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EXPERIMENTAL RESULTS OF TESTS SIMULATING
PLUGGING OF A K TUBE WITH I & E SLUGS

by

G. M. Hesson and D. E. Fitzsimmons

July 7, 1958

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EXPERIMENTAL RESULTS OF TESTS SIMULATING
PLUGGING OF A K TUBE WITH I & E SLUGS

PURPOSE

The purpose of this report is to present results of an experimental program directed toward determining the degree of protection offered by the Panellit protection system to flow losses to a single process tube containing I & E fuel elements in K reactor.

INTRODUCTION

This report is one of a series (1,2,3,4)* reporting results of transient heat transfer experiments designed to define the degree of protection the Panellit system offers to the hazards arising from process tube coolant flow reductions.

The experiments involved measuring the transient behavior of a reactor process tube mockup following deliberate flow reductions sufficient to eventually lead to boiling burnout conditions. The measured responses to the flow reductions could then be used to determine the probability of a Panellit trip before damaging conditions were reached should a similar incident occur at a reactor.

These transient experimental programs were undertaken because earlier Panellit protection procedures were based on steady state data. The steady state data could not give the time sequence of events following a flow reduction and, consequently, could not determine when a Panellit trip would be secured nor if it would be early enough to reduce the reactor power in time to prevent reactor damage. The Panellit protection procedures were therefore made conservative, although the degree of conservatism was not known. The transient programs have shown that the Panellit protection systems based on steady state data were unduly conservative and have lead to less restrictive procedures (5,6).

The transient programs completed to date encompass solid slug geometry in all reactor types. This report covers the case of I & E slugs in the K geometry.

* Numbers in parenthesis refer to entries in the bibliography.

1. HW-52424 A "Results of Experimental Tests Simulating Sudden Plugging of a BDF Process Tube", J.M. Batch, G.M. Hesson, W.L. Thorne, 9/23/57.
2. HW-52424 B "Results of Experimental Tests Simulating Slow Plugging of a BDF Process Tube", G.M. Hesson, W.L. Thorne, 10/14/57.
3. HW-54329 "Results of Transient and Steady State Experiments Investigating Hazards of Flow Reductions in a K Process Tube", G.M. Hesson, W.L. Thorne, 1/2/58.
4. HW-55282 "Interim Report on Flow Hazard Experiments with I & E Fuel Elements in C Reactor", G.M. Hesson, D.E. Fitzsimmons, 3/10/58.
5. HW-51659 "Specification A-020 Process Tube Instability Limits", K.W. Hess, 7/22/57.
6. HW-53379 "Method for Empirical Calculation of Instability Limits", K.W. Hess, S.M. Graves, 11/12/57.

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SUMMARY

An electrically heated metal rod in a K process tube was used to simulate the nuclear heating of a 32 slug train of C I & E slugs in a K reactor tube. This assembly was used to determine steady state boiling curves extending to flows corresponding to boiling burnout. The assembly was also used in transient experimentation conducted by partially but rapidly closing a valve upstream of the tube and monitoring the flow, Panellit tap pressure, rod surface temperature, and other variables with high speed recording instruments. When temperatures were reached which might damage the assembly, a scram was simulated by manually reducing the electrical power to the heater rod.

CONCLUSIONS

Of primary importance, the data show that the Panellit protection system as now exists and specified in Specification A-020⁽⁵⁾ offers adequate protection against hazards arising from flow reductions for conditions as extreme as those investigated; i.e., 80 per cent flow reduction to a tube operating at 1250 KW tube power and 125°C outlet water temperature.

Supporting and secondary conclusions are presented below:

1. In event of a sudden plugging incident upstream of the Panellit tap, protection can be assured in one of the following regions:
 - a. At high tube powers and moderate plugging incidents a low Panellit trip will not necessarily be secured, but the pressurization due to steam formation in the tube makes a Panellit high trip very probable.
 - b. At high tube powers and severe flow reductions, a low Panellit trip will be secured although at the low flows the pressurization due to steam formation is not large and a high Panellit trip will not necessarily be secured.
 - c. At low tube powers the pressurization due to steam formation is not large and a high Panellit trip will not necessarily be secured. However, at low tube powers burnout conditions are reached only at very low flows. Any flow reduction sufficient to lead to burnout is so severe that a Panellit low trip would be secured.

The extent of each of these regions varies with outlet water temperature and with the initial Panellit pressure, but they overlap by wide margins. For the range of conditions studied protection was assured within at least one of these regions.

2. A Panellit low trip cannot be assured in event of a moderate sudden plugging incident upstream of the Panellit tap because the initial Panellit pressure drop is not as great as would be predicted. This has been tentatively ascribed to local boiling effects due to the high top of annulus water temperatures which cushion the pressure drop.
3. In the event of a slow gradual plugging incident upstream of the Panellit tap, the steady state boiling curves describe the course of the Panellit pressure. These make evident that a low Panellit trip cannot be relied upon. At tube powers above 600 or 700 KW the pressurization due to steam formation is sufficient that a Panellit high trip would be effective. At tube powers below these no Panellit protection exists.

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4. The experimental program included plugs upstream of the Panellit tap only. The course of the tube behavior in the event of a plugging incident downstream of the Panellit tap can be calculated from these experimental data. Such calculations show that, for any initial Panellit pressure of operational interest, a Panellit high trip would be secured as early as or earlier than would a Panellit trip for a corresponding plug upstream of the Panellit tap.
5. The steady state data for the I & E slug case conforms quite closely to that for the solid slug case.
6. The transient data for the I & E case shows a much greater reliability of a high trip backup in event of sudden plugs upstream of the Panellit tap than did the solid slug case. This may be due to real differences between the I & E and solid slugs; but, more likely, is the result of improved experimental apparatus and techniques developed since the solid slug case experiments were made.

EXPERIMENTAL EQUIPMENT

A detailed description of the experimental equipment is given in the report on transient tests with the solid slug case, HW-54329⁽³⁾. The interested reader is referred to that document.

The apparatus used in these tests differs from that used in the solid slug tests in three major respects. First, in the I & E case axial holes cannot be drilled in the rod to adjust the power generation along the rod by means of varying the cross-sectional area of the rod to electrical flow. Consequently, the power generation along the length of the rod is changed only by changing rod materials, and its approximation to the cosine heat generation of a slug train is more coarse than was that of the solid slug case. A detail of the rod design and its heat generation characteristics is presented in Figure 1.

Secondly, the rod surface thermocouple installation method was improved. This not only gave more accurate indications of the rod surface temperature, but also in the performance of the experiments gave a better indication of temperatures which might damage the equipment, thus permitting a longer delay before initiation of the scram. It has been calculated that the rod thermocouple installation gives temperature from 20 to 70°C higher than the actual temperature at the surface of the heated rod.

Thirdly, improved recording instruments were used to follow the course of the variables through the transient.

EXPERIMENTAL PROCEDURES

The steady state characteristics of the process variables were determined for a given constant tube power by throttling the flow to the tube with a valve upstream of the Panellit tap. All runs were made with an initial annulus to hole flow ratio of 2.5. After steady state conditions were reached for each flow adjustment, measurements were made of the flow, tube inlet pressure and other variables. The tests were continued to flows associated with boiling burnout, as evidenced by a sharp rod surface temperature excursion.

Sudden plugging of the coolant flow stream was accomplished in the following manner: Initial conditions were established and the system allowed to reach steady state. Even though a variety of initial flows were used the valves on either side of the venturi were so adjusted that the venturi throat i.e., Panellit tap, pressure was approximately 180 psig. The coolant flow was then suddenly reduced by rapidly

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partially closing the valve upstream of the venturi. The degree of closure was fixed by a pre-set stop on the valve. The important process variables were then monitored with individual high speed recording instruments. Each run was continued until boiling burnout, i.e., film boiling, conditions were reached as indicated by a rapid rise in the rod surface temperature. The power to the heater rod was then manually reduced.

DISCUSSION

Theory

The theoretical behavior of a tube undergoing a flow reduction has been developed, at least qualitatively, elsewhere^(1,2,3). For purposes of this report these are summarized briefly, as follows:

A. Steady State Boiling Curves

A steady state boiling curve describes the relationship between the coolant flow and an upstream pressure (i.e. Panellit pressure) for a tube operating at constant tube power. For flows sufficiently high that no boiling occurs in the tube, a decrease in flow results in a decrease in the Panellit pressure. This continues until the flow reduction is sufficient that steam formation starts someplace in the tube. The steam formation increases the resistance to flow, and further flow reductions require increased upstream pressures to cause flow through the tube. If these increased pressures required to maintain flow raise above the pressure supplied to the tube, the flow will undergo a further self-sustained reduction to values so low that boiling burnout is likely. If the increased pressures to maintain flow do not raise above the pressure supplied to the tube, stable steady state points on the boiling curve can be established until the flow is reduced to the boiling burnout flow. The increase in pressure is dependent upon the tube geometry and is increased at higher flows, i.e., higher tube powers.

B. Transient Behavior

If a process tube is subjected to a sudden reduction in the coolant flow due to a plugging incident upstream of the Panellit tap, the Panellit pressure drops along the non-boiling isotherm and will reach a value of that of non-boiling water flowing through the tube at the reduced flow. If the reduced pressure is greater than that necessary to prevent boiling the Panellit pressure will remain at its non-boiling pressure while the water increases in temperature. When the water temperature increase is sufficient to start boiling, the Panellit pressure will increase and the flow undergo a further self-sustained decrease due to the added resistance to flow offered by the steam formation. The Panellit pressure continues to increase and the flow continues to decrease, and, if allowed to continue would eventually reach a new stable point on the boiling curve. This point may be, however, at a flow associated with boiling burnout.

EXPERIMENTAL RESULTS

Steady State

The steady state data are summarized in Figure 2. This is a plot of the Panellit pressure normalized to 180 psig at 125°C outlet water temperature plotted against the square of the flow divided by the flow necessary to give 125°C outlet water. Determinations were made at 500, 750, 1000 and 1250 KW, and were continued until incipient boiling burnout conditions were reached, as evidenced by a sharp rise in rod surface

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temperature. A line connects these boiling burnout points on Figure 2. Lines OA represent tube coolant supply lines for flow conditions just sufficient to lead to boiling burnout for the respective tube powers. Points A represent the theoretical flow and Panellit pressure immediately following a sudden plug upstream of the Panellit tap. Points B represent the burnout conditions at the respective tube powers following a plugging upstream of the Panellit tap, either fast or slow. That is, a sudden plug upstream of the Panellit tap just sufficient to lead to boiling burnout would theoretically result in an initial Panellit pressure and flow drop to Points A for the respective tube powers. The flow would then experience a self-induced decrease with a corresponding Panellit pressure increase to Points B at which time boiling burnout starts. A slow plugging incident would result in a flow decrease and Panellit pressure change along the boiling curve. At the lower tube powers this could continue until Points B were reached. At higher tube powers the flow decrease would continue until the supply curve, (Lines OA) become tangent to the boiling curve, after which the flow and pressure would follow up the Lines OA until Points B were reached. The curves in Figure 2, then define those flow reductions which could lead to boiling burnout and gross damage to the reactor.

Figure 3 is selected boiling curves from these experiments plotted with similar curves from the K reactor solid slug experiments. These show little difference between the I & E and the solid slug cases.

Figure 4 is a cross plot constructed from Figure 2. It is a plot of Panellit pressure plotted against tube power for parameters of $(F/F^*)^2$, i.e., square of the flow divided by flow to give 125°C outlet water. This curve permits an estimation of the normalized boiling curve for tube powers other than the ones determined experimentally.

Transient Data

The transient data are summarized in Figures 5, 6, 7 and 8. Figures 5, 6, and 7 are for 125°C outlet water and tube powers of 750, 1000, and 1250 KW, respectively. Figure 8 is for 100°C outlet water and 1000 KW tube power. The figures are plots of Panellit pressure versus flow with parameters of time. The flow is plotted on a squared scale. Point R is the rear header pressure; Point F is the front header pressure; and Point N is the normal operating point, i.e., 180 psig Panellit pressure and flow necessary to give the desired outlet water temperature. Line NR is the theoretical non-boiling isotherm and gives the theoretical minimum Panellit pressure for given sudden plugs upstream of the Panellit tap. The zero time line gives the minimum Panellit pressures actually attained.

Two further lines complete the figures. These lines represent terminal, or near terminal, conditions of the experimental runs. These lines are the experimental scram line which gives the conditions at the time of power reduction to the heater rod and the film boiling line which gives conditions at the start of film boiling as was evidenced by a sharp increase in rod surface temperature.

Line FP of Figure 7 represents the course of a transient resulting from a plug which results in a flow reduction to 20 gpm to a tube operating at 1250 KW, 125°C outlet water temperature and 180 psig Panellit pressure. Theoretically, upon occurrence of the plug the flow and pressure would drop to Point P at 20 gpm and 55 psig. Once steam formation started the flow and pressure would follow up line PF towards Point F at the front header pressure. Experimentally, the flow and pressure dropped to Point P' at 18 gpm and 99 psig. Steam formation started one second later and the flow and pressure started up line P'F. The intersections of line P'F with the time lines give the flow and pressure at increasing times

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from the plugging incident. For example, at three seconds the flow was down to about 15 gpm and the Panellit pressure up to about 188 psig. At a little less than six seconds film boiling started and at about 6 1/2 seconds the power was reduced. A K reactor has about a two second delay between the time of Panellit trip and time of effective power reduction. Applying this to this example, the Panellit trip would have had to occurred at 4 1/2 seconds, at which time the flow and Panellit pressure were about 13 gpm and 230 psig.

The measured initial top of rod temperature in these runs ranged from 175 to 205°C, increasing with increasing tube power and outlet water temperature. Film boiling started when the measured top of rod temperature was from 220 to 250°C, the lower values occurring at the greater flow reductions. Following the start of film boiling the top of rod surface temperature rose at rates of 40 to 75°C per second. The rate of rise increased with tube power and degree of plug.

Some comments concerning these curves in Figures 5 through 8 are warranted. First, the curves are smoothed through experimental points. The spread of the points is such that a ± 10 psig should be assigned to the time lines.

Second, the Panellit pressures are those measured at the venturi throat with a high speed sensing device. The indicated pressures in no way include the effects of the dynamic response of the Panellit gage and its accessory components.

Third, transient runs with mild flow reductions were made and progressed to film boiling which the steady state data indicated should have reached a stable non-burnout operating point. This indicates that there was a change in the geometry of the experimental test section between the steady state runs and the transient runs. This point will be discussed later.

INTERPRETATION OF EXPERIMENTAL RESULTS AS TO REACTOR PROTECTION

The purpose of these tests was to determine if and under what conditions a safe Panellit trip, either low or high, would be secured in event of any creditable coolant flow plugging condition which could lead to gross damage to the reactor. This section of this report examines the experimental data in this respect.

Slow Plugs

In the event of a slow gradual plug upstream of the Panellit tap, the Panellit pressure will change with the flow in a manner described by the normalized steady state boiling curves. Examination of the curves of Figure 2 shows that at tube powers of 750 KW and greater the increase in pressure due to steam formation is sufficient that a Panellit high trip would be secured before boiling burnout conditions were reached in case a Panellit low trip was not effected. This is not true at 500 KW. Figure 4 can be used to interpolate between the experimental curves of Figure 2, and indicates that the Panellit high trip backup becomes questionable between tube powers of 600 to 700 KW. The tube power at which the Panellit high trip becomes questionable is dependent upon the Panellit pressure at normal flow conditions, and the above conclusions are true for normal Panellit pressures of about 180 psig.

Fast Plugs

The boiling burnout conditions are defined approximately by the steady state data. That is, on Figure 2 the intersections of the lines OA with the non-boiling isotherm give the theoretical flows for each tube power following a sudden plugging incident.

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which are just sufficiently low to lead to burnout. Flow reductions to these flows or less would lead to boiling burnout, if not detected. Flow reductions to flows greater than these could, if not detected, result in operation with bulk boiling in the tube, but would result in neither immediate nor serious damage to the reactor. These flows are only approximate, since the experimental evidence shows that the initial flow and pressure drops do not follow the isotherm and that the boiling curves are not highly accurate in the region of low flows. The data do show, however, that as the tube power decreases there is a significant decrease in the relative flow which first leads to burnout.

The problem is, then, to insure that flow reductions greater than those leading to burnout be detected and the reactor scrambled. The data presented in Figures 5 through 8 give evidence bearing on this. The zero time line gives the minimum Panellit pressures obtained. The minimum Panellit pressures are not as low as the isotherm theoretically predicts. The discrepancy increases with increasing tube power, with increasing outlet water temperature and, within limits, with increasing degree of flow reduction. The maximum discrepancy obtained was about 50 psig. This discrepancy decreases the probability of obtaining a Panellit low trip.

There are two factors which compensate for the lessened reliability of the Panellit low trip. At low tube powers, the flow reduction necessary to reach burnout conditions is large. So large, in fact, that a flow reduction which could lead to burnout would have an initial Panellit pressure drop great enough that even though the drop is not as great as theoretically predicted, it still would be sufficient to effect a Panellit low trip.

At high tube powers the pressurization due to steam formation is sufficient that a high Panellit trip is probable for those cases where the low Panellit trip is questionable. Indeed the regions of flow reductions where the high Panellit trip is effective and the low Panellit trip is effective overlap, giving a region where double protection exists.

The extent of these regions of protection depend upon the initial Panellit pressure, the range between initial Panellit pressure and the Panellit low trip, the range between the Panellit low and high trip, and the outlet water temperature. The data show, however, that for any conditions of operational interest the regions overlap and a safe reactor shutdown will be secured for any case up to that as extreme as those investigated.

For example, if the initial Panellit pressure were about 180 psig, a low trip set according to Specification A-020⁽⁵⁾ and the high trip set 100 psi above the low trip, the data show that:

1. A tube operating at 1250 KW and 125°C outlet water temperature could reach burnout conditions if it were subjected to a flow reduction to about 38 gpm. However, an adequate high Panellit trip would be secured for any flow reduction down to about 11 gpm. Furthermore, any flow reduction giving flows less than about 27 gpm will result in a low trip. In other words, for flow reductions down to 27 to 38 gpm protection is offered by a Panellit high trip; for flow reductions down to 11 to 27 gpm double protection exists, that is the course of the Panellit pressure is such that either a low or high trip would be secured; and for flow reductions down to less than 11 gpm protection is offered by a Panellit low trip.

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2. A tube operating at 750 KW and 125°C outlet water temperature could reach burn-out conditions if it were subjected to a flow reduction to about 15 gpm. However, an adequate high Panellit trip would be secured for any flow reduction down to about 7 gpm. Furthermore, any flow reduction to flows less than 21 gpm will result in a low trip. In other words, any flow reduction great enough to result in burnout will have a double protection, that is, both a low and a high trip would be secured, down to a flow of 7 gpm. Flow reductions to less than 7 gpm would have protection by the low trip.

This experimental program did not define the maximum flow reduction against which the Panellit system offers protection. A complete flow stoppage would surely result in damage to the reactor because of the post-scrum nuclear heating due to fission product decay. Other experiments with C reactor I & E geometry ⁽⁴⁾ show that protection exists to a flow reduction down to 3 gpm to a tube operating at 1250 KW and 125°C outlet water. The maximum flow reduction against which the Panellit system offers protection is one to give a flow something less than 3 gpm.

The above discussion pertains to plugs upstream of the Panellit tap. Simple calculations show that should plugs of the same degree occur downstream of the Panellit tap a high Panellit trip would be secured as early as, if not earlier, than the Panellit trip for the upstream plug case.

In applying these data to a reactor questions arise as to the accuracy of the simulation of the experimental apparatus to a reactor. These questions have been examined in earlier reports and the conclusion reached that the experimental equipment is a reasonable and probably conservative representation of the reactor. New questions arise in this case, however. The first of these is concerned with the accuracy of the simulation of the interjunction flow between the hole and the annulus. The heater rod was drilled with pairs of 1/16 inch holes at 9 inch intervals to simulate the flow between the hole and annulus at the slug junctions. Such holes have been calculated to give the same interjunction flow as was experimentally attained with a slug column in a straight process tube.

The second question has to do with warping of the heater rod. The heater rod warps due to vertical thermal gradients in the rod. There is evidence that this causes the rod to bow upwards, aggravating the eccentricity effects. The most important result of this is probably that it gives an earlier start to film boiling than would occur in a reactor, a conservative simulation. It would also probably result in an increase in the discrepancy between the theoretical and actual minimum Panellit pressures. The Panellit low trip would be more reliable than the experiments indicate. Finally the bowed tube might affect the degree of pressurization due to steam formation, introducing some uncertainty as to the flow reduction at which the Panellit high trip backup ceases to be effective, an uncertainty of perhaps ± 1 gpm.

Finally, the experience to date has shown that the normalized boiling curves in the region of flow flows are reproducible to about ± 20 psig. The net result of this is that the experimentally determined flows which first lead to burnout can vary by about ± 2 gpm.

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It may be pointed out that the experimental scram was dictated by the necessity to prevent damage to the apparatus. Severe damage could result from very extensive operation at measured rod surface temperatures of about 400°C. The criteria for initiating a scram was the start of film boiling, which started at measured rod surface temperatures of 220 to 250°C. Following the start of film boiling and prior to the scram the rod surface temperatures increased at a maximum rate of about 75°C per second, indicating that 5 to 6 seconds would be needed to reach 660°C, the melting point of aluminum.

In general then it may be concluded that the experimental apparatus is a reasonable representation of a reactor process tube and inaccuracies in the representation are such that the experimental results are conservative.

It should be pointed out that this analysis is based on the pressures at the Panellit tap and does not take into account the dynamic response and reliability of the Panellit gages and their associated components. The ability of the Panellit gage to faithfully follow the pressures at the Panellit tap is another problem which was not considered in this program.

The conclusions reached in this program of I & E slugs are at variance with those reached from the program of solid slugs in the K geometry. In the solid slug case a Panellit high trip backup in event of plugs upstream of the Panellit tap was not demonstrated and the conclusion was made that the use of such a backup was not feasible. This difference may be due to reasons: 1) the solid slugs have a higher initial average temperature and they reach burnout conditions faster than do I & E slugs, and/or 2) significant improvements in the experimental apparatus and techniques developed between the solid and I & E program permits a better determination of the course of the transient. A comparison of the data for the two cases indicates that the latter reason is probably correct. Further investigation of the solid slug case with the experimental improvements is therefore warranted.

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FIG. 1 HEATER ROD ASSEMBLY AND HEAT GENERATION

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FIGURE 31 COMPARISON OF GENERALIZED COLLING CURVES FOR SOLID ANSIEE SLUGS IN K REACTOR

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Figure 4.
Cross Plot of Generalized Boiling Curves for I & E
Slugs in K Reactor

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Figure 5

Panellit Pressure-Flow Responses to a Sudden Plug in K I & E Geometry

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Figure 6
Panellit Pressure-Flow Responses to a Sudden Plug in KI & E Geometry

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Figure 7.

Panellit Pressure-Flow Responses to a Sudden Plug in K I & E Geometry

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Figure 8

Panellit Pressure-Flow Responses to a Sudden Plug in K I & E Geometry

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