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RESULTS OF THERMAL-HYDRAULIC EXPERIMENTS

WITH KVNS SELF-SUPPORTED FUEL IN A ZIRCALOY

TUBE -- K REACTOR

by

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and

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RESULTS OF THERMAL-HYDRAULIC EXPERIMENTS
WITH KVNS SELF-SUPPORTED FUEL IN A ZIRCALOY
TUBE -- K REACTORS

PURPOSE

This document presents laboratory data pertaining to the heat-transfer and fluid-flow conditions within a K Reactor process channel using self-supported fuel and a ribless Zircaloy coolant tube. Data are included to show the steady-state hydraulic-demand characteristics during normal conditions and during conditions which simulate a slow flow reduction by plugging upstream of the Panellit pressure tap.

INTRODUCTION

One of the operating limits used to prevent fuel element melting and fuel channel damage in the Hanford production reactors is specified as a maximum outlet water temperature from each fuel channel. This water temperature limit is used in combination with specified trip settings on the Panellit gage so that a reactor shutdown will be initiated if the coolant flow decreases to the point where flow instability will result in the process channel. This combination of coolant temperature and Panellit gage limits is referred to as T-A-I (Trip-After-Instability) limits.

At present, the T-A-I limits for reactor process channels are calculated from an analytical model⁽¹⁾ which is used to predict the onset of flow instability. The simplified model was designed to be conservative and, by laboratory experiments, has been demonstrated to be conservative for the conditions for which it was conceived. But the conditions associated with the onset of flow instability are dependent upon the power generation rates and the geometry of the coolant passage, both of which have changed considerably over the last few years.

One specific geometry effect which needs further investigation is the effect that fuel element self-supports might have on the onset of flow instability. Laboratory experiments for the C-Reactor overbore program⁽²⁾ comprized the first full-scale heat-transfer simulation of self-supported

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- (1) HW-53379. "Method for Empirical Calculation of Instability Limits," K. W. Hess and S. M. Graves, November 12, 1957.
- (2) HW-71075. "Results of Heat Transfer Experiments for the C-Overbore Geometry," E. D. Waters and M. R. Kreiter, November 10, 1961.

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fuel charges for Hanford production reactors. Those experiments showed unusually large pressure drops across the fuel charge during early stages of boiling in the experimental assembly. It was concluded that the simplified model would have to be modified before calculating instability limits for that geometry.

The retubing of K Reactors with smooth-bore Zircaloy tubes and the use of self-supported fuel elements represents a geometry quite similar to the C-overbore assembly. Hence, it was necessary to conduct the present experiments to determine the degree of applicability of the simplified model to this geometry.

SUMMARY AND CONCLUSIONS

Laboratory experiments were conducted with an electrically-heated, full-scale model of a charge of KVNS self-supported fuel elements in a smooth-bore Zircaloy process tube. Ceramic spacers 0.086-inch high were used to represent the self supports of the KVNS fuel elements; this allowed a maximum eccentricity of 20.6 per cent from the normal 0.102-inch annulus.

A total of 129 steady-state runs were made for determining the pressure-drop flow relations across the assembly at constant tube powers of 675, 970, 1360, 1750 and 1940 kw. The dimensional data are presented in Figures 1 and 2, and the generalized steady-state boiling demand curves are presented in Figure 3.

The generalized boiling curves show a non-conservative deviation from the analytical model previously used in establishing the instability limits (T-A-I limits) for individual tube outlet temperatures. The KVNS geometry will require modified instability limits such as those specified for the C-overbore smooth-tube geometry⁽³⁾.

The conditions for incipient film boiling were briefly investigated for the KVNS fuel and tube geometry. Film boiling was initiated at outlet coolant enthalpies corresponding to about 15 per cent steam quality at the end of the fuel charge with tube powers of 1360 to 1940 kw. The flow rates at film boiling are comparable to those found previously for ribbed tube geometries and can be approximated as GPM at Film Boiling = 0.014 x kw.

It was determined that reducing the rear header pressure below 60 psig had no effect on the film boiling flow rate or the heater rod surface temperature at film boiling because of critical flow conditions in the outlet fittings.

(3) HW-75523. "Instability Limits for Smooth-Bore Process Tubes," P. A. Carlson, November 6, 1962 (Secret).

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Circumferential water temperature measurements were made at the end of the heater rod and at five feet upstream from the end. R values, defined as the ratio of maximum water temperature rise at some point to the bulk coolant temperature rise along the same length,

$$\frac{\Delta T_{\max}}{\Delta T_{\text{bulk}}},$$

were calculated from these measurements. The R values at the upstream location were larger than those at the downstream location and the upstream values varied considerably with tube power. The R values at the downstream end compare favorably with those obtained previously from laboratory and in-reactor experiments, i.e., $R = 1.19$ for 20.6 per cent eccentricity. The larger R values upstream indicate that downstream values should be adjusted before use in fuel jacket and process tube corrosion rate calculations or predictions.

Local boiling at the end of the active charge will occur with outlet temperatures in excess of about 138°C (280°F).

Transient upstream plugging tests were not conducted with this assembly because the transient Panellit pressure response is postulated to be the same as that for the C-overbore smooth-tube geometry.

EXPERIMENTAL EQUIPMENT

Nuclear heat was simulated by electrical dc resistance heating in a 1.520-inch OD x 0.420-inch ID metal test section with a heated length of 28.1 feet. The test section was self-supported in a 1.724-inch ID Zircaloy process tube and thus simulated a 38-piece charge of KVNS fuel elements. Different metal alloys were used in the test section so that the stepped cosine power distribution resulted in a peak specific power to average-specific power ratio of 1.40. Small holes were drilled at nine inch intervals along the test section length to connect the internal and external flow channels to simulate the interjunction flow characteristics of reactor fuel charges. Thermocouples were imbedded in the heater rod surface to monitor temperature at various locations.

Ceramic self-supports were used to position the test section within the Zircaloy coolant tube. The ceramic pieces were arranged in four axial rows equally spaced around the periphery of the rod. With the 0.086-inch thick ceramic pieces positioned to straddle a vertical plane through the rod axis, the resultant minimum (bottom) and maximum (top) annuli were 0.081-inch and 0.123-inch, respectively. This represents a 20.6 per cent eccentricity toward the bottom of the tube. As shown in the sketch below, the ceramic self-supports were of the same general size and shape as actual metal self-supports used on fuel elements, but the end tabs of the ceramic pieces were made thicker than normal to provide for fastening the pieces to the metal rod by small countersunk screws.

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Sketch of Ceramic Self-Supports

During the early experiments, it was found that the end tabs (beyond the screw holes) broke off in many instances. These broken end tabs accumulated near the downstream end of the heater rod creating a condition of partial annulus plugging. The heater rod was removed from the tube and all end tabs were physically broken off before reinstallation of the heater rod. Subsequent data showed little evidence of annulus plugging.

Two different coolant streams were metered and introduced at the inlet end of the test section (through non-standard reactor piping) to the annulus and hole flow channels.

The ratio of inlet annular flow to hole flow rates was maintained at 1.81 by the metering system upstream of the test section. The two streams could mix along the heater rod length through the "interjunction flow" holes described above. An annular stream and a hole stream were withdrawn separately from the downstream end of the heated length. Temperature sensing elements were positioned to measure the temperature of each stream as well as the bulk outlet temperature after the streams were mixed but prior to flow through a dummy section, through a rear nozzle and pigtail and into the rear header. The dummy section was charged with seven KV self-supported perfs. The outlet nozzle was a standard K-Reactor outlet nozzle which had been modified and fitted with a perforated plate over the outlet port according to Drawing H-1-33449. The outlet pigtail and the pigtail adapter fittings (0.870-inch ID) were standard K-Reactor hardware.

Special provisions were made for investigating the circumferential coolant temperatures during the steady-state experiments. Thermocouple flanges, having the same inside diameter as the coolant tube, were located at the end of the heater rod and at a distance of five feet upstream from the end of the heater rod. Eight thermocouples were inserted radially through

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each flange at various circumferential positions. These thermocouples allowed the measurement of minimum and maximum annulus coolant temperatures and gave an indication of the amount of coolant mixing which occurs along the annulus.

DISCUSSION

Hydraulic-Demand Curves

A principal purpose of the subject experiments was to obtain data for the flow rate and pressure drop across a prototypical KVNS fuel channel assembly as a function of the heat generation rate in the fuel charge. Such data are presented in Figures 1 and 2. For each tube power, a flow rate high enough to prevent boiling was established. Then, the flow rate was reduced in small steps while flow rates, pressures, and temperatures were recorded after each step.

As mentioned under the previous heading, partial annulus plugging was encountered during the experimental program. This situation was corrected and the experiments were continued. Data for the 1940- and 1750-kw curves of Figures 1, 2, and 3 were obtained after the equipment modification was made and are considered completely valid data. Data for the 675-kw curve were obtained before appreciable breaking of the self-support tabs occurred and should be valid. The 970- and 1360-kw curves show slight evidence of annulus plugging (as indicated by deviation from the all-liquid lines of Figures 1 and 2) and hence can only be accepted with some skepticism.

The pressure drop data are presented in Figure 3 as generalized hydraulic demand curves. (The generalizing technique is presented in HW-42469-C⁽⁴⁾.) The generalized curves are useful to identify flow reductions which might lead to fuel element melting via flow instability. This is done by constructing a supply curve from the front header pressure and tangent to the hydraulic demand curve. The point of tangency represents a condition of incipient hydraulic instability for plugging upstream of the Panellit pressure tap. Construction of various supply curves shows that flow instability could not occur for a tube power of 1360 kw with a 450 psig front header pressure. The minimum tube power which could have flow instability is estimated to be 1400 kw.

Comparison of the hydraulic demand curves of Figure 3 with the analytical model which is used to establish T-A-I limits shows that the model would not predict conservative limits for the KVNS geometry. For example, while

(4) HW-42469-C. "Technical Note on Generalization of Boiling Curves," L. H. McEwen, J. M. Batch and K. G. Toyoda, April 18, 1956.

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the model indicates that a sudden plugging to a Panellit pressure of 153 psig would allow flow instability, the data for 1750 kw show that instability could occur with plugging to a Panellit pressure of 161 psig. While the difference between the model and the data is not large, it is significant and shows that an extra safety margin must be used in establishing limits for the high tube power cases under the present T-A-I limit (low trip) philosophy.

The deviation of experimental data from the analytical model results from deviation from the non-boiling hydraulic-demand curve during early stages of flow reduction. This is similar to the condition found for the C-overbore geometry⁽²⁾. It is postulated that this condition is caused by the initiation of local boiling under or downstream of the self-supported fuel pieces. The similarity between the present data and the data for the C-overbore experiments would indicate that the instability limits which were specified⁽³⁾ after the previous tests could also be applied to the present geometry.

Film Boiling

The conditions for incipient film boiling were briefly investigated for the KVNS fuel and tube geometry. For the higher tube power runs, the flow reductions were continued until film boiling conditions were encountered at some location on the test section as indicated by abnormal increases in test section surface temperature. The terminal (film boiling) points were at significantly reduced flow rates and resulted in net steam generation within the test section. The conditions at the terminal points are given in the following table:

TABLE I.

Tube Power kw	Flow Rate gpm	Tube Inlet Pressure psig	End-of-Heater-Rod Pressure psig	Steam Quality at E-O-H-R weight %
1360	19.4	357	244	15.1
1750	20.0	442	310	14.6
1940	26.4	484	337	14.2

Thus, reactor operation at flow rates less than those presented above, or to the left of the terminal points on Figures 1 and 2 for these tube powers, would result in bulk boiling with high fuel temperatures. However, the terminal points were all attained with steady-state operation for long enough time to record data without damaging the copper-nickel heater rod. Maximum heater surface temperatures were about 550°F.

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The deviation of experimental data from the analytical model results from deviation from the non-boiling hydraulic-demand curve during early stages of flow reduction. This is similar to the condition found for the C-overbore geometry⁽²⁾. It is postulated that this condition is caused by the initiation of local boiling under or downstream of the self-supports with the reduced flow rates and slight eccentricity allowed by the self-supported fuel pieces. The similarity between the present data and the data for the C-overbore experiments would indicate that the instability limits which were specified⁽³⁾ after the previous tests could also be applied to the present geometry.

Film Boiling

The conditions for incipient film boiling were briefly investigated for the KVNS fuel and tube geometry. For the higher tube power runs, the flow reductions were continued until film boiling conditions were encountered at some location on the test section as indicated by abnormal increases in test section surface temperature. The terminal (film boiling) points were at significantly reduced flow rates and resulted in net steam generation within the test section. The conditions at the terminal points are given in the following table:

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The effect of rear header pressure on film boiling flow rate was investigated briefly for the 1360-kw tube power case. After recording data for incipient film-boiling conditions with a 60-psig rear header pressure, the rear header pressure was slowly decreased to 30 psig. It was found that test section temperatures did not change. In fact, the flow rate showed no tendency to change and the rear nozzle barrel pressure and all pressures upstream of that point showed no change. This shows that critical flow conditions existed in the rear header fittings and that rear header pressure variations at least over the range 0 to 60 psig would not effect the film-boiling conditions. It is safe to assume that critical flow also exists at incipient film-boiling conditions for the higher tube powers; hence, variations in rear header pressures up to 60 psig would not affect the steady-state film-boiling flow rate or surface temperatures. It is highly probable that rear header pressures up to 100 psig would not affect the film-boiling conditions.

The effect of annulus plugging on film-boiling flow rate is not known with certainty, but the data indicate that the effect is small. Data curves are shown on Figure 1 for two different run series with a tube power of 1360 kw. It is apparent that different degrees of annulus plugging were present yet the film-boiling flow rates for the two runs were identical. This indicates that annulus plugging could effect the tube inlet pressure at incipient film-boiling without appreciably effecting the film boiling flow rate.

Comparison of the data in Table I with similar data for other reactor geometries⁽⁵⁾⁽⁶⁾ shows that the film-boiling flow rates for the KVNS geometry are about the same or slightly lower than those for the old reactor geometries but slightly higher than those for the KIV tube and fuel geometry. It would be expected that the KVNS data would fall near the data for C-overbore in Figure 1 of HW-71074 because both fuel geometries are of the self-supported type. Since they do not, it is suspected that some uncontrolled parameter (such as the relative location of the thermocouples to the spot where film boiling first begins) is the cause of the differences for the different geometries. Since no heater-rod damage occurred, the data at least indicate a safe operating range. As reported previously⁽⁷⁾, the use of steady-state film-boiling flow-rate

- (5) HW-71074. "Experimental Boiling Burnout Conditions for Hanford Production Reactors," E. D. Waters and J. M. Batch, September 20, 1961.
- (6) HW-74669. "Results of Laboratory Heat Transfer Experiments for K Reactor Fuel Channels," M. R. Kreiter and J. E. Hammond, October 9, 1962.
- (7) HW-71377. "Possibilities for Relaxing Process Tube Flow Trip Requirements for Hanford Reactors," E. D. Waters, G. M. Hesson, and J. M. Batch, October 17, 1961, page 11.

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data in establishing "required high trip" limits of a revised procedure for setting trip limits is quite conservative when compared to "required scram" flow rates during transient-instability occurrences.

Annulus Coolant Temperatures

The difference between the 0.086-inch spacers used in the present experiments and the nominal 0.102-inch annulus resulted in a 20.6 per cent eccentric placement of heater rod with respect to the coolant tube axis. Since eccentric placement causes differences in the annulus coolant temperatures at any axial location, the degree of eccentricity can affect the safety margin on boiling and fuel-jacket burnout.

During the present experiments, the annulus coolant temperatures were measured at eight circumferential positions at each of two axial locations. These locations were at the end of the heater rod and five feet further upstream. Results of these measurements are illustrated in Figures 4 and 5 and they show the coolant temperature variation around the simulated fuel channel at different flow rates and tube powers.

The temperature variations in the annulus of a Hanford process tube are often expressed mathematically as R values⁽⁸⁾. R is defined as

$$R = \frac{\Delta T_x}{\Delta T_{bulk}}$$

where the ΔT_x is the measured temperature rise from the tube inlet to any point, x, in the coolant channel and ΔT_{bulk} is the average or bulk temperature rise to that point. Of course, R has the largest numerical value, R_{max} , at the point of smallest annulus gap with eccentric placement.

The values of R_{max} were determined from data of many experimental runs such as those illustrated in Figures 4 and 5. It was found that the value of R_{max} is a function of both tube power level and the axial location of measurements. This is illustrated in Table II. (The values in Table II are the averages of several runs. Where two rows of values are given for a tube power, this represents data from a different series of runs. This gives an idea of the reproducibility of the data.)

The average value of R for the downstream location is 1.19. This compares quite favorably with R values reported previously for both laboratory experiments and in-reactor experiments⁽⁸⁾⁽⁹⁾, as illustrated in Figure 6.

(8) HW-74248. "Basis for Establishing Minimum Support Height for KVN Fuel Elements," P. A. Carlson, July 11, 1962.

(9) Personal Communication - P. A. Carlson.

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The downstream R value is considerably lower than a calculated value based on an assumption of no circumferential mixing. The measured R value is 0.81 times the calculated value. One can only conclude that there is appreciable circumferential mixing.

TABLE II.

Tube Power kw	$\frac{\Delta T_{\text{annulus avg.}}}{\Delta T_{\text{bulk tube}}}$	$\frac{\text{Upstream R}}{\Delta T_{\text{max}}/\Delta T_{\text{bulk}}}$	$\frac{\text{Downstream R}}{\Delta T_{\text{max}}/\Delta T_{\text{bulk}}}$	$\frac{\text{Ratio of R}}{\text{Up/Down}}$
675	1.080	1.31	1.18	1.11
970	1.090	1.30	1.17	1.11
1360	1.093	1.30	1.19	1.09
	1.097	1.27	1.21	1.05
1750	1.098	1.28	1.21	1.06
	1.108	1.26	1.22	1.03
1940	1.067	1.22	1.17	1.04
	1.085	1.22	<u>1.19</u>	1.03
avg 1.19				

It is apparent from Table II that the R value is larger at the upstream location than at the end of the heated section, but the difference between the two values decreases as the tube power increases. The larger values of R at the upstream location indicate that over the last five feet of heater rod the temperature difference around the circumference is dissipated (by mixing) faster than it accumulates. But the reason for the change in R_{max} with tube power for the upstream location is not known.

One might postulate that this condition results from the effects of bubbles formed in the narrowest part of the annulus by subcooled boiling. As discussed later, the local subcooling for low tube powers is less than for high tube powers at equal bulk outlet temperatures. This fact, plus the fact that the high coolant velocities associated with high tube powers would tend to suppress subcooled boiling, might indicate that subcooled boiling in the minimum annulus would be more vigorous at low tube powers. The resultant bubbles would tend to cause flow channeling and cause extraordinarily high values of R_{max} at the upstream location. Then, near the end of the heater rod, the heat flux is too low to produce subcooled boiling. The cessation of subcooled boiling allows normal or increased mixing and the R value decreases rapidly. Since the prediction of subcooled boiling and its effects on flow shift are very difficult or impossible at this time, this postulate cannot be proven.

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The fact that the R values at the upstream location are larger than at the downstream location indicates a possible correction may be desirable in the R value which is used in fuel jacket and process tube corrosion rate calculations or predictions⁽¹⁰⁾. While the correction is not large for the higher tube powers, it would be significant for the intermediate and low tube powers as indicated by the ratio shown in column 5 of Table II. The upstream location of the present tests represents a distance of about seven fuel elements from the downstream end of a charge. It corresponds approximately to the region of highest observed fuel and tube corrosion rates in the reactors.

One other bit of information is available from the annulus coolant temperature measurements; that concerns the approach to local boiling at the downstream end of the active charge. Although this could be deducted from the measured R values, it is shown directly in Figure 7 as $\Delta T_{\text{subcooling}}$ versus bulk outlet temperature. The data show that the local subcooling is lower for low tube powers than for high tube powers. From this figure, it is apparent that boiling would not be encountered with this geometry at 60 psig rear header pressures until the bulk outlet temperature reaches about 280°F.

Similar data for the upstream location confirm that boiling will be approached first at the downstream end of the heated section.

Transient Experiments

Transient experiments were not conducted for the KVNS fuel and smooth-tube geometry. The decision not to run transient tests was based upon the similarity in characteristics between the C-overbore and the KVNS data, and the mechanical difficulties encountered with the ceramic self-supports used on the KVNS heater rod.

The principal purpose of transient experiments of the front-plugging type has been to investigate the deviation between the predicted minimum Panellit pressure and the actual minimum Panellit pressure during upstream plugging occurrence. Experiments for the old reactor ribbed-tube geometries have shown that this deviation is small⁽¹¹⁾. Later, the C-overbore tests indicated that this deviation is small even with smooth-bore tubes and self-supported fuel. Hence, there was little incentive to conduct front plugging transients with the KVNS fuel and smooth-bore tube geometry.

(10) HW-79518. "Tube-3 Fortran Program: Technical Description," R. D. Jensen, November 4, 1963.

(11) HW-67139. "Laboratory Data for Review of Outlet Water Temperature Limits for BDF Type Reactors," E. D. Waters and D. E. Fitzsimmons, December 11, 1960.

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Total Pressure Drop Across a Tube

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Figure 2.
Active Section Pressure Drop

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Figure 3.
Generalized Hydraulic-Demand Data

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Angle from Top of Rod Looking Upstream - Degrees

Figure 4.

Circumferential Water Temperatures

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Figure 5.

Circumferential Water Temperatures

Figure 6.

Relation Between Eccentricity and $R_{\max}$

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Figure 7.

Subcooling at End of Heated Section

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