not achieved. This corroborates the conclusion reached by Rosenthal and Miller (Ref. 16, Page 29), that "for periods in the range of 6 msec the power rose so rapidly that the flux was relatively high when the first bubble formed, and film boiling began almost immediately after the first boiling surge".

Despite the plausibility of the hypotheses presented in the foregoing discussion of Run 883, definite experimental proof is lacking. Further work, therefore, with better time indexing and definition of the Fastax films, and more sensitive voltage and current vs. time recording instruments would be required to establish these hypotheses.

There are three points of importance omitted from the foregoing discussion. One is the use of calculated negative values of heat flux in preparing the aforementioned graphs. It is expected that the errors inherent in the data are relative. Therefore, the general shape of the graph and consequent discussion would still be true when the figures are adjusted accordingly. If the errors are not relative and should change in algebraic sign with the elapsed time of the run, the resultant changes in the curve shapes might make invalid the foregoing discussion regarding results from analyses of Figures 23, 24 and 25. Note that the calculated negative heat flux is accounted for if the sample was thinner or narrower than the average size assumed.

Secondly, while the adiabatic and calculated curves coincide, initially, on the resistance-energy plot, they do not on the time-temperature graph. In general, the adiabatic lines on the resistance-energy curves have been raised, as required, so that the initial resistance for the adiabatic case agrees with that obtained from extrapolating the data to the start of the run. For Run 883, however, the initial base temperature selected for calculation of the adiabatic and

transient conduction curves was 25°C as compared to 70°C which is obtained by extrapolating the curve to the apparent initial resistance. In many runs, including Run 883, the initial resistance, thus obtained, was thought to be unreliable because of the high value of temperature corresponding to it. For this reason, and because small errors would affect its value greatly (see Section F), a reasonable base temperature of 25°C was assumed for calculation of the adiabatic and transient conduction temperature curves.

Thirdly, the graphs of energy vs. time, resistance vs. energy, and temperature vs. time may not be independent. Since all calculated values are obtained only from voltage and current measurements, a question arises as to whether or not a change in slope, or "break", on one curve is paralleled by a similar change on the others. If so, analyses based on two or more of these curves, as has been done in this report and in the Rosenthal-Miller work, may not lend additional weight to the argument. That is, the information obtained by analyzing more than one such curve may be repetitions. The proof of independence or interdependence appears to be complex, being linked with transient inductive effects in the electrical circuit, with transient changes in the power supply itself and with the complex transient effects in the test specimen including changing heat transfer to the surroundings, non-uniform heating, pinch effect forces, etc. Since analyses of the data for heat transfer purposes were outside the original scope of work of this project further study along these lines has been deferred. It is evident, however, that future work on the heat transfer aspects of fast transient heating must investigate the question of interdependence of the graphs noted above.

In examining the debris left from Run 883, it appears that the voltage taps were approximately 1/10" away from the central portion of the sample. Calculation shows that the actual test section voltages should therefore be corrected

by multiplying by 0.94. Curves of temperature as a function of time thus corrected, for the calculated and adiabatic cases, are shown in Figure 26. Comparison of the corrected and uncorrected curves shows no marked difference except that the temperatures attained in the corrected curves are somewhat less than those in the same time interval.

In summary of the analysis of Run 883, the initiation of nucleate boiling was not clearly delineated, although the data clearly did show a change evidently corresponding to the start of film boiling. The initiation of nucleate boiling, therefore, either is obscured by erratic behavior of the data, or does not occur in the tests herein reported. These covered initial exponential power periods from 0.5 to 2.5 msec. A plausible explanation, which accords with work by Rosenthal and Miller⁽¹⁶⁾, is that true nucleate boiling does not occur, because the heating rate is so rapid at the instant when the first bubbles appear that film boiling conditions are attained almost immediately thereafter. However experimental evidence is lacking to establish this explanation. Consequently more precise measurements must be made to obtain transient heat transfer data as compared to the relatively coarser data required for the burnout tests of this investigation.

From study of the films and the debris left from underwater burnout runs with Group I metal samples, no evidence was found for any self-sustained chemical reactions, which might provide energy in excess of the recorded electrical energy input. However, because of the prominence of aluminum as a fuel cladding material in low pressure, water-cooled reactors, two runs (976 and 977) were made with special Al specimens to determine whether reaction of this metal with water is initiated by the fast transient heating and explosion of a closely adjacent piece of the same metal.

The test specimens were constructed as shown in Figure 27 and, as before, were employed in the runs with the long axis placed vertically. Fastax films were taken of the ex-

plosions along with the data as in the other underwater runs. Graphs of the logarithm of energy input to the specimen vs. time and of resistance vs. energy for Run 976 are shown on Figures 28 and 30. By comparison with similar data for Run 970, shown on Figures 11 and 16, the mode of specimen heating appears to be identical for both runs. Since the sample used in the latter test was constructed in accordance with Figure 1, it is inferred that the difference in shape does not affect the heating mode.

Examination of the films and of the test specimen after failure reveal that two explosions occurred during each of these runs. The first explosion, like those discussed in the foregoing sections, resulted from rapid heating and vaporization of the major central portion of the 0.090" OD specimen which left intact pieces, 1/8" to 3/16" long at each end. In the course of the run the insulators separating the test section and the shield softened and blew out of position. Almost immediately the short remaining ends of the specimen then rapidly deflected and welded themselves to the 0.010" thick aluminum shield thereby restoring current flow. Within a few milliseconds these ends overheated, causing the second explosion, in the course of which the shield slipped downward, breaking the electrical circuit.

The sequence of events in these runs, with two explosions and an intermediate point of arc welding, provided a more drastic test than originally intended. Nevertheless, careful inspection of both the internal and external surfaces of the shields after the runs revealed no evidence of corrosive attack. The original finishing marks, scratches, and surface patina remained unaffected except for some internal arc splatter adjacent to the points where welding of the specimen ends had occurred.

It is therefore concluded that any reaction of Al with water that might have occurred in these runs was confined to the vaporized metal and no attack occurred on an unheated piece

of Al located within the explosion fields. It is also to be noted that in Run 970 no attack was found on the specimen ends which remained after burnout and which also were in the path of the explosion. This conclusion confirms results of an extensive number of heat transfer burnout tests with electrically heated Al at Columbia, all of which were accompanied by underwater arcing, and which were performed at higher water temperature and pressure than the runs discussed herein. Several of these other tests were analyzed in quest of evidence of a sustained aluminum-water reaction⁽²⁰⁾. All of the work at Columbia with underwater burnouts of large aluminum heaters simulating fuel elements, undertaken since 1953 when the referenced analysis was made, including at least 40 major burnout tests to which the fast transient heating runs discussed herein may be added, serves only to confirm the conclusion of that reference: ". . . even at temperatures as high as the melting and arcing points and in the presence of liquid water or steam, aluminum does not react readily with water."

In conclusion of the discussion of the underwater burnout tests with Group I metals, regarding the initiation of boiling in the transient period range herein reported, techniques will have to be evolved to determine the true mode. These may be extensions of use of present equipment, such as the high speed camera with telephoto lens, or more elaborate procedures. Redesign of the test section to minimize the boiling area may aid in this investigation for all metals in Group I by localizing the growth of bubbles. Included in these changes are the requirements for a faster, more sensitive oscillograph and for more complete measurement of the physical characteristics of the specimens including calibration of those quantities necessary for adequate resolution of the data for heat transfer purposes. These changes are dictated by the increased accuracy required in data for heat transfer as against those for burnout information.

In addition, it would be desirable to continue the work

initiated by Rosenthal-Miller, for more rapid transients within the capabilities of the equipment at Columbia. This would necessitate some equipment changes, especially in the electrical circuitry, to obtain power transients following their exponential paths. Further modifications could also be made for those reactors in which the transient heating of the fuel elements follows more complex paths.

2. Group II - Zr and U

The tests with Zr and U exhibit results which differ from the Group I metals discussed above. Runs 988 (Zr) and 989 (U) have been chosen as typical of the tests made with these metals. Graphs of the energy vs. time data for these runs are presented in Figures 31 and 32, and of resistance vs. energy in Figures 33 and 34. The dotted lines in the latter are the adiabatic heating curves. Similar data plots of other underwater Zr and U runs are included in the Appendix.

It is noted from Figures 31 and 32 that, after a brief initial interval of 6 msec in Run 988 and 4 msec in Run 989, energy varies linearly with time through the remainder of the transient. This is explained by noting from Figures 33 and 34 that the changes in resistance of the specimens after the initial intervals are within 10-12% of the average value of resistance over the balance of the transient. This is evidently the result of the phase change which occurs with these metals, shown in Figures 33 and 34 by the change in slopes of the resistance-energy curves. This drop in resistance is absent in the tests with the Group I metals, in which no phase change occurs.

The total transient pulse times in the Group II tests were comparable to the Group I tests and ranged approximately between 9 and 28 milliseconds. With slower transients than these the energy-time relation might be expected to show an increase in slope toward the end, particularly with U specimens (see Page A-62). The Group II tests were not analyzed with respect to the points of inception of nucleate and film

boiling because of uncertainty concerning the internal energy changes in the specimens during phase change which could affect heat flux calculations significantly.

Of considerable importance with the Group II tests were observations made from the films of the burnout runs indicating that metal-water reaction occurred after the power pulse ended. In the case of the Zr films strong afterglow of the unvaporized fragments of the samples are seen after the explosions. This endured for a period of 0.8 to 1 second during which the fragments continued to evolve gas. Figure 56 presents an enlargement of one 8x16 mm frame (about 0.3 seconds after explosion) which shows a glowing Zr fragment and a gas envelope around it. In the U films the unvaporized specimen fragments which remain in the field of view do not glow after the explosion, although generation of bubbles at their surface continues for several tenths of seconds. The films of the Group I metals do not show these effects.

Photomicrographs of the Zr and U fragments from Runs 988 and 989 and photographs showing new and the burned out specimens are presented in Figures 35 to 38. The micrographs compare the structure of unheated metal with a section through the heated fragment including a portion of the surface.

The heated Zr fragment (Figure 36) shows three zones: a non-metallic grey-black layer 0.001" thick at the surface; an intermediate non-metallic white layer 0.0008" thick; and, finally, the zirconium metal which has a Widmanstatten structure indicative of rapidly quenched metal. This may be compared with the structure of an unheated section (Figure 36) which shows equiaxed grains typical of annealed metal. Vicker's diamond pyramid microhardness (DPH) impressions with a 50 gram load gave the following results:

Burned out Zr:	Grey-black zone	620
	White interm. zone	1000
	Widmanstatten zone	490
Unheated Zr:		160

From both the micrographs and the hardness measurements, it appears that the outer zones are oxide layers. These are equivalent to a penetration of 0.001" to 0.0015" of the Zr specimen, which represents a significant reaction rate, as it took place during a period of about 0.8 to 2 seconds. However, the fact that greater penetration did not occur despite the high reaction rate tends to indicate that a self-sustained reaction does not take place between glowing Zr and 75°F water. It appears more likely that the reaction which did occur was confined to the interval while the glowing metal was being quenched. The observation that the heated Zr fragments glowed after the explosion, whereas the U fragments did not, is probably due to the greater heat capacity of the former specimens which were 0.040" thick as compared to only 0.010" thickness of the latter. It would be interesting to perform tests at higher ambient water temperatures to learn whether conditions for self-sustained Zr-water reaction can be attained, with comparable transient tests.

Considering the U fragments (Figure 38), the structure of the heated section noticeably shows recrystallization to large grain sizes, as contrasted to the unheated section which shows striated grains typical of cold worked metal. No measurable non-metallic layer was found at the surface. Diamond pyramidal microhardness values (50 g. load) of 150 - 200 were obtained for both microstructures. It appears therefore that no reaction took place between the heated U fragment and the water, although it reached a high enough temperature to glow just before the explosion. The bubbles observed in the films of the post-explosion U fragments evidently were steam. These results are in accord with the observation reported by Barnes⁽²²⁾ that glowing uranium does not react readily with water.

3. Pressures Resulting From Thermal Transients

In four underwater burnout runs the overpressure, measured $2\frac{1}{2}$ " from the samples, averaged 16.4 ± 4.5 psi as a result of the explosions, for transients with total pulse times ranging from 5.5 to 22 milliseconds, as shown in Table 1A.

In thermal transients produced by electrical energy, unlike those caused by nuclear heating, both the local magnetic forces produced by the pinch effect and the inhomogeneous heating, accentuated by the pinch effect, add to the pressure waves produced. It is believed, therefore, that the pressure waves resulting from thermal explosions of specimens heated by nuclear transients under similar circumstances, i.e. in a liquid coolant with a free surface, would probably be of lesser magnitude. Conversely, a thermal transient in a partially confined space, such as a nuclear fuel coolant channel, could produce pressure waves of greater magnitude. Application of the results obtained must therefore be used with caution.

C. Non-Burnout Tests

Prior to making the burnout tests already discussed, preliminary tests were run using longer pulse times to check the proper functioning of the instruments and electrical circuits. In these runs the samples reached steady state conditions, in which the electrical power dissipation equalled heat transfer to the surroundings, and burnout did not occur. They were not originally intended to provide data within the scope of work of the project, but an attempt to analyze one such run was made to indicate the possibilities of using the techniques and equipment for transient heat transfer tests.

Run 882 which employed a copper specimen was chosen as the typical case. The data for this run are presented in Table 3. Since no definite straight line portion was found on the log energy vs. time curve, shown in Figures 39 and 40, calculation of a transient conduction curve was not attempted. The detailed analysis made of this run is summarized in the following discussion.

Figure 41 shows a plot of average specimen temperature, calculated from the instantaneous resistance, as a function of time, with the adiabatic heating temperature plotted for comparison, the values being determined at one millisecond intervals. While the calculated temperatures lie above the adiabatic curve,

TABLE 3
DATA FOR RUN 882
Taken From Oscillograph Traces

TIME (t) (Msec)	CURRENT ^(a) (Inches)	VOLTAGE ^(b) (Inches)	POWER (Inches ²)	INTEG. ENERGY (Inches ² - Msec)	INTEG. ENERGY (E) (Gm-Cal)	RESISTANCE (R) (Milliohms)	TEMPERATURE (T) (°C)
0.0	0	0	0	0	0	-	
1.0	0.14	0.08	0.01	0.02	-	0.70	94
2.0	0.18	0.12	0.02	0.11	0.01	0.81	150
3.0	0.24	0.14	0.03	0.31	0.02	0.70	94
4.0	0.26	0.16	0.04	0.50	0.03	0.75	125
5.0	0.32	0.18	0.06	0.87	0.04	0.68	81
6.0	0.36	0.20	0.07	1.18	0.06	0.68	81
7.0	0.40	0.22	0.09	1.69	0.08	0.67	75
8.0	0.44	0.24	0.11	2.31	0.11	0.67	75
9.0	0.46	0.26	0.12	3.09	0.15	0.70	94
10.0	0.48	0.28	0.13	3.90	0.19	0.70	94
11.0	0.50	0.28	0.14	4.67	0.23	0.68	76
12.0	0.52	0.30	0.16	5.61	0.28	0.70	94
13.0	0.54	0.30	0.16	6.68	0.33	0.68	81
14.0	0.56	0.32	0.18	7.77	0.38	0.70	94
15.0	0.58	0.32	0.19	8.90	0.44	0.67	75
16.0	0.60	0.34	0.20	10.11	0.50	0.70	94
17.0	0.60	0.34	0.20	11.30	0.56	0.70	94
18.0	0.60	0.34	0.20	12.55	0.62	0.70	94
19.0	0.60	0.35	0.21	13.85	0.68	0.70	94
20.0	0.60	0.35	0.21	15.16	0.75	0.70	94
21.0	0.60	0.36	0.22	16.59	0.82	0.60	110
22.0	0.60	0.36	0.22	17.98	0.88	0.73	110
23.0	0.60	0.38	0.23	19.28	0.95	0.76	125
24.0	0.62	0.38	0.24	20.81	1.02	0.74	115
25.0	0.62	0.39	0.24	22.31	1.10	0.76	120

TABLE 3 (continued)

TIME (t) (Msec)	CURRENT ^(a) (Inches)	VOLTAGE ^(b) (Inches)	POWER (Inches ²)	INTEG. ENERGY (Inches ² - Msec)	INTEG. ENERGY (F) (Gm-Cal)	RESISTANCE (R) (Milliohms)	TEMPERATURE (T) (°C)
26.0	0.62	0.40	0.25	23.96	1.18	0.79	140
27.0	0.64	0.40	0.26	25.37	1.25	0.76	125
28.0	0.65	0.40	0.26	27.11	1.33	0.75	120
29.0	0.65	0.41	0.27	28.62	1.41	0.76	125
30.0	0.65	0.41	0.27	30.35	1.49	0.76	125
31.0	0.65	0.42	0.27	32.03	1.58	0.79	140
32.0	0.65	0.43	0.28	33.82	1.66	0.80	145
33.0	0.65	0.43	0.28	35.54	1.75	0.80	145
34.0	0.65	0.44	0.29	37.32	1.84	0.82	155
35.0	0.65	0.44	0.29	39.21	1.93	0.82	155
36.0	0.65	0.45	0.29	40.87	2.01	0.83	160
37.0	0.65	0.45	0.29	42.71	2.10	0.83	160
38.0	0.65	0.45	0.29	44.40	2.18	0.83	160
39.0	0.65	0.45	0.29	46.34	2.28	0.83	160
40.0	0.65	0.46	0.30	48.29	2.38	0.86	175
41.0	0.66	0.47	0.31	50.19	2.47	0.86	175
42.0	0.66	0.48	0.32	52.11	2.56	0.88	185
43.0	0.66	0.48	0.32	53.97	2.66	0.88	185
44.0	0.66	0.49	0.32	56.13	2.76	0.90	195
45.0	0.67	0.50	0.34	58.11	2.86	0.91	200
46.0	0.67	0.50	0.34	60.27	2.97	0.91	200
47.0	0.68	0.49	0.33	62.35	3.07	0.87	180
48.0	0.68	0.49	0.33	64.37	3.17	0.87	180
49.0	0.68	0.49	0.33	66.50	3.27	0.87	180
50.0	0.68	0.48	0.33	68.51	3.37	0.86	150
51.0	0.68	0.48	0.33	70.63	3.47	0.86	150
52.0	0.68	0.48	0.33	72.66	3.57	0.86	150

TABLE 3 (continued)

TIME (t) (Msec)	CURRENT ^(a) (Inches)	VOLTAGE ^(b) (Inches)	POWER (Inches ²)	INTEG. ENERGY (Inches ² - Msec)	INTEG. ENERGY (E) (Gm-Cal)	RESISTANCE (R) (Milliohms)	TEMPERATURE (T) (°C)
62.0	0.67	0.49	0.33	93.31	4.59	0.88	185
72.0	0.67	0.49	0.33	113.80	5.60	0.88	185
82.0	0.68	0.50	0.34	134.80	6.63	0.90	197
92.0	0.68	0.50	0.34	156.10	7.68	0.90	197
102.0	0.68	0.50	0.34	177.30	8.72	0.90	197

Calibrations for Run #882

- (a) 1030 amperes per inch
 (b) 1.25 volts per inch

which is impossible, the rate of temperature increase with time is greater for the adiabatic curve, which agrees with theory. The difference in temperature is about 45°C at the beginning of the run and about 20°C at the peak, which apparently corresponds to the initiation of nucleate boiling, occurring after 45 milliseconds have elapsed. Explanation for the discrepancy lies in the fact that far greater care is required for heat transfer purposes than that employed in experiments beamed at explosions caused by fast transient heating. Thus, a 10% change in resistance at 200°C (from 0.91 to 0.82 milliohms) results in a calculated temperature of 160°C ; while a 10% change in energy at 200°C (from 3.3 g-cal to 3.0 g-cal) results in an adiabatic temperature of 190°C . This would correspond to an error in test specimen dimensions of about 10%, i.e. 10% less cross-sectional area or 10% greater length than the average size assumed. As a consequence, a small error in measurement of voltage or current results in a relatively large error in temperature calculated for the specimen as compared to the adiabatic curve. Further discussion of the possible errors in the data is presented in Section F.

To check the existence of the peak, a second set of measurements was taken independently of the first set by another person over the interval 42-62 milliseconds at 1 msec intervals. The new data values were then used to calculate sample temperatures. These, denoted "rechecked" temperatures, are compared graphically with the "original" temperatures in Figure 42. In this figure the location of a peak is not defined, and therefore the point of initiation of nucleate boiling is uncertain. It may be noted that both the original and second sets of voltage and current measurements were within 0.02 inches of each other in a measured span of $1/2$ to $2/3$ of an inch on the traces. It is therefore apparent that such data for heat transfer purposes respond readily to what should normally be trivial differences in reading values from

recorded traces, and thus must be traced with greater span per increment of reading than has been recorded.

It would have been desirable to show the relationships in Run 882 between heat flux and both time and temperature. However, because of the uncertainty in the actual time-temperature curves and the resultant uncertainty in dT/dt (necessary in calculating heat flux by difference between generated and stored power), these curves were not sought.

As noted in Run 883 (see Page 23), the voltage taps in Run 882 were located approximately $1/10''$ away from the central portion of the sample. As before the voltage was therefore corrected by a factor of 0.94 and the time-temperature curves were adjusted accordingly for both specimen temperature and adiabatic temperature as shown in Figure 43. On comparing Figures 41 and 43, two main differences appear to exist. The temperature discrepancy is less in the corrected curves and their slopes show greater deviation, particularly after 20 milliseconds.

In summary of the discussion of the non-burnout runs, it appears that these do not show the linear intersection on the log energy-time curve. Initiation of nucleate boiling can be determined, however, from more sensitive traces of voltage and current using the techniques and equipment employed for this project, which would also yield transient heat transfer data. By employing high melting point specimens, such as platinum, transient heat transfer tests appear to be possible in which the samples reach a state of film boiling without burnout.

D. Burnout Tests Under Mineral Oil

Six runs were made with the test specimens immersed in a water-white hydrocarbon oil instead of water. The purpose of these runs was to obtain data, including Fastax films, of metal explosions in a liquid substantially inert to normal chemical reaction with metals. By comparison with films of underwater explosions of the same metals it was hoped that evidence might be obtained to show whether chemical reaction accompanied any of the underwater explosions.

The "oil runs" employed test specimens identical with those shown in Figure 1. The runs and metals tested are as follows:

<u>Metal</u>	<u>Run</u>
Zr	995, 1000
Al	996
U	997
Cu	998
Ag	999

Data plots of energy vs. time are presented in Figures 44-49, and of resistance vs. energy in Figures 50-55. The oil used was "Ervol-NF" (L. Sonneborn Sons, New York, N. Y.), which has a boiling point range of 650-750°F. Data are listed in Table 1B.

The data plots of these runs, when compared to those for underwater burnouts, show that the mode of specimen heating is essentially similar in both cases. Thus the plots of log energy vs. time for Al, Cu and Ag (Figures 45, 47, 48) show two distinct periods with a transition zone between them. As is the case with the underwater runs with these metals, this transition zone probably represents the interval from incipient to developed boiling at the specimen surfaces. The similarity of the Zr and U runs is shown by the linearity of the energy-time curves after an initial interval (Figures 44, 46, 49), and, by the zone of the phase change shown on the resistance-energy graphs (Figures 50, 52, 55). Dissimilarities between the plots for the under-oil and underwater runs - such as the longer transition zones for Ag, Al and Cu, and, the more rapid rise of resistance vs. energy for Zr and U following phase change - are, most probably, due to differences in the thermal properties of the two liquids.

The Fastax films of the oil runs proved to be somewhat more difficult to interpret than those of the underwater runs owing to retarded settling of the explosion debris which left the field of view quite dark. The following observations, however, are of interest:

1. In general the under-oil explosions were similar

Table 1B

SUMMARY OF BURNOUTS UNDER OIL

Oscillograph Run Number	Metal	Coolant	Film Speed Pict./Sec. X10 ³	Pressure Test No.	Peak Pwr. Watts X10 ³	Total Transient Time (M-Sec)	Total Energy Input (GM-Cal)	Pressure Change in Coolant P.S.C.
996	AL	Oil	7.5*	None	30.4	8.0	12.6	-
998	CU	Oil	14.5*	None	33.1	10.0	19.2	-
999	AG	Oil	14.5*	None	24.1	10.0	14.4	-
997	U	Oil	14.5	None	13.7	10.0	23.6	-
995	ZR	Oil	7.5	None	20.9	26.0	89.5	-
1000	ZR	Oil	14.5	None	25.2	26.0	119.3	-

* denotes estimated values

to those under water, as might be inferred from the data plots already discussed, except that they appeared to be less violent. This may be due to greater damping of the moving metal vapor-oil interface in the more viscous medium.

2. The afterglows of the unvaporized fragments of Zr, seen in the films of underwater burnouts, endured for periods of 0.8-1.0 seconds. In the under-oil films, similar Zr fragments glowed for periods of only 0.4-0.5 seconds, about half as long. Unfortunately published heat transfer data are lacking on the relative quenching speeds in oil and water, which would enable comparison of the two afterglow periods. It seems reasonable, however, to expect longer quenching times in oil than in water, since both the thermal conductivity and the molal heat of vaporization are lower for oil. If verified, this would indicate that the underwater Zr fragments did manifest a tendency to self-sustained reaction by glowing longer than would be expected. Further experimental study is required to prove this possibility.

3. The unvaporized fragments of U in both under-oil and underwater burnout runs show gas evolution for an extended period after the explosions occurred, although no afterglows were observed. Because no corrosion was found in the case of an underwater fragment, it is inferred that the gas is due to boiling of the respective liquids while quenching takes place.

In summary of the discussion of the oil runs, it is concluded that no additional evidence was found to indicate the occurrence of self-sustained metal-water reactions with Ag, Al, Cu or U following their fast transient heating and explosion. The data indicate, however, that a self-sustained Zr-water reaction may have occurred, but further proof is required. The data plots of energy-time and of resistance-energy for fast transient heating of metals under water and under oil show that the mode of energy storage in the specimens during the transient is similar. The explosions of metals under oil are somewhat less violent than those under water, apparently due to damping

of the expanding metal vapor-liquid interface in the more viscous liquid.

E. General Transient Burnout Correlation

Assembling the data from all the explosion runs, a graph has been prepared which shows the relationship between the total time of the transient and the total energy generated by the metal specimens up to the point of burnout. The total transient pulse times covered by the data range from 3 to 28 milliseconds. The graph is shown in Figure 57, the seven metals included being identified by different symbols.

The graph shows that the total generated energy and/or the total pulse time, required for burnout, increase with the increasing melting points of the metals tested.

F. Analysis Of Errors

Errors due to displacement of either or both of the voltage and current traces in time could lead to large errors in the results derived for power, integrated energy and resistance. In the tests reported herein it is believed that the time lag error is negligible because the sample inductance is small. Hence the voltage does not lead the current. In addition no tests were conducted in which the rise time was greater than the critical response speed of the oscillograph.

Values of current and voltage were calculated by measuring the traces in inches and multiplying by the calibration factor. Assuming a reading error of 0.02 inches, the resulting percentage errors in voltage and current are shown in Table 4 for Runs 882 and 883. The original traces for these runs are exhibited in Figures 7 and 58.

Since current and voltage values were used to calculate average specimen temperature, the values shown in Table 4 were utilized to show the consequent errors in temperature, and are given in Table 5. It is apparent that the effect of these errors on calculated specimen temperature is greater in the early, low temperature stages of a run, than in later, high temperature stages.

Table 4

Errors in Measured Data

Time (Milliseconds)	Run 882				Run 883			
	Reading(inches)		Percentile Error		Reading(inches)		Percentile Error	
	Current Voltage		Current Voltage		Current Voltage		Current Voltage	
1.0	0.14	0.08	14%	25%	0.24	0.04	8%	50%
20.0	0.35	0.60	6%	3%	2.30	1.30	1%	2%
45.0	0.50	0.67	4%	3%	----	----	----	----

The results shown are only for the uncorrected readings (the voltage is not multiplied by 0.94).

Table 5

Errors in Temperature (Actual)

Run 882

Time (Milliseconds)	Resistance (Milliohms)	Temp (°C)	Resistance Error* (%)	Resistance Limits		Temperatures	
				High (Milliohms)	Low (Milliohms)	High (°C)	Low (°C)
1.0	0.70	94	39	0.97	0.43	230	<0
20.0	0.70	94	9	0.76	0.64	130	75
45.0	0.91	200	7	0.97	0.85	230	170

Run 883

1.0	0.83	155	58%	1.31	0.35	380	<0
20.0	2.77	962	3%	2.85	2.69	985	930

*Taken from total error of V and I, Table 4.

In the multichannel oscillograph employed there were several empty galvanometer slots. An error, estimated at 5%, could therefore appear in the recorded traces due to flux from the unshielded positions. The effect this could have on calculated specimen temperature may be estimated from Table 5.

The adiabatic temperature is calculated from the physical characteristics of the sample and the integrated energy. It might therefore appear that errors in adiabatic temperature would be approximately the same as errors in measured resistance. Actually the errors must be totalled and divided by the integrated energy to obtain the true adiabatic temperature error. Accordingly, Table 6 has been prepared to show the effect of incorrectly reading the traces. It is apparent from this Table that the error in adiabatic temperature is small or absent at the beginning of a run, and about equal to the resistance error at elevated temperatures.

In general, the base temperature selected for the calculation of the adiabatic and transient conduction curves was 25°C because of the relative uncertainty of the initial calculated sample temperature. However, in the resistance-energy graphs, the adiabatic curve was generally translated to what was presumed to be the initial resistance. These discrepancies in the data may have been caused by the preliminary runs that were made with long pulse times (i.e. slow transients) to check the functioning of the equipment. Despite the small samples employed, these runs probably heated the specimens so that ensuing runs started with the metal at higher than ambient temperature.

Errors in sample size are reflected by errors in calculated resistance and sample weight. Errors in the calculated adiabatic and specimen temperatures follow. The sample size error in these runs is probably no greater than 10% in terms of resistance or heat capacity. This amounts to a 10% error in measured voltage with consequent errors in temperature shown in Tables 5 and 6.

Table 6

Errors in Temperature (Adiabatic)

Run 882

Time (Milliseconds)	Energy (g cal)	Temp (°C)	Energy Error, assumed (%)	Energy Limits		Temperature Limits	
				High (g cal)	Low (g cal)	High (°C)	Low (°C)
2.0	0.01	24.5	39*	0.01	0.01	24.5	24.5
20.0	0.75	65	9	0.82	0.68	67	60
45.0	2.86	181	7	3.06	2.66	193	170
2.0	0.02	24.5	58*	0.03	0.01	24.5	24.5
19.0	19.3	990	3**	19.9	18.7	1020	960

* Error from voltage and current readings at one millisecond

**Error from voltage and current readings at 20 milliseconds

Errors due to displaced voltage taps have been discussed above and generally gave voltage readings 10-11% high.

In summary of this discussion, the magnitude of errors encountered is much greater when analyzing the data for transient heat transfer purposes, in lieu of the original objective, i.e. for burnout information. It is evident that most of the inherent and characteristic errors encountered can be eliminated or minimized by taking the necessary measurements for heat transfer purposes with the proper precautions, techniques and instruments. Basically the equipment and methods employed in this investigation can readily be adapted for experimental studies of transient heat transfer.

IV. SUMMARY OF CONCLUSIONS

1. Analysis of the behavior of Ag, Al, Cu, Sn, Zn, Zr and U in thermal transients with total pulse times of 3 to 28 msec, based upon instantaneous values of current and voltage input to the specimen, give results which appear to be consistent. With Ag, Al, Cu, Sn and Zn, where no microstructural phase changes occur the energy changes up to burnout may be represented fairly accurately by two straight lines on a semi-logarithmic plot of energy vs. time. The exponential period of the initial interval of the transient is about half that of the final interval. Initial periods from 0.5 to 2.5 msec were covered in the tests. The point of intersection of the two lines corresponds within about 1 1/2 msec with the onset of boiling. In the case of Zr and U, where phase changes occur, the energy input vs. time is better represented by a linear function after the first few milliseconds of the transient.

2. Neglecting possible correction due to pinch effect, the peak values of power, integrated energy and temperature at the point of burnout are within 2-5%, 5-10% and 2-5% respectively of the values reported.

3. The peak overpressure attained in the liquid, measured 2 1/2 inches from the specimen, was 16.4 ± 4.5 psi during the explosions.

4. Similar results were obtained with explosions of Ag, Al, Cu, U and Zr specimens under mineral oil and under water.

5. General correlation of the burnout data shows that the total generated energy and/or the total transient pulse time, required for burnout, increase with the increasing melting points of the metals tested.

6. Evidence was not found of self-sustained metal-water reactions caused by fast transient heating and explosion of Ag, Al, Cu, Sn, U and Zn. Tests with special Al specimens showed that reaction of Al with water at 75°F ambient is not initiated by the explosion of a closely adjacent piece of Al.

Examination of unvaporized fragments of a heated Zr specimen, however, showed significant reaction with 75°F water with a penetration of 0.001" to 0.0015" of the metal taking place during an estimated interval from 0.8 to 2 msec when the glowing fragment was being quenched. Comparing the quenching times observed in Fastax films of post-explosion Zr fragments under oil and under water, a tendency to self-sustained Zr-water reaction is indicated, but further experimental proof is required.

7. Heat transfer analysis of the data which were obtained primarily for burnout purposes, exemplified by detailed study of two typical runs, show too much scatter for direct utility. However the analysis does indicate that true nucleate boiling was probably not achieved in the runs with initial transient periods of 0.5 to 2.5 msec. This is in accord with observations reported by Rosenthal and Miller⁽¹⁶⁾ for periods "in the range of 6 msec." The analysis also shows that the point of initiation of film boiling occurs within less than 1 msec of the instant where the data points and upper straight line coincide on the log energy-time plot.

REFERENCES

1. a. Dietrich, J. R. and Layman, D. C., "Transient and Steady State Characteristics of a Boiling Reactor", ANL-5211, Confidential (Feb. 1954).
b. Dietrich, J. R., "Experimental Investigation of the Self-Limitation of Power During Reactivity Transients in a Subcooled, Water-Moderated Reactor", ANL-5323, Confidential (1954).
2. Ransohoff, J. A. to Guttman, K., U. S. Government Office Memo, "An Analysis of the Borax Experiments As They Pertain to APPR", Secret (Nov. 17, 1954).
3. Saltsburg, H. M., "Metal-Water Reactions", KAPL-1493 (April 2, 1956 - declassified 5/17/56).
4. Higgins, H. M. and Schultz, R. D., "The Reaction of Metals in Oxidizing Gases at High Temperatures", IDO-28000 (April 30, 1957).
5. Tick, S. J., "APB Fast Transient Test on Stainless Steel Clad Copper Strips (Second Series)", rCU-2-56-At-187-Ch.E., Columbia University (Feb., 1956).
6. Stark, W. A., "Fast Transient Heat Transfer in a Clad Element - Stagnant Water System", CU-17-56-At-187-Ch.E., Columbia University (Sept., 1956).
7. Markels, M. Jr., and Stark, W.A., "Fast Transient Heat Transfer in a Clad Element - Stagnant Water System", CU-26-57-At-187-Ch.E. (Jan. 2, 1957). (Presented Nov., 1956 at Reactor Heat Transfer Conference, Hotel Statler, New York, N.Y.)
8. Park, J. K., RP1823, Jnl. Res. Nat. Bur. Stds., 39(1947).
9. a. Anderson, J. A., Astrophysical Jnl., 51, 37(1920).
b. Anderson, J. A., and Smith, S., *ibid.*, 64, 295(1926).
10. Sobolev, N. N., J. Exper. Theor. Phys., USSR, 17, 986(1947).
11. a. Kvartskhava, I. F., Pliutto, A. A., Chernov, A. A., and Bondarenko, V.V., Soviet Physics, J. Exper. Theor. Phys., 3, 1, P.40.
b. Bondarenko, V. V., Kvartskava, I. F., Pliutto, A.A., and Chernov, A.A., Soviet Physics, J. Exper. Theor. Phys., 1, 2, P.221.
12. Kleen, W., Ann. Physik, 11, 403(1931).
13. Day, P. B., Jnl. Opt. Soc. Amer., 43, 817.
14. Barrington, Brit. Jnl. App. Phys., 7, 11(1956).
15. Northrup, E.F., Phys. Rev., 24, 474(1907).

REFERENCES (continued)

16. Rosenthal, M. W., and Miller, R. L., "An Experimental Study of Transient Boiling", Unclassified, ORNL-2294 (Chemistry) (Apr. 29, 1957).
17. Ulrich, A. J., "Results of Recent Analyses of Borax II Transient Experiments", ANL-5532 (April, 1956).
18. American Institute of Physics Handbook, Pages 4-13 (1957).
19. Sweny, J. W., "Bubble Growth on Rapidly Heated Surfaces (Task II Elements)", TAGTM-10, Columbia University (May 3, 1956).
20. Bendler, A. J., "Review of Underwater Burnouts of 2S Aluminum Electrically Overheated", Secret, CU-11-53-At-dP-Ch.E., Columbia University (May 15, 1953 - declassified 1957).
21. Bonilla, C. F., "Nuclear Engineering", P. 401, McGraw-Hill Book Co., Inc. (1957).
22. Barnes, A. H., quoted in DPC-53-1-5 (LMA), Argonne National Laboratory (Mar. 6, 1953).

APPENDIX

SECTION I - FIGURES AND GRAPHS

<u>Figure</u>	<u>Description</u>	<u>Page No.</u>
1	Drawing of Test Specimen	A 1
2	Photograph - Arrangement of Apparatus	A 2
3	Sketch - Electrical Circuit	A 3
4	Photograph - MG Set	A 4
5	Photograph - High Speed Breaker	A 5
6	Sketch - Operating Sequence	A 6
7	Typical Oscillograph Trace (Run 883. Cu)	A 7
8	Energy-Time Curve, Run 883 (Cu)	A 8
9	Energy-Time Curve, Run 907 (Ag)	A 9
10	Energy-Time Curve, Run 968 (Zn)	A 10
11	Energy-Time Curve, Run 970 (Al)	A 11
12	Energy-Time Curve, Run 969 (Sn)	A 12
13	Resistance-Energy Curve, Run 883 (Cu)	A 13
14	Resistance-Energy Curve, Run 907 (Ag)	A 14
15	Resistance-Energy Curve, Run 968 (Zn)	A 15
16	Resistance-Energy Curve, Run 970 (Al)	A 16
17	Resistance-Energy Curve, Run 969 (Sn)	A 17
18	Resistance-Energy Curve, Run 887 (Cu)	A 18
19	Resistance-Energy Curve, Run 930 (Cu)	A 19
20	Resistance-Temperature Curve, Average Cu Sample	A 20
21	Time-Temperature Curve, Run 883	A 21
22	Time-Temperature Curve, Run 883 With Curves Approximating Data	A 22
23	Heat-Flux Time Curve, Run 883	A 23
24	Heat-Flux Temperature Curve, Run 883, Rectilinear Coordinates	A 24
25	Heat-Flux Temperature Curve, Run 883, Logarithmic Coordinates	A 25
26	Corrected Time-Temperature Curve, Run 883	A 26
27	Drawing - Modified Al Sample (Mod. No. 2)	A 27
28	Energy-Time Curve, Run 976, (Al, Mod. No. 2)	A 28
29	Adjusted Pool Boiling Curve for Sub- merged Plate	A 29
30	Resistance-Energy Curve, Run 976, (Al, Mod. No. 2)	A 30
31	Energy-Time Curve, Run 988 (Zr)	A 31
32	Energy-Time Curve, Run 989 (U)	A 32
33	Resistance-Energy Curve, Run 988 (Zr)	A 33
34	Resistance-Energy Curve, Run 989 (U)	A 34
35	Photographs - Zirconium Specimens	A 35
36	Photomicrographs - Burned Out Specimens, Zr	A 36
37	Photographs - Uranium Specimens	A 37
38	Photomicrographs - Burned Out Specimens, U	A 38
39	Energy-Time Curve, Initial Portion, Run 882 (Cu)	A 39
40	Energy-Time Curve, Final Portion, Run 882 (Cu)	A 40

SECTION I - FIGURES AND GRAPHS (continued)

<u>Figure</u>	<u>Description</u>	<u>Page No.</u>
41	Time-Temperature Curve, Run 882	A 41
42	Original and Rechecked Data Points, Time-Temperature Curve, Run 882	A 42
43	Corrected Time-Temperature Curve, Run 882	A 43
44	Energy-Time Curve, Run 995 (Zr)	A 44
45	Energy-Time Curve, Run 996 (Al)	A 45
46	Energy-Time Curve, Run 997 (U)	A 46
47	Energy-Time Curve, Run 998 (Cu)	A 47
48	Energy-Time Curve, Run 999 (Ag)	A 48
49	Energy-Time Curve, Run 1000 (Zr)	A 49
50	Resistance-Energy Curve, Run 995 (Zr)	A 50
51	Resistance-Energy Curve, Run 996 (Al)	A 51
52	Resistance-Energy Curve, Run 997 (U)	A 52
53	Resistance-Energy Curve, Run 998 (Cu)	A 53
54	Resistance-Energy Curve, Run 999 (Ag)	A 54
55	Resistance-Energy Curve, Run 1000 (Zr)	A 55
56	Photograph - Zr Sample Exhibiting Afterglow	A 56
57	General Burnout Graph	A 57
58	Oscillograph Trace, Non-Burnout Run (882 Cu)	A 58
	Resistance-Temperature Curve (Al)	A 59
	Resistance-Temperature Curve (Ag)	A 60
	Resistance-Temperature Curve (Sn)	A 61
	Resistance-Temperature Curve (U)	A 62
	Resistance-Temperature Curve (Zn)	A 63
	Resistance-Temperature Curve (Zr)	A 64
	Adiabatic Temperature-Energy Curve (Cu)	A 65
	Energy-Time Curve, Run 887 (Cu)	A 66
	Energy-Time Curve, Run 892 (Cu)	A 67
	Energy-Time Curve, Run 895 (Cu)	A 68
	Energy-Time Curve, Run 898 (Cu)	A 69
	Energy-Time Curve, Run 901 (Cu)	A 70
	Energy-Time Curve, Run 929 (Cu)	A 71
	Energy-Time Curve, Run 930 (Cu)	A 72
	Energy-Time Curve, Run 951 (Cu)	A 73
	Energy-Time Curve, Run 903 (Ag)	A 74
	Energy-Time Curve, Run 910 (Ag)	A 75
	Energy-Time Curve, Run 967 (Ag)	A 76
	Energy-Time Curve, Run 913 (Zn)	A 77
	Energy-Time Curve, Run 916 (Zn)	A 78
	Energy-Time Curve, Run 918 (Sn)	A 79
	Energy-Time Curve, Run 920 (Sn)	A 80
	Energy-Time Curve, Run 971 (U)	A 81
	Energy-Time Curve, Run 973 (U)	A 82
	Energy-Time Curve, Run 972 (Zr)	A 83
	Energy-Time Curve, Run 987 (Zr)	A 84
	Energy-Time Curve, Run 990 (Zr)	A 85

SECTION I - FIGURES AND GRAPHS (continued)

<u>Description</u>	<u>Page No.</u>
Resistance-Energy Curve, Run 882 (Cu)	A 86
Resistance-Energy Curve, Run 892 (Cu)	A 87
Resistance-Energy Curve, Run 895 (Cu)	A 88
Resistance-Energy Curve, Run 898 (Cu)	A 89
Resistance-Energy Curve, Run 901 (Cu)	A 90
Resistance-Energy Curve, Run 929 (Cu)	A 91
Resistance-Energy Curve, Run 951 (Cu)	A 92
Resistance-Energy Curve, Run 903 (Ag)	A 93
Resistance-Energy Curve, Run 910 (Ag)	A 94
Resistance-Energy Curve, Run 967 (Ag)	A 95
Resistance-Energy Curve, Run 913 (Zn)	A 96
Resistance-Energy Curve, Run 916 (Zn)	A 97
Resistance-Energy Curve, Run 918 (Sn)	A 98
Resistance-Energy Curve, Run 920 (Sn)	A 99
Resistance-Energy Curve, Run 971 (U)	A 100
Resistance-Energy Curve, Run 973 (U)	A 101
Resistance-Energy Curve, Run 972 (Zr)	A 102
Resistance-Energy Curve, Run 987 (Zr)	A 103
Resistance-Energy Curve, Run 990 (Zr)	A 104
SECTION II - Rosenthal-Miller Equations	A 105
SECTION III- Integration of Circuit Equation	A 106
SECTION IV - Table of Nomenclature	A 107

FIGURE 1

<u>METAL</u>	<u>THICKNESS</u>	<u>BURNOUT RUNS</u>
<u>COPPER</u>	<u>.010</u>	<u>883, 887</u> <u>892, 895</u> <u>898, 901</u> <u>929, 930</u> <u>998*</u>
<u>SILVER</u>	<u>.010</u>	<u>903, 907</u> <u>910, 967</u> <u>999*</u>
<u>ZINC</u>	<u>.010</u>	<u>913, 916</u> <u>968</u>
<u>TIN</u>	<u>.010</u>	<u>918, 920</u> <u>969</u>
<u>ZIRCONIUM</u>	<u>.040</u>	<u>972, 987</u> <u>988, 990</u> <u>995*, 1000*</u>
<u>URANIUM</u>	<u>.010</u>	<u>971, 973</u> <u>989, 997*</u>
<u>ALUMINUM</u>	<u>.010</u>	<u>970, 996*</u>

* - IN PARAFFIN OIL

COLUMBIA UNIVERSITY
DEPT. OF CHEMICAL ENGINEERING
TEST SPECIMEN
TASK II

FIGURE 2
ARRANGEMENT OF APPARATUS

A-3

TASK II CIRCUIT
DIAGRAM
FIGURE 3

PVOSGANIAN 5/15/57

FIGURE 4
VIEW OF MG SET

FIGURE 5
VIEW OF HIGH SPEED BREAKER

FIGURE 6
OPERATING SEQUENCE, TASK II

FIGURE 7
TYPICAL OSCILLOGRAPH TRACE

A-20

FIGURE 20
TEST SECTION
TEMPERATURE AS A FUNCTION
OF CALCULATED RESISTANCE

FIGURE 23
HEAT FLUX AS A
FUNCTION OF TIME
RUN 843

FIGURE 27
ALUMINUM SAMPLE
MODIFICATION NO. 2

FIGURE 29
ADJUSTED POOL BOILING CURVE
FOR SUBMERGED PLATE

A-29
 $Q/A \text{ (BTU/HR-FT}^2\text{)}$

A-33

FIGURE 35
NEW AND BURNED OUT ZIRCONIUM SPECIMENS

The upper shows a new specimen.

The lower shows the burned out specimen from Run 988. Photomicrographs of the lower specimen, shown in Fig. 36, were taken at positions corresponding to 0.1 inches and 0.9 inches on the scale.

FIGURE 36

PHOTOMICROGRAPHS OF BURNED OUT ZIRCONIUM SPECIMEN (RUN 988)

A-36

Magnification X250

Unaffected zone at wide end of specimen gripped by power contacts. Corresponds to 0.1 inches of scale on Fig. 35. Shows equiaxed grains typical of annealed Zr.

Magnification X500

Section corresponding to 0.9 inches of scale on Fig. 35. Edge of section shown in upper part of picture. Shows outer grey-black oxide layer (0.001"), intermediate white oxide layer (0.0008"), and Widmanstatten structure of remaining Zr.

FIGURE 37
NEW AND BURNED OUT URANIUM SPECIMENS

The upper shows a new specimen.

The lower shows the burned out specimen from Run 989. Photomicrographs of the lower specimen, shown in Fig. 38, were taken at positions corresponding to 1.1 inches and 2.0 inches on the scale.

FIGURE 38

PHOTOMICROGRAPHS OF BURNED OUT URANIUM SPECIMEN (RUN 989)

Magnification X250

Unaffected zone at wide end of specimen gripped by power contacts. Corresponds to 1.1 inches of scale on Fig. 37. Shows striated grains typical of cold worked material.

Magnification X250

Section corresponding to 2.0 inches of scale on Fig. 37. Edge of unvaporized fragment shown at right hand corners of picture. Shows no measurable oxide layer. Uranium grains have recrystallized.

A-112

A-4.3

RUN NO. 995 ZR
ENERGY VS. TIME
(IN PARAFFINOL)
FIGURE 4A

A-50

$R \times 10^3 (\Omega)$

A-55

FIGURE 56
SAMPLE OF ZIRCONIUM EXHIBITING AFTERGLOW

A-59

A-60

1000

900

800

700

600

500

400

300

200

100

TEMPERATURE VS
RESISTANCE
(SILVER)

RESISTANCE ($\Omega \times 10^3$)

0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0

TEMPERATURE VS.
RESISTANCE
(10^3)

TEMPERATURE °C

200

100

0

4

5

6

7

RESISTANCE ($R \times 10^3$)

A-62

1000

900

800

700

600

500

400

300

200

100

0

TEMPERATURE °F

TEMPERATURE
VS.
RESISTANCE
(CURANTON)

7

8

9

10

11

12

13

14

15

16

17

18

RESISTANCE ($R \times 10^{-3}$)

TEMPERATURE VS
RESISTANCE
(ZINC)

500

400

300

200

100

0

TEMPERATURE (°F)

RESISTANCE ($R \times 10^{-3}$)

0

1

2

3

4

5

6

179-A

A-65

COPPER
TEST SECTION ADIABATIC
TEMPERATURE AS A FUNCTION
OF INTEGRATED ENERGY INPUT

A-102

$R \times 10^3 (\Omega)$

A-103

SECTION II - ROSENTHAL-MILLER EQUATIONS

Equation 6

$$T = \frac{(q/A)_{G,0}}{\sqrt{K\rho C_p}(1-B^2/A)} \left[\sqrt{p} e^{t/p} \operatorname{erf} \sqrt{t/p} - B e^{t/p} + B e^{t/B^2} \operatorname{erfc} \sqrt{t/B^2} \right]$$

Equation 7

Simplified Equation 6, assuming $B=0$

$$T = \frac{\sqrt{p} (q/A)_{G,0}}{\sqrt{K\rho C_p}} e^{t/p} \operatorname{erf} \sqrt{t/p}$$

$(q/A)_{G,0}$ is the initial heat generation rate at time $t = 0$
 $T =$ the temperature elevation of the metal surface above the surrounding coolant as a function of time

SECTION III - INTEGRATION OF CIRCUIT EQUATION

The usual integration for the circuit equation on page 3 assumes constant total resistance (R_T) and thus yields:

$$i = \frac{V_G}{R_T} (1 - \exp[-R_T/L])$$

However, in the present case the major portion of R_T consists of the "load", i.e. the test sample resistance, which is changing as a function of temperature and hence time. Consequently integration of the differential equation cannot be carried out as above. An energy balance, viz.

$$\frac{dE}{dt} = i^2 R = M c_p \frac{dT}{dt}$$

can also be written. If we express R , resistance of the sample, as

$$R = R_0 (1 + aT + bT^2 + \dots)$$

two simultaneous non-linear differential equations are obtained:

$$(1) \quad V_G = R_0 (1 + aT + bT^2) i + L \frac{di}{dt} + R_E i$$

$$(2) \quad M c_p \frac{dT}{dt} = [R_0 (1 + aT + bT^2)] i^2$$

where R_E = the "excess" resistance, i.e. that of the generator windings and external circuit (all resistance except that of the sample). They can be solved by difference methods, assuming V_G is constant (obtained as open-circuit voltage of the generator), R_E is known, and L is obtained as on page 4. Such calculations are tedious, and were not carried out because of time limitations. The results would of course be true only for adiabatic heating, and would be somewhat more involved if corrections for heat transfer to the water are included.

SECTION IV - TABLE OF NOMENCLATURE

B - equal to $\frac{H}{\sqrt{K\rho C_p}}$

C_p - specific heat of coolant or metal, $\frac{\text{Btu}}{\text{lb}^\circ\text{F}}$ or $\frac{\text{Cal}}{\text{gm}^\circ\text{C}}$

E - integrated energy, gm. cal.

e - base of natural logarithms

H - heat capacity of sample per unit surface area, $\frac{\text{Btu}}{\text{ft}^2^\circ\text{F}}$

I, i - electric current, amps.

K, k - thermal conductivity of coolant, $\frac{\text{Btu}}{\text{hr ft}^2 \frac{^\circ\text{F}}{\text{ft}}}$

L - total circuit inductance, henries

P - heat generation rate, $\frac{\text{Btu}}{\text{hr}}$ or $\frac{\text{gm. cal.}}{\text{millisecond}}$

P_0 - initial heat generation rate, $\frac{\text{Btu}}{\text{hr}}$ or $\frac{\text{gm. cal.}}{\text{millisecond}}$

p - period, milliseconds or hours

R - test section resistance, ohms or milliohms

R_0 - initial or base test section resistance, ohms or milliohms

T - temperature, $^\circ\text{F}$ or $^\circ\text{C}$

t - time, milliseconds (msecs) or seconds

V - electrical potential, volts

V_G - generator potential, volts

erf(y) - error function of y

erfc(y) = [1.0 - erf(y)]

ρ - density of coolant, $\frac{\text{lb}}{\text{ft}^3}$

$\left(\frac{q}{A}\right)_{G,t}$ - heat generation rate per unit surface area at time t, $\frac{\text{Btu}}{\text{hr ft}^2}$

$\frac{Q}{A}$ - heat flux, $\frac{\text{Btu}}{\text{hr ft}^2}$