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RESULTS OF RECENT ANALYSES OF BORAX II
TRANSIENT EXPERIMENTS

by

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RESULTS OF RECENT ANALYSES OF BORAX II TRANSIENT EXPERIMENTS

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Heat transfer information relating to the shut-down mechanism of the Borax II reactor is discussed. Pertinent quantities are presented as a function of time for a typical power transient. A proportionality is established between the transient steam pressure pulse and $-\dot{k}_{ex}$. The heat transfer from fuel plate to water is divided into conduction and boiling phases. Conduction and boiling are shown to exhibit equilibrium behavior except during the transient steam pressure pulse. Because of the incompleteness of the data a definitive description of the phenomena during this pulse is not possible.

INTRODUCTION

Ten Borax II power excursions have been analyzed using the oscillograph records. Starting with reactor power and surface temperature of a representative central fuel plate, and in some cases water channel pressure, all as a function of time, k_{ex} , $\dot{k}_{ex}$, k_{ex} and heat flux were calculated as a function of time. In Table I the power excursions are listed. Nomenclature is defined in Appendix A.

These transients were produced in Reactor II.^a

^aJ. R. Dietrich, "Experimental Determinations of the Self-Regulation and Safety of Operating Water-Moderated Reactors," Paper 481, International Conference on Peacetime Uses of Atomic Energy, Geneva, Switzerland (August, 1955)

Table I

POWER RUNS ANALYZED

<u>Water Conditions</u>	<u>Run Number</u>	<u>P_i(psig)</u>	<u>T_i(°F)</u>	<u>τ(sec)</u>
Atmospheric subcooled	#6 11-5-54	0	79	0.072
	#7 11-10-54	0	80	0.043
	#7 11-5-54	0	80	0.033
Atmospheric saturated	#2 11-10-54	0	203	0.189
	#3 11-11-54	0	202	0.097
	#1 11-5-54	0	201	0.066
	#3 11-10-54	0	196	0.033
300 psig saturated	#3 11-18-54	300	417	0.360
	#4 11-18-54	300	417	0.081
	#6 11-18-54	300	420	0.030

The heat flux into the water from the surface of a centrally located fuel plate was calculated by an energy balance method by subtracting the power absorbed in the plate from the power produced in the plate to give the power absorbed in the water. Details are given in Appendix B.

In Figure 1 there is reproduced the Heiland Oscillograph record of a typical power excursion, Run #7 11-5-54. The appropriate traces are labeled. The quantities of major interest in the shutdown process are shown in Figure 2 for the same run. The power fuel plate, surface temperature rise and heat flux into the water, all for a location near the center of the core, are plotted against time. Also included is a plot of k_{ex} against time. In this figure there may be seen the rapid rise in the heat flux from the surface of the fuel plate associated with boiling. It is seen that there is a lag in the decrease of k_{ex} as a result of steam formation; this constitutes the major delay of the system and is due to the inertia of the water.

 k_{ex} , $\dot{k}_{ex}$, $\ddot{k}_{ex}$ AND P AS A FUNCTION OF TIME

At the suggestion of J. R. Dietrich, a method was worked out by H. J. Wheeler^b for AVIDAC calculation of k_{ex} as a function of time.

^bReactor Engineering Division Quarterly Report, Section II. July, August, September, 1955.
ANL-5511 (January 1956) p. 160

FIGURE I

OSCILLOGRAPH TRACE FOR REPRESENTATIVE RUN

$T_i = 80\text{ }^\circ\text{F}$ $T_{i\text{ sat}} = 203\text{ }^\circ\text{F}$

$P_i = 0\text{ psig}$ $\tau = .033\text{ sec}$

Trace Number:

1 - Log of Reactor Power

2 - Fuel Plate Surface Temperature

3 - Pressure Transducer Trace

Run #7 11-5-54

FIGURE 2
POWER, PLATE TEMPERATURE, HEAT FLUX, k_{ex} FOR REPRESENTATIVE RUN

This was later extended to give $\dot{k}_{ex}$ and $\ddot{k}_{ex}$ as a function of time in the hope that a correspondence could be found between $\ddot{k}_{ex}$ and the transient gauge pressure generated by the steam. Figure 3 shows k_{ex} , $\dot{k}_{ex}$, $\ddot{k}_{ex}$ and P for the subcooled run of Figure 1. Since during the shutdown process the change in k_{ex} introduced is almost proportional to steam volume, it seems reasonable to say that $-\ddot{k}_{ex}$ should be proportional to steam pressure. The superposition of pressure and $-\ddot{k}_{ex}$ results from a normalization proportionality constant of -4.05 units $\ddot{k}_{ex}/\text{psig}$. The only other trace available from a subcooled run gives a constant of -2.89 units $\ddot{k}_{ex}/\text{psig}$. This normalization is shown in Figure 4. The average of these was -3.5 units $\ddot{k}_{ex}/\text{psig}$. Consequently, for the initial pressure pulse of all runs, -3.5 units $\ddot{k}_{ex}/\text{psig}$ was used to give pressure when only $-\ddot{k}_{ex}$ is available.

Limitations affecting accuracy of the transient pressure measurements are discussed in Appendix C. It is estimated that the transient pressure data are good only to a factor of 2 or 3 and are probably too high.

THE CONDUCTION PHASE AND THE INITIATION OF BOILING FOR SUBCOOLED RUNS

Figure 5 shows heat flux plotted against the surface temperature rise from the initial temperature, ΔT_i , for two subcooled runs. In the first portion of the curves, (a), with slope 1, the heat transfer is by conduction. Convection does not have time to occur. The exponentially increased quantity of heat energy is stored in the plate and the water in a proportion which is constant in time and depends on τ for the excursion.^c

After the plate temperature has risen above saturation to a sufficient extent the heat transfer becomes predominantly boiling heat transfer, (b), with corresponding increase in slope. A transition point could be defined for reference as the intersection of the conduction curve and the boiling curve. The temperature rise is then terminated by reactor shutdown.

Actually, for heat transfer rates higher than $1.5 \times 10^6 \text{ BTU/hr ft}^2$ in these two runs, T_{sat} is changed by transient steam pressure, which occurs only after the initiation of boiling. But since this section is primarily concerned with conduction and the initiation of boiling, discussion of changes in T_{sat} will be deferred to a later section.

^cReactor Handbook, Vol. II, Chapter 1.8, p. 141.

FIGURE 3
 $k_{ex}, \dot{k}_{ex}, \ddot{k}_{ex}, P$ FOR REPRESENTATIVE RUN

FIGURE 5
SUBCOOLED RUNS
Q/A VS ΔT_i

As the plate temperature falls, a conduction heat flux cannot be re-established at the previous high level, because the heat already transferred to the water does not allow such steep temperature gradients as existed before. Thus heat transfer by boiling is and remains predominant, and a boiling heat transfer curve, (c), is traced out.

It can be seen in Figure 5 that the conduction curves are different for the different periods. The points of transition from conduction to boiling are different, but the boiling heat transfer curves are the same. This is true even though one curve is traversed much faster than the other.

THE CONDUCTION PHASE AND THE INITIATION OF BOILING FOR A RUN WITH SMALL SUBCOOLING

A similar plot is shown in Figure 6 for an excursion only 7°F subcooled. Here saturation temperature is reached at such low values of ΔT_i that the data are inaccurate; accordingly a calculated conduction curve for this T is drawn in for reference. Nevertheless, the data are sufficiently accurate to show that the conduction phase exists after the plate has passed saturation temperature. As in the subcooled runs there is a transition point which is roughly at the intersection of the conduction and boiling curves and which in this case is about 50°F above saturation temperature. A look at the transient pressure for this run reveals that not until the temperature is 60°F above initial saturation temperature is the pressure high enough to raise the boiling point by 1°F . Even though the pressure is not known very accurately this is enough to show that the conduction phase is not maintained by an increase in saturation temperature, after initial saturation temperature is reached.

HOW MUCH SUPERHEAT IS REQUIRED BEFORE BOILING BEGINS?

It may be said for all ten runs that, below the transition point but above the boiling point, any boiling heat transfer which takes place is small compared to conduction heat transfer. This gives an answer to the frequently asked question: "When does boiling begin?" The answer for the conditions prevailing in these runs is, even for saturated initial conditions, significant boiling begins when the surface temperature reaches the temperature corresponding to the intersection between the conduction curve and the boiling curve. In Appendix D the effect of errors in measurement and method are discussed in relation to the above conclusions.

FIGURE 6
SLIGHTLY SUBCOOLED RUN
Q/A vs ΔT_i

HEAT FLUX BEHAVIOR AFTER THE TRANSIENT PRESSURE PULSE

Up to this point we have been concerned with the conduction heat transfer phase and the initiation of boiling, so the role of the transient pressure in changing the saturation temperature during the progress of the excursion has not been important. In making the customary plot of heat flux vs ΔT_{sat} the effects of transient pressure are brought into focus.

First, however, the heat flux data points which are taken after the pressure pulse has subsided can be plotted as a function of $\Delta T_{i,\text{sat}}$, which equals ΔT_{sat} , leaving out the data points during the pressure pulse. Saturation temperature after the pressure pulse is assumed to correspond to initial pressure (see Appendix C). This appears in Figure 7 for saturated runs, in Figure 8 for subcooled runs, and in Figure 9 for runs pressurized at 300 psig. At 300 psig the pressure pulse is so small that the change in saturation temperature at the peak of the pulse is less than 2°F , so all data points which occurred after the transition point had been passed are plotted.

The data curves of Figures 7, 8 and 9 are very similar in shape and magnitude to saturated and subcooled boiling curves for steady state conditions. For reference each figure has drawn on it a line of slope 3 which is obtained by passing a line through the atmospheric saturated data. This will be called the atmospheric characteristic, saturated, or ACSAT. Other lines, PCSAT and ACSUB, are constructed in a similar way. The shift to higher heat flux of the pressurized characteristic, saturated, PCSAT, in Figure 9 at 300 psig is normal. A shift to higher heat flux for the subcooled atmospheric data is normal if a significant fraction of the heat transfer is by forced convection of subcooled water.^d Data for boiling heat transfer to subcooled water by forced convection can be correlated in the following way. The component of heat flux due to forced convection assuming there had been no boiling is subtracted from the total heat flux. The boiling component, which is left, can then be correlated with saturated boiling data. In these three subcooled excursions the bulk water is still somewhat subcooled at the end of the excursion. Presumably the motion of this water being forced from the core could explain the increased heat transfer above the saturated case. The line through the atmospheric subcooled data is labeled ACSUB.

^dWarren M. Rohsenow "Heat Transfer with Evaporation," Heat Transfer Symposium, University of Michigan (1952) pp. 133-138.

FIGURE 7
SATURATED DATA AFTER THE PRESSURE PULSE
Q/A VS $\Delta T_{i,sat}$

FIGURE 8
SUBCOOLED DATA AFTER THE PRESSURE PULSE
 $Q/A = \Delta T_{i,sat}$

FIGURE 9
PRESSURIZED RUNS Q/A vs $\Delta T_{i,sat}$

CONCLUSIONS ABOUT HEAT FLUX BEHAVIOR AFTER THE TRANSIENT PRESSURE PULSE

The fact that these points define curves reasonably well despite the fact that the curves are traversed at considerably different speeds in the different runs means that any transient component in the heat transfer must be small. One is led to believe that if the same quantities were measured for the same surface under steady state conditions the same curves that appear in Figures 7, 8 and 9 would be obtained.

The data of Figure 9 also provide a clue as to why pressurized excursions are less violent. It can be seen that a given heat flux occurs at lower T_{sat} . This means the transition point is reached and boiling occurs sooner, so that dT_{surf}/dt is smaller.

HEAT FLUX BEHAVIOR DURING AND AFTER THE TRANSIENT PRESSURE PULSE

If all data points which are taken after the beginning of the transient pressure are shown on a Q/A vs. ΔT_{sat} plot, the effect of changes in saturation temperature can be observed. Data for saturated runs appear in Figure 10 and for subcooled runs in Figure 11. Data points before transient pressure are left out to avoid the transition region between the conduction phase and boiling as much as possible. ACSAT and ACSUB lines are included for reference to show what the relationship between Q/A and ΔT_{sat} would have been had the pressure remained 0 psig. Data points during the transient pressure pulse are connected by lines with an arrow to indicate the chronological order. Pressures in psig are given for each data point for pressures greater than 1 psig.

Consider the saturated runs in Figure 10. Another way of stating the conclusion of the last section is to say that the ACSAT and PCSAT lines would give the relationship between Q/A and ΔT_{sat} for this aluminum surface in measurements at equilibrium pressure of 0 psig and 300 psig, respectively. The PCSAT and the ACSAT lines are two of a family of lines of constant pressure existing for all equilibrium pressures, with increasing pressure associated with decreasing ΔT_{sat} for constant heat flux.^e It can be seen in Figure 10 that during each run a loop is executed which should cross the family of constant pressure lines. (One of the lines, based on the transient pressures, however, is sketched in for 9 psig.) By comparing the

^eData of Addoms for pool boiling on a 0.024-inch diameter wire of platinum. Ref. d, p. 125.

FIGURE 10
SATURATED DATA DURING AND AFTER PRESSURE PULSE
Q/A vs ΔT_{sat}

FIGURE II
SUBCOOLED DATA DURING AND AFTER PRESSURE PULSE
Q/A vs ΔT_{sat}

lines for transient pressure changes with the ACSAT and PCSAT lines for equilibrium pressure changes shown in Figure 9 it can be seen that the constant pressure lines in the transient case are more widely spaced.

If changes in ΔT_{sat} , when caused by changes in T_{surf} , affect the heat flux with no observable delay, which they do in these excursions, then it seems reasonable to assume that changes in ΔT_{sat} caused by changes in T_{sat} should also affect the heat flux with no observable delay. This assumption means that heat transfer during transient pressure should be equilibrium in nature and that the family of lines of constant pressure based on equilibrium pressure saturated data should coincide with those based on transient pressure saturated data.

The ACSAT and PCSAT lines do represent equilibrium pressure saturated data, but heat flux data during the pressure pulses in Figure 10 are not transient pressure saturated data due to the increase in saturation temperature. They are transient pressure subcooled data for water which is being accelerated. The concept previously applied to boiling heat transfer into subcooled water with forced convection has at least some reality here. When the transient pressure pulse occurs, the water suddenly finds itself subcooled and being accelerated. As the pressure is relieved the subcooling is reduced, but meanwhile the velocity has been increased. After the pressure pulse the velocity is considerable but the subcooling is zero, so during the pressure pulse a component of heat flux due to forced convection of subcooled water is to be expected in addition to the saturated boiling component of heat flux. It is this saturated boiling component of the transient heat flux which is to be used on a plot of Q/A vs. ΔT_{sat} for comparison with equilibrium pressure saturated data. This comparison would tell whether the heat transfer which takes place during the pressure pulse were equilibrium in nature or not.

Unfortunately not enough information is at hand to make this comparison. But the following two assumptions would cause the data to approximately satisfy the conditions for equilibrium heat transfer during the transient pressure pulse. First, assume that the transient pressures for all runs are too high by a factor of about 2. This is within the range of accuracy of the measurements. Secondly, assume that the saturated boiling component of heat flux is smaller than the total heat flux by a factor of 2 or 3. Then the data points during the pressure pulse are moved very close to the ACSAT line. This is the location to be expected if the transient pressure saturated heat transfer is equilibrium in nature.

On the other hand, if transient pressure is simply assumed to have no effect and heat flux is plotted against $\Delta T_{i, \text{sat}}$, a surprisingly well-defined curve is obtained. For the saturated runs in Figure 12 the line through the data points has a slope 3.43, while ACSAT has a slope 3. For the subcooled runs in Figure 13 the line coincides exactly with ACSUB.

In conclusion, because of the limited scope of the data, an adequate description of heat flux behavior during the transient pressure pulse is not possible.

Appendix E discusses the effect of errors in the method on the above conclusions.

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FIGURE 12
SATURATED RUNS $Q/A = \Delta T_{i,sat}$

FIGURE 13
SUBCOOLED RUNS Q/A vs $\Delta T_{i,sat}$

APPENDIX A
NOMENCLATURE

<u>Symbol</u>	<u>Units</u>	<u>Quantity</u>
k_{ex}		Excess k
$\dot{k}_{ex}$	sec^{-1}	$\frac{dk_{ex}}{dt}$
$\ddot{k}_{ex}$	sec^{-2}	$\frac{d^2 k_{ex}}{dt^2}$
P_i	psig	Initial gauge pressure in the reactor before the excursion.
P	psig	Gauge pressure in the center of a centrally located coolant channel.
τ	sec	Reactor period in the excursion before shutdown process starts.
Δt	sec	Time interval between data points.
$\frac{Q}{A}$	$\frac{\text{BTU}}{\text{hr ft}^2}$	Heat flux from a centrally located fuel plate surface into the water.
T_i	$^{\circ}\text{F}$	Initial temperature of entire reactor before excursion.
T_{sat}	$^{\circ}\text{F}$	Saturation temperature of the water.
$T_{i,sat}$	$^{\circ}\text{F}$	Initial saturation temperature of the water.
T_{surf}	$^{\circ}\text{F}$	Surface temperature of centrally located fuel plate.
ΔT_{sat}	$^{\circ}\text{F}$	$T_{surf} - T_{sat}$
ΔT_i	$^{\circ}\text{F}$	$T_{surf} - T_i$
$\Delta T_{i,sat}$	$^{\circ}\text{F}$	$T_{surf} - T_{i,sat}$

NOMENCLATURE (Cont'd.)

<u>Symbol</u>	<u>Units</u>	<u>Quantity</u>
ACSAT		Atmospheric saturated characteristic curve for boiling heat transfer.
ACSUB		Atmospheric subcooled characteristic.
PCSAT		Pressurized saturated characteristic.

APPENDIX B

For these ten runs, the thermocouple readings were the primary source of power calibration for each run. The thermocouple readings were corrected for the lag in response of the thermocouple galvanometers, whose natural frequency (100 cps) and damping were known. The thermocouple lag was much smaller than the galvanometer lag. On the basis of heat conduction theory for the fuel plate geometry and from experiments with insulated and uninsulated fuel plates, a ratio of surface temperature for the bare fuel plate in water to the average temperature of an ideal, perfectly insulated plate was determined to be 0.80 during an exponential rise in temperature for the average period of these runs. The ion chamber readings for these runs were calibrated by requiring that this ratio be maintained during the time when both temperature and power rose exponentially. An indication of the accuracy of the use of thermocouple readings for each run as primary standard is obtained by comparing peak powers for this group of runs by this method to one using foil activation during the same runs as primary standard. For these runs the average ratio of peak power by foil to peak power by thermocouple is 0.96 and the root mean square deviation in the ratio is 0.36.

The energy stored in the plate was calculated from heat capacity and T_{surf} as the average plate temperature. Since the average temperature is higher than surface temperature, an error is introduced which is discussed later.

APPENDIX C

TRANSIENT PRESSURE MEASUREMENT ACCURACY

Based on scatter of the transient pressure data it is estimated that the measurements are accurate to about a factor of 2 or 3. Since the transducer hydrodynamic system was underdamped, all of the pressures recorded were probably too high, by as much as a factor of 2. The estimated natural frequency of the pressure transducer before the run was more than 50 cps. The galvanometer which recorded pressure had a natural frequency of greater than 100 cps. The pressure traces are more useful as an indication of relative amplitude than of absolute amplitude.

The given variation of the proportionality of pressure and $-\ddot{k}_{ex}$ indicates the accuracy. The proportionality is dependent on the local void coefficient which varies with position in the reactor and therefore varies with τ .

The coincidence of $-\ddot{k}_{ex}$ and the initial pressure pulse for the subcooled runs is striking, but for all saturated runs the measured pressure pulse lags behind $-\ddot{k}_{ex}$. This lag probably results from gas pockets in the water-filled probe or the sensing chamber of the pressure transducer. It is very difficult to avoid bubbles when the transducer is filled with boiled water at room temperature and used in saturated water.

The correspondence between $-\ddot{k}_{ex}$ and pressure ends after the first positive pressure pulse. The moderator is being acted on by elastic forces in the core structure. Possibly these forces cause a large negative peak in $-\ddot{k}_{ex}$ when the steam pressure falls and the core returns to its original shape, but the peak cannot be attributed to negative steam pressure. Also, reactor power is measured by an ion chamber outside the core. It is assumed that the neutron leakage, which the ion chamber senses, is proportional to the core power. However, the relative leakage increases with an increase in the steam content of the core. Since no allowance was made for this, the values of power, k_{ex} , $\dot{k}_{ex}$ and $\ddot{k}_{ex}$ are less reliable for increased steam content in the core.

The transient response of the transducer system becomes slower after the first peak. This may be due to gas coming out of solution during low pressure or to actual boiling in the transducer probe, either of which would cause a change in the response of the system. For lack of better information, the pressure was assumed to return to its initial value after the first pulse.

APPENDIX D

THE EFFECT OF ERRORS ON CONCLUSIONS REGARDING CONDUCTION AND INITIATION OF BOILING

To what extent do the errors in the data affect the conclusions? For small temperature rise, the per cent error in temperature reading was great and a corresponding scatter can be seen in the heat flux values. But the smallest transition temperature rise for an atmospheric pressure run is about 30°F. It is adequately defined. The transition temperatures for the pressurized runs vary from 3 to 10°F; in addition the thermocouple signals included a large a-c pickup which had to be subtracted out. The result is that temperature data for pressurized excursions have a great deal of scatter, but these do not contradict the interpretation of the behavior based on atmospheric pressure runs.

The heat flux was calculated by subtracting the power appearing as stored heat in the plate from the fission power produced in the plate, using the surface temperature as the average plate temperature. In Figure 14 the data for Run #7, 11-5-54, which appears in Figure 1, are replotted as circles. The triangles represent the same data when an approximation of the temperature at the boundary between clad and fuel was used as the average temperature. Also shown is the conduction curve calculated from the surface temperature. For the three sub-cooled runs taken together the deviation of the triangles from the calculated conduction averages to about zero with an average deviation of about 20%. Run #7, 11-5-54 gave the largest deviation. These corrections in the curves, although not negligible, do not require a reinterpretation of the data.

FIGURE 14

SUBCOOLED RUN WITH CORRECTION, Q/A VS ΔT_i

#7 11-5-54
 $P_i = 0$ psig

$T_i = 80$ °F
 $\tau = .033$ sec.

APPENDIX E

EFFECT OF ERRORS ON CONCLUSIONS REGARDING HEAT FLUX BEHAVIOR DURING AND AFTER THE PRESSURE PULSE

Much of the discussion of Appendix D applies here. In Figure 15 the triangles and crosses are the values of the heat flux obtained when an approximation of the temperature of the fuel clad interface was used as the average temperature. The triangles are plotted against $T_{i, sat}$; the crosses are the same heat fluxes plotted against T_{sat} . The ACSAT line at 0 psig and the 9-psig line from Figure 10 are included for reference. Comparison of this run with the same one in Figure 10 and in Figure 12 shows that the curve is not changed substantially by the correction insofar as the conclusions of this paper are concerned.

FIGURE 15
SLIGHTLY SUBCOOLED RUN WITH CORRECTION
Q/A vs ΔT