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EFFECTS OF FUEL ELEMENT HEAT CAPACITY ON REACTOR OUTLET TEMPERATURES FOLLOWING FLOW REDUCTION OR POWER SURGES

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EFFECTS OF FUEL ELEMENT HEAT CAPACITY
ON REACTOR OUTLET TEMPERATURES FOLLOWING
FLOW REDUCTION OR POWER SURGES

By G. M. Hesson and R. W. Moulton

September 15, 1959

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EFFECTS OF FUEL ELEMENT HEAT CAPACITY
ON REACTOR OUTLET TEMPERATURES FOLLOWING
FLOW REDUCTION OR POWER SURGES

Purpose

The purpose of this report is to present a semi-quantitative discussion of the effect of the heat capacity of the process tube assembly on the outlet water temperature following a mild inadequate cooling incident involving an entire reactor.

Introduction

One of the factors limiting reactor power levels is the strength of the effluent piping. Present downcomers have bursting strengths approximating 2 to 4 psig. This corresponds to a saturation pressure of water only slightly above 100°C. Reactor power levels are limited to maintain bulk outlet water temperatures below this point. The present limits are several degrees below 100°C to allow for temperature surges which could occur as a result of periods of inadequate cooling.

Inadequate cooling incidents such as BPA outages, pump failures, power surges, etc., are infrequent but they do occur. In general such an incident would initiate an immediate reactor shutdown. However, there is a finite period of time after the start of the incident before the start of the power reduction becomes effective. During this period of time the bulk outlet water temperature increases above normal and the reactor power limits based on the bulk outlet water temperature must allow for this effect.

One factor which tends to suppress these temperature surges is the heat capacity of the system. This report presents some laboratory data bearing on this topic and discusses in a semi-quantitative manner the heat capacity effect. No attempt is made to examine all reactor events in detail but rather to suggest an order of magnitude for the effect of heat capacity. An integration of the heat capacity effect into the bulk outlet water temperature limits should involve more detailed calculations.

Summary and Conclusions

The heat capacity of a process tube and its contents may be considered as a single lumped heat capacity. Results for laboratory experiments with metals other than uranium indicate that this effective lumped heat capacity would be approximately 75 per cent of the heat capacity of the uranium in the fuel.

Calculations using this effective lumped heat capacity show that following a ramp change in cooling conditions such as would result from flow decay following a BPA outage, the outlet water temperature increase from an individual tube would reach about 54 per cent of the steady state value in two seconds, and about 66 per cent of the steady state value in three seconds. Following a step change in cooling conditions, such as could result from a power surge, the outlet water temperature increase from an individual process tube would reach about 85 per cent of the steady state value in two seconds and 94 per cent of the steady state value in three seconds. These temperature peaks do not persist for any significant period of time.

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When the effect of heat capacity on outlet water temperatures is combined with the effects of mixing in the rear piping* it is concluded that the increase in water temperature following a rapid flow decrease or power surge would be quite small. A calculation of the exact increase, however, is subject to considerable uncertainties which can best be evaluated from actual reactor tests such as programmed in HW-60864 RD.**

Discussion

Production reactors may be subjected to short periods of operation where the amount of cooling provided is less than that required for normal operation. Examples of incidents which could cause inadequate cooling situations are electric power failure and/or reactor power surges. Each of these incidents should result in an immediate scram. However, there is a significant time lag between the initiation of the scram and the first reduction in power level. This time lag approximates two seconds for the "K" reactors and three seconds for the "C" and "O" reactors. The reason for this lag is the time required for the insertion of the VSR's combined with the associated nuclear characteristics of the reactor.

During the time interval before effective power reduction occurs the bulk outlet water temperature will rise. The amount and duration of this rise is of extreme importance in establishing normal bulk outlet water temperature limits. While incidents of this type are not frequent they do occur and must be considered in establishing reactor operating conditions. The bulk outlet water temperature limits are set by the fact that the present downcomers cannot be pressurized much above about 2 psig. The allowable bulk outlet water temperature must, therefore, be maintained below 100°C by an amount that will be adequate to accommodate any surges that occur. Every added degree in allowable bulk outlet water temperature is of considerable value in terms of increased reactor power level. These two factors dictate the best choice of operating conditions.

Flow Loss

A power or pump failure will result in an immediate but gradual flow decay. During the time interval before the scram becomes effective the water temperature will rise. This rise in water temperature is very significantly affected in the first few seconds of the transient by the heat capacity of the system.

This problem is quite complex if it is examined accurately and in detail. One approach to the problem is to use an equivalent lumped heat capacity for the process tube, fittings, and contents. The calculated value for this heat capacity must be corrected by a factor which will incorporate some of the peculiarities of the transient (i. e., the complete assembly does not see the whole temperature change).

Transient runs have been made in the laboratory utilizing an electrically heated prototype heater rod. Data from these runs is presented in Figure No. 1. In order to correct for various differing flow rates, these same data were replotted in Figure No. 2 against the flow-time product. A discussion of the experiments is presented in Appendix I. Reasonable correlation at least in the first few seconds of the transient is evident.

* Results of calculations on mixing in the rear piping are given in HW-51327, "Preliminary Analysis of Bulk Outlet Water Temperatures", S. S. Jones, p. 6.

** HW-60864 RD, "DR Reactor Bulk Temperature Program", S. S. Jones.

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The slope of the curve in Figure No. 2 is a direct function of the equivalent heat capacity of the system. For the data presented here, the measured value of the slope showed an equivalent heat of 10.5 pounds of water.

The dimensions of the heater rod and the known specific heat values for the materials of construction allow one to compute a theoretical heat capacity. This value as calculated is 14.0 pounds of water equivalent. It would be expected that the apparent heat capacity would be less than the actual heat capacity.

The ratio of apparent heat capacity to calculated heat capacity (10.5 : 14.0) was used to predict the effective heat capacity of a reactor process tube and contents. In making this computation the jackets, end caps, and process tubes were not included so the calculated result should be conservative. The calculated heat capacity for the tube assembly for the "O" reactors is 8.5 pounds of water equivalent and the resulting apparent heat capacity is 6.4 pounds of water equivalent.

The apparent heat capacity noted above (6.4 pounds of water equivalent) was used as a basis for the prediction of temperature transients following incidents. A sample calculation is presented in Appendix II. An algebraic integration of the differential equation for a ramp change of flow was not available. The integration for this case was done graphically. It is believed that all the results obtained by these calculation techniques are conservative and that the actual temperature rise will be less than the predicted values.

The results of the calculations for flow loss are presented in Figure No. 3. These data indicate that a scram delay of two seconds will result in a water temperature rise of 3°C. This represents only about 54 per cent of the equilibrium temperature rise for this time interval. If the scram becomes effective in two seconds, the temperature then rapidly drops and at two and one-half seconds it would be lower than before the transient started. The maximum temperature would persist for only a very short time interval.

A three second scram delay imposes a more serious upset on the system. As shown in Figure No. 3, the temperature rise will approximate 6°C, about 66 per cent of the equilibrium temperature rise. Again within about one-half second after the scram becomes effective, the temperature will drop to a value equal to or less than the pre-transient condition.

Power Surge

A power surge can result in a more severe temperature upset than a flow decrease. This is true because the change can occur more rapidly and to a greater degree, than for a flow loss upset before the scram becomes effective. It has been assumed that a power surge of ten per cent occurs instantaneously. The results of these calculations are presented in Figure No. 4.

A scram delay of two seconds results in a water temperature rise of about 7°C which is approximately 85 per cent of the equilibrium rise corresponding to the power surge. One-half second after the scram becomes effective the water temperature will have dropped to pre-upset levels.

If the scram delay is three seconds instead of two seconds, the water temperature will approach more closely to the equilibrium temperature. A rise of about 8°C (94 per cent of the equilibrium value) will be realized. Again, one-half second after the scram becomes effective pre-transient water temperatures will be reached.

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Mixing

Mixing of the water outlet streams from the reactor will result in lower maximum temperature rises after incidents than would otherwise be the case.*** Mixing occurs in three places; first, the rear header; second, the vertical riser; and third, between risers. Because of different time lags required for the various outlet streams to reach a prescribed point in the system, the mixing effect can be great on the predicted temperature rise. This is true because of the short time interval that a particular outlet water stream remains at its maximum temperature level.

The mixing effectiveness can be poor or good. All mixing is beneficial and the three types of mixing noted above are additive. A reasonable and conservative estimate of the mixing effect is that it can reduce the temperature rise by fifty per cent. The heat capacity effect and the mixing effect tend, therefore, to both act together in reducing the actual temperature rise.

Combined Effects

With mixing of the outlet streams (calculated on a conservative basis), the temperature rise on flow loss would be $1\frac{1}{2}^{\circ}\text{C}$ at a two second scram delay and 3°C for a three second scram delay. The temperature rise for a 10 per cent power surge (instantaneous), when the effect of mixing is included, would be about 3°C for a two second scram delay and about $3\frac{1}{2}^{\circ}\text{C}$ for a three second scram delay. This would indicate that operation of the reactor within these approaches to 100°C would not result in pressurization of the reactor downcomer.

These calculations are not intended to cover every reactor incident that could occur. They are intended instead to point out the magnitude of the heat capacity effect to present results which would be typical for some reactor incidents. It is recommended that more detailed calculations be performed before the heat capacity effect is incorporated into the bulk outlet water temperature limits.

G. M. Hesson

G. M. Hesson, Engineer
Thermal Hydraulics Operation

R. W. Moulton / by H. M. H.

R. W. Moulton, Engineer
Thermal Hydraulics Operation

*** HW-51327, "Preliminary Analysis of Bulk Outlet Water Temperatures", S. S. Jones, p. 6.

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FIG. 2

Experimental Transient Outlet Water Behavior

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FIG. 1

Experimental Transient Outlet Water Temperatures

FIGURE 3

Assumptions:

1. Flow initially 6 lbs/sec
2. Water initially heated from 68°F to 212°F
3. Flow had 3.3 gals/sec
4. No mixing

TEMPERATURE TRANSIENTS FOLLOWING FLOW LOSS

FIGURE 4

TEMPERATURE TRANSIENTS FOLLOWING POWER SURGE

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APPENDIX I

EXPERIMENTAL DETERMINATION OF LUMPED HEAT CAPACITY

Problem: The problem is (1) to determine if assigning a single lumped effective heat capacity to a process tube and its contents is a reasonably valid approximation in determining transient outlet water temperature from the tube, and (2) if the approximation is valid, what is the relation between the effective and the true heat capacity.

Solution: If the process tube and its contents can be assigned a lumped heat capacity, the following diagram describes the system:

where

Q = heat input in BTU/sec

F = flow, lb/sec

T = temperature above reference temperature, $^{\circ}\text{C}$

M = effective heat capacity, BTU/ $^{\circ}\text{C}$

Applying a heat balance to this system

Input - Output = Accumulation

$$Q d\theta - F T d\theta = M \frac{dT}{d\theta} d\theta$$

or

$$\frac{dT}{d\theta} + \frac{FT}{M} = \frac{Q}{M}$$

This can be integrated to

$$\frac{T_f - T}{T_f - T_1} = e^{-\left(\frac{F'}{M} \theta\right)}$$

where

T_f = final temperature, $^{\circ}\text{C}$

T_1 = initial temperature, $^{\circ}\text{C}$

θ = time, seconds

F' = heat flow (flow x heat capacity) $\frac{\text{BTU}}{\text{sec-}^{\circ}\text{C}}$

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To experimentally determine the relation between an effective and actual heat capacity, several step changes in flow were imposed on an electrically heated mockup of a Hanford reactor process tube. The step changes were of such size as to cause a change in outlet water temperature of 10 to 20°C, were such that both increases and decreases in flow were incurred, and were such that flows after the step change were from 29 to 55 gpm.

If the assumption that there exists an effective heat capacity which can describe the course of transient water temperature behavior, then plots of the temperature parameter $T_F - T/T_F - T_i$ against θ should be straight lines of slope $-F'/M$. Such plots of the experimental data are shown in figure 1. These plots indicate that over the first few seconds the assumption of a lumped effective heat capacity is reasonable.

Furthermore, if the assumption is valid, plots of the parameter $T_F - T/T_F - T_i$ against $F'\theta$ should yield straight lines for all flows with a slope of $-1/M$. Such a plot of the experimental data is shown in figure 2. The negative of the reciprocal of the slope is then M , the value of the effective heat capacity. This turns out in this case to be 10.5 BTU/°C, or the equivalent of 10.5 pounds of water. The actual heat capacity of the heater rod used in the experimental tests was 14.0 BTU/°C or the equivalent of 14 pounds of water. The relationship of the effective to actual heat capacity for the experimental test section over the first few seconds of a temperature transient is then the ratio 10.5:14.

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APPENDIX II

SAMPLE CALCULATION

Problem: A process tube and contents with an equivalent lumped heat capacity of 6.4 lbs. of water is operating at steady state conditions. The water flow is 6 lbs. per second. The inlet temperature is 68 °F and the outlet temperature is 212 °F. If a power failure occurs resulting in a flow decay of 3.3 per cent of the initial flow per second, calculate the variation of outlet water temperature with time.

Basis: Reference temperature = 68 °F
Power input constant
Uniform temperature throughout process tube assembly

Calculations:

Power input = $(212 - 68)(6) = 864$ BTU/sec
Let T = temperature of system (above 68 °F) - °F
Let θ = time after power failure - seconds
Let F = flow - lbs/second
 $F = (6)(1 - 0.033 \theta)$
Input = Output + Accumulation
In time $d\theta$, the temperature change will be dT .
 $(864)(d\theta) = (6)(1 - 0.033 \theta)(T)(d\theta) + 6.4 dT$
 $(135)(d\theta) = (0.9375)(T)(d\theta) - (0.0309375)(\theta)(T)(d\theta) + dT$

$$\left(\frac{dT}{d\theta}\right) = 135 - 0.9375 T + 0.0309375 \theta T$$

$$\left(\frac{dT}{d\theta}\right) + (0.9375 - 0.0309375 \theta)T = 135$$

$$T \left[\frac{e^{0.9375 \theta}}{e^{0.015469 \theta^2}} \right] = 135 \int_0^\theta \frac{e^{0.9375 \theta}}{e^{0.015469 \theta^2}} d\theta + C$$

when $\theta = 0$, $T = 144$ °F
 $C = 144$

$$T = \left(\frac{e^{0.015469 \theta^2}}{e^{0.9375 \theta}} \right) \left[(135) \int_0^\theta \frac{e^{0.9375 \theta}}{e^{0.015469 \theta^2}} d\theta + 144 \right]$$

This equation can be evaluated by plotting the group $\left(\frac{e^{0.9375 \theta}}{e^{0.015469 \theta^2}} \right)$ vs. " θ "

for various values of " θ " and accurately determining the area under the curve for the value of the definite integral.

For the time interval from zero to two seconds, an evaluation of this integral shows the following result:

$$135 \int_0^2 \frac{e^{0.9375 \theta}}{e^{0.015469 \theta^2}} d\theta = 771.3$$

$$T = \frac{(1.064)(771.3 + 144)}{(6.52)} = 149.4 \text{ °F}$$

$$\text{Temperature rise} = 149.4 - 144.0 = 5.4 \text{ °F}$$

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