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PRELIMINARY ANALYSIS OF K-REACTOR DOWNCOMER APPROACH SECTION
PRESSURES DURING TEMPERATURE TRANSIENTS

By

D. S. Rowe

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PRELIMINARY ANALYSIS OF K-REACTOR DOWNCOMER APPROACH SECTION PRESSURES DURING TEMPERATURE TRANSIENTS

PURPOSE

The purpose of this report is to present a preliminary analysis of pressures in the K-Reactor downcomer approach section during bulk outlet water temperature transients.

INTRODUCTION

During the past few years, significant flow increases have been made at the K Reactors without much consideration of the ultimate downcomer flow capability as governed by reactor outlet water temperature transients. Although the present flow rates are being adequately handled by the

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BNCC-55

S. M. Graves

-2-

March 26, 1965

downcomer, some question exists as to whether or not the downcomer approach section is strong enough to withstand the pressure increases which accompany certain temperature transients. The ultimate question to be answered is, "What is the allowable flow which will not cause a catastrophic failure of the downcomer during steady state or during a coolant temperature transient of given rate and magnitude?" Because of the strength uncertainty, no further flow increases are being allowed until a thorough study is completed.

The overall study of this problem includes stress analysis* to determine the allowable pressures within the downcomer and hydraulic analysis to determine flow capability. The steady state part of the hydraulic analysis is being conducted primarily with scale model studies.** The transient part is an analytical effort with the preliminary results presented in this report.

SUMMARY AND CONCLUSIONS

This report presents a preliminary analytical study of pressure transient behavior in the K-Reactor downcomer approach section (Figure 1) during water temperature transients. Since it is very difficult, if not impossible, to calculate the pressure transient once boiling begins in the approach section, actual transient analysis is only carried out up to the time boiling occurs. Only estimates of pressures are made for the final conditions of some cases.

Five transient cases are investigated to determine the effect of the rate and magnitude of the transient and riser temperature differences. These five cases are shown in the table.

Case	Temperature Rise	Initial Temperature		Flow gpm
		Near Riser °C	Far Riser °C	
1	0.5°C/sec for 20 sec	97	93	210,000
2	" " "	93	97	"
3	2°C/sec for 3 sec	97	93	"
4	" " "	93	97	"
5	" " "	95	95	"

Bulk Average 95°C. Boiling Temperature 99°C (14.2 psia).

*Being conducted by General Electric Company, Advanced Technology Laboratories.

**Being conducted at the Washington State University Albrook Hydraulic Laboratory.

DECLASSIFIED

BNCC-55

S. M. Graves

-3-

March 26, 1965

The analysis shows that cases with similar initial riser temperature conditions behave in a similar manner for both the fast and slow transient. We can put the five cases into three groups for comment:

1. Hot Near Side Riser - Cases 1 and 3.

For these cases a large overflow of the cooler far side stream occurs before boiling begins in the approach section. This causes a siphon effect which tends to reduce the pressure in the approach section and cause near side stream boiling.

It is very difficult to predict maximum pressures under these conditions.

2. Hot Far Side Riser - Cases 2 and 4.

When the far side riser is hot, overflow nearly coincides with the time of surface boiling and does not cause a significant siphon effect.

Pressure estimates are possible for conditions of this type.

3. Equal Riser Temperatures - Case 5.

Effects similar to the case of the hot near side riser could be expected but with less severity.

An estimate of the approximate range of pressures at the top of the approach section for the five cases is shown in the following table:

Case	Maximum Pressure Range*	
	Lower Value psig	Upper Value psig
1	4.6	11
2	4.6	No Estimate
3	2.1	9
4	2.1	No Estimate
5	1.0	No Estimate

*At the bottom of the approach section, the pressures are about 4.5 psig greater.

DECLASSIFIED

BNCC-55

S. M. Graves

-4-

March 26, 1965

The upper value pressure is a pessimistic (no-worse-than) value and is based upon rather conservative assumptions. The lower value corresponds to the vapor pressure of the hottest water. Pressures would be at least that high.

The following conclusions and recommendations are made:

1. Temperature, rather than flow, is the primary factor affecting allowable downcomer operating conditions. The question posed in the Introduction should be more concerned with, "What temperature?" rather than, "What flow?" since, if boiling did not occur in the approach section during a transient, the transient would be no worse than steady state. No significant change in the results of this analysis would result if the flow rates were, say, $\pm 10\%$.
2. Any significant amount of vapor, produced during boiling, can not be adequately vented from the downcomer; therefore, pressures at least equal to the vapor pressure occur during boiling transients.
3. Additional approach section strength should be provided since, during a significant boiling transient, the pressure exceeds the 4 psig tentatively being considered as the maximum allowable pressure. Strengthening the approach section to withstand about 20 psig could possibly prevent a catastrophic failure during temperature transients investigated here; however, this should be investigated further.
4. Analytical prediction of pressure during the boiling part of the transient is very difficult, if not impossible. The time and money spent on future analytical or experimental work to get this information should be weighed against measures which would eliminate the transient problem. If strengthening the approach section would not provide enough insurance against a catastrophic failure, then other alternatives should be considered.
5. The transient problem would be eliminated if either the reactor bulk outlet temperature is reduced or the downcomer pressure is increased enough to prevent boiling during temperature transients. If the temperature reduction is ruled out, two different methods of pressurization could be used. First, a constant pressurization of 4 to 5 psig would eliminate the possibility of boiling for a transient to 107°C . Second, self pressurization would occur if a restricted overflow is used. Relief or control valves in the overflow pipes at the top of the approach section could be used to limit the pressure buildup during the transient.

DECLASSIFIED

BNCC-55

S. M. Graves

-5-

March 26, 1965

6. Redesign of the present downcomer entrance elbow is suggested since it causes a significant restriction to flow from cavitation. The suggested redesign (Figure 8) would not eliminate the transient problem, but would provide a significant increase in flow capability for the future.

METHOD OF ANALYSIS

The flow through the downcomer approach section is channel flow with a free surface. For such flow, very little is known about its hydrodynamics during boiling. The elevation pressure gradient, bubble growth and collapse, air bubbles, and bubble rise rates are some of the things which cause difficulty when trying to describe the flow field. During transient water temperatures, the problem becomes even more complex.

The approach taken in this analysis is to analyze the flow up to the time of possible boiling. From the information available at that time, estimates of how the flow could behave and what pressures could exist are made. While this does not give complete answers, it gives estimates of maximum pressures for some cases and shows where potential problems exist.

To develop the equations needed for this analysis, we must make some assumptions. Consider some of the more significant ones:

1. Mass Flow into the Approach Section is Constant.

With the large pressure drop across the reactor, the changes in approach section pressure would have a negligible effect. Also, since the most severe temperature transients are caused by flow decreases, this assumption is conservative.

2. The Saturation Temperature of the Water is a Constant 99°C.

This temperature is equivalent to a low barometric pressure condition and also assumes the vent system maintains it constant. This assumption would be conservative.

3. Dissolved Air Does Not Come Out of Solution.

Some air will come out of solution when the temperature rises. For a preliminary study, ignoring this effect would be acceptable to avoid the difficulties it would present if included.

4. The Two Riser Flow Streams Do Not Mix in the Approach Section.

With the relatively short distance the flow travels in the approach section, as compared to the depth, this would be realized. Model studies⁽¹⁾ have also shown this to be a valid assumption.

5. The Water Level is Flat and Remains that Way Until Boiling Occurs.

While this is not really true, it is sufficient for purposes of this analysis. Actually, waves of some sort are probably set up once the transient is under way.

6. Flow Out of the Approach Section through the Elbow Behaves Like Discharge through Orifices in Parallel.

During normal outlet temperature operation (95°C), reactor test data⁽²⁾ indicate that boiling is probably occurring in the upper one-third of the downcomer. The discharge through the elbow is, therefore, governed by the vapor pressure of the water being discharged. This is the most significant assumption and will be discussed in detail later.

With these assumptions, the transient prior to boiling can be described without much difficulty. What we essentially have is a box with flow entering at one side and the bottom, and flow leaving through orifices at various heights at the other end. The discharge through each orifice is governed by the water elevation above the orifice and the vapor pressure of the water being discharged. The discharge coefficient for each orifice is not known but an effective average coefficient (0.91) is calculated from reactor test data.^{(2)*} As more data become available, this analysis could be improved upon by using a variable discharge coefficient for each flow channel.

In the appendix, the following equation is developed to describe the rate of liquid volume increase in the approach section:

(1)(2) References are listed on Page 12.

*This is the most recent actual test data but it is somewhat out of date. Since the tests of Reference (2), the downcomer orifice plate holes have been rounded. This should not be of much concern since the data used would give conservative results. In this analysis, 10 flow channels are calculated to be full, at steady state, which may be a little more than are actually being used.

DECLASSIFIED

BNCC-55

S. M. Graves

-7-

March 26, 1965

$$\frac{dV}{dt} = \frac{m_T}{\rho} - C_d \frac{288 \text{ g}}{\rho} \sum_{i=1}^N A_i \sqrt{P_i - P_{\text{sat}}}.$$

This equation is nonlinear; therefore, a Runge-Kutta approximation procedure was used for its solution. An explanation of the calculation procedure is included in the appendix.

RESULTS

Five transient cases are analyzed to determine the effect of unequal riser temperatures and the rate and magnitude of the transient. The specific conditions used are shown in the table.

Case	Initial Temperatures		Transient Conditions	
	Near Side	Far Side	Rate	Duration
1	97	93	0.5°C/sec	20 sec
2	93	97	"	"
3	97	93	2.0°C/sec	3 sec
4	93	97	"	"
5	95	95	"	"

Flow Rate at Pump, 210,000 gpm.

Boiling Temperature, 99°C, corresponds to a low barometric pressure situation (14.2 psia).

The effect of unequal riser temperature is more significant than the type of transient; therefore, let us discuss the results* of the cases with similar riser temperature conditions together.

Near Side Riser Hot

This condition (Cases 1 and 3) shows the possibility of some pressure surges which are difficult to predict. This comes about in the following way. As the near side flow begins passing through the downcomer entrance elbow, the increasing vapor pressure of the water reduces the flow rate. This causes the water level to rise and, eventually, a large part, if not all, of the far side stream will begin to overflow through the overflow pipes. Since it is still subcooled, a siphon effect is created with a potential pressure reduction of about 3 psig (Figure 2) and 1.5 psig (Figure 4) for the fast and slow transients, respectively. This is low

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DECLASSIFIED

BNCC-55

S. M. Graves

-8-

March 26, 1965

enough to cause considerable boiling of the hot near side stream within the approach section. Two effects occur, however, which would prevent a large amount of boiling caused by the pressure reduction. First, since a pressure drop is required to force water out the overflow, pressures as low as the vapor pressure of the cooler far side stream would not occur. Second, part of the near side stream will probably be overflowing and, because it will be boiling, it will tend to raise the approach section pressure to its vapor pressure. Since it is difficult to estimate how much vapor would be produced during such boiling, it is difficult to predict pressures; therefore, no maximum pressure estimate will be made for these two cases. The pressures could be at least as high as the vapor pressures of the hottest water.

Far Side Riser Hot

Large potential pressure surges as in the previous case are not as likely for this condition (Cases 2 and 4). During the liquid level rise of the transient, overflowing is nearly coincident with boiling. This boiling would be limited to the top surface; since, enough elevation pressure exists over the near side stream to suppress its boiling.

For these cases, some estimates of the maximum pressure can be made. With the overflowing water near saturation or boiling, the overflow pipes would be more effected by a two-phase flow discharge than the downcomer entrance elbow. If the overflow is not very restrictive, a minimum value of the maximum pressure would be about 4.6 psig which corresponds to the vapor pressure at 107°C. Actually, a value higher than this could be expected, but is difficult to determine without the flow characteristics of the overflow and more information about the boiling. If we consider some limiting conditions, we can get a rough estimate of the maximum pressure. If the overflow is assumed to be plugged and the 0.91 discharge coefficient is retained for the entrance elbow, a pressure of about 7 psig could be expected for the slow transient. This is composed of about 3.5 psig required to pass the flow plus about 3.5 psig for an increase in vapor pressure above atmosphere. If the discharge coefficient is reduced to 0.61 (minimum value for an orifice), pressures of about 10 to 11 psig could be expected. For the fast transient, these values are reduced by about 1.6 psig.

Equal Riser Temperatures

With equal riser temperatures of 95°C, results similar to those of the cases with the hot near side riser are found, although not as severe (Figure 6). A potential pressure reduction of about 1.5 psig exists for this case when the overflow occurs. The maximum pressures would be less than for the corresponding transient with the near side riser hot (Case 4).

DECLASSIFIED

BNCC-55

S. M. Graves

-9-

March 26, 1965

DISCUSSION

Of the assumptions used to develop the equations used in this analysis, those involving the discharge through the downcomer entrance elbow are the most significant. Let us discuss this discharge and see how the assumptions could affect the results.

From Reference (2), it is concluded that the water in the upper one-third of the downcomer is in a free fall. This is based on the pressure data for channel number 3 which indicates that the flow and water level in the downcomer decreases as the temperature increases. Also, additional flow channels are used as the temperature increases, indicating that a restriction is building up in the elbow. While the data does indicate that the inner channels are boiling and beginning to choke, it is not conclusive that this is occurring in the outer channels since the pressure data are limited. Additional reactor tests are to be conducted (by S. S. Jones) to investigate this further.

Reference (2) also presents data which give a very large pressure loss at the entrance to the elbow even during cold flow. If the data are assumed correct, the losses are much too great for a typical elbow. An explanation for this loss is separation at the leading edge of the cell structure. The near side flow enters the elbow at angles ranging from about 5 to 25 degrees which are large enough to cause separation and boiling (cavitation) at the cell entrance.*

The suspicion of cavitation at the entrance to the inner channels was confirmed by an actual inspection** of the K-Reactor downcomer approach section. The inspection showed very clearly where cavitation had been occurring on the upper surfaces at the entrance to the cell structure. The relative area of cavitation was also clearly visible along the vertical sections of the cell structure as shown in Figure 7. It appeared that boiling had been occurring in various amounts at the entrance of the first five channels. For the outer channels, boiling regions were not visible at the leading edge of the cells, but boiling could have occurred farther inside the elbow.

For the methods used in this analysis, it is not very important if some channels are not boiling if pressures are close to the saturation pressure. If an outer channel is a couple degrees subcooled, this would cause about 1 psi error in the downstream pressure. Since the pressure drop is on the order of 3 to 4 psi, an error of 1 psi in a couple of channels would not introduce errors large enough to change the results of this analysis significantly.

*This flow pattern is similar to that through stalled stator blades in an axial flow compressor.

**By S. S. Jones, D. S. Rowe, and others on February 19, 1965; details are in Reference (3).

DECLASSIFIED

BNCC-55

S. M. Graves

-10-

March 26, 1965

The assumption of a uniform discharge coefficient is the most significant assumption regarding discharge from the approach section. With cavitation of variable amounts in the inner channels, a uniform discharge coefficient would not exist. The discharge would be influenced by fluid temperature, pressure, angle of entry, and geometry of the channel - all of which vary for each channel. Until the discharge is more fully understood, an analysis of greater accuracy than that presented can not be performed.

It would be expected that the inner channels would have the lowest discharge capacity. This, together with the near side stream arriving at the elbow about 3 sec earlier than the far side, makes the near side riser flow the more sensitive flow stream. Because of this, it is expected that the actual level rise is faster than calculated. This would be more so for the near side hot case than for the far side hot case; since, the average angle of entry of the near side stream increases as the level rises and more flow channels are being used by the near side stream.

Current estimates of the allowable downcomer approach section pressure are about 4 psig with a potential of 20 psig if some reinforcing is done. It is apparent from the results of Case 1 that a pressure of at least 11 psig would exist at the bottom of the approach section. If the 4 psig is a realistic limit, something should be done to make the approach section stronger.

The primary reason a transient problem exists is because boiling occurs in the approach section. If this could be eliminated, the transient strength problem would be eliminated. The two basic methods of preventing boiling are to operate with sufficiently reduced temperature or increased pressure. Reducing temperature may not be very satisfactory since a decrease in reactor power would result unless the flow is increased an equal amount. Increasing pressure could be accomplished several ways:

1. Pressurization of the Approach Section.

This could be done using air pressurization of the downcomer of about 4 to 5 psig. An air compressor and/or air storage tank system could be used to provide the pressure. The present vent system could probably be retained but would require higher settings on the vent valves. No air would be forced out the effluent pipe at these pressures except for the amount entrained by the flow. As an added benefit of pressurization, higher flow capacity would result.

2. Self Pressurization.

If the overflow pipes were limited at the top of the approach section, a self pressurization would occur during a transient. In this case, all flow would be forced out through the

DECLASSIFIED

BNCC-55

S. M. Graves

-11-

March 26, 1965

downcomer. The pressure increase required to maintain flow would suppress boiling in the approach section. The method of limiting this pressure requires some study but could include relief or control valves. These devices would not allow overflow until a set pressure was reached. It is important that these devices not allow a large pressure reduction within the approach section when they open, but maintain the pressure high enough to prevent boiling.

Since higher flows are anticipated for the K Reactors, pressurization would permit this without much modification other than strengthening of the approach section. But, if significant future increases are to be made, a redesign of the entrance elbow and approach section may be required; since, the elbow is presently more restrictive to flow than the orifice plate. If the loss could be made small in the elbow, the full head of the approach section would be available to drive the effluent flow. A suggested possible alteration is shown in Figure 8. The principal modification is to drop the ramp at the entrance of the elbow and replace the constant area elbow with one of gradually decreasing area channels. The effect of this modification would be to:

1. Permit the flow to enter parallel to the cell structure and eliminate the entrance separation in the inner channels.
2. Reduce the probability of cavitation in the elbow. Proper area variation in the elbow could maintain a nearly uniform pressure in any channel. With uniform pressure and accelerating flow in the elbow, separation would not occur.
3. Providing a platform from the far side riser entrance to the near side deflector and, possibly, removing the guide vanes would give smoother entry for the far side stream. Actual visual observation of the flow shows a hump in the water surface over the deflector, indicating the deflector and/or guide vanes are obstructing the far side flow entry.

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Attachments:

References

Appendix

Figures 1 through 8

DECLASSIFIED

-12-

BNCC-55

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- (1) Claud C. Lomax and E. Roy Tinney. Model Test of the Inlet to K-Downcomer, HW-WSU-4, Washington State University, January 31, 1962. (Secret)
- (2) D. H. Hutton and P. H. Frieling. Interim Report--Rear Face Piping Study at Elevated Bulk Outlet Temperature--KE Reactor, HW-72366. General Electric Company, Hanford Atomic Products Operation, January 17, 1962. (Secret)
- (3) Stephen S. Jones. KE Downcomer Flow Test and Preliminary Flow Analysis, RL-REA-871, General Electric Company, Hanford Atomic Products Operation, March 22, 1965. (Secret)

REFERENCE DRAWINGS*

1. H-1-22362 Downcomer Arrangement, Elevation and Sections
2. H-1-22381 Downcomer Arrangement, Plan and Sections
3. H-1-22340 Process Piping Outlet Face Arrangement
4. H-1-22374 Downcomer Approach Section
5. H-1-22322 Downcomer Approach Section Details
6. H-1-22369 Downcomer Entrance Elbow
7. H-1-22366 Downcomer Orifice Plate Details
8. H-1-24506 Downcomer Orifice Plate Details

*All are unclassified.

APPENDIXDETERMINATION OF AVERAGE DISCHARGE COEFFICIENT

For each channel of the downcomer entrance elbow, assuming each behaves like an orifice, the flow rate can be written as

$$m_i = C_d A_i \sqrt{288 \rho g (P_i - P_{sat})}, \quad (1)$$

and for the total flow at steady state

$$m_T = C_d \sum_{i=1}^N A_i \sqrt{288 \rho g (P_i - P_{sat})}. \quad (2)$$

Solving for C_d gives

$$C_d = \frac{m_T}{\sqrt{288 \rho g} \sum_{i=1}^N A_i \sqrt{P_i - P_{sat}}}, \quad (3)$$

where m_T = Total flow at approach section (lb/sec).

ρ = Density (lb/cu ft).

g = Acceleration of gravity (32.2 ft/sec²)

N = Number of full channels.

A_i = Area of the i th channel (sq ft).

P_i = Pressure at entrance of i th channel (psia).

P_{sat} = Saturation pressure (psia).

From the test data of Reference (2), at about 94°C, eight downcomer channels are full. The flow rate at the pump is 184,000 gpm. Using this and the data tabulated in Table I, we can calculate the average discharge coefficient:

$$C_d = \frac{(184,000)(0.00223)(62.5)}{\sqrt{(288)(60.0)(32.2)}(37.6)} \quad (4)$$

$$= 0.91.$$

DECLASSIFIED

-14-

BNCC-55

TABLE I.

DATA FOR CALCULATING THE AVERAGE DISCHARGE COEFFICIENT*

Channel Number	Centerline Elevation (ft)	Area, A_1 (sq ft)	P_1 (psia)	$A_1 \sqrt{P_1 - P_{sat}}$
1	53.3	2.21	16.6	4.7
2	53.9	2.21	16.3	4.6
3	54.6	3.30	16.0	6.6
4	55.5	3.30	15.7	6.3
5	56.2	2.21	15.4	4.1
6	56.8	2.21	15.1	3.9
7	57.4	2.21	14.9	3.8
8	58.0	2.21	14.6	3.6

$$\sum_{i=1}^8 A_i \sqrt{P_i - P_{sat}} = 37.6$$

*14.5 psia atmospheric pressure, $P_{sat} = 12.0$ psia.

EQUATION FOR RATE OF LIQUID LEVEL RISE

Since the rate of level increase occurs without a significant change in pressure at the surface, we can write the change in liquid volume as

$$\frac{dV}{dt} = v \frac{dM}{dt}, \quad (5)$$

where $\frac{dM}{dt}$ = Net mass accumulation in the approach section (lb/sec).

v = Specific volume (cu ft/lb).

From a mass balance, we find that

$$\frac{dM}{dt} = m_{Total} - \sum_{i=1}^N m_i. \quad (6)$$

DECLASSIFIED

-15-

BNCC-55

If equations (2), (5), and (6) are combined, we get

$$\frac{dV}{dt} = \frac{mT}{\rho} - C_d \frac{288 \text{ g}}{\rho} \sum_{i=1}^N A_i \sqrt{P_i - P_{sat}} \quad (7)$$

$$= f(V, t) .$$

The pressure ahead of each effective orifice, P_i , is obtained directly from the sum of elevation pressure and atmospheric pressure. The pressure downstream of each effective orifice is taken to be the vapor pressure of the water being discharged at that time. Since the water streams from the two risers do not arrive at the same time, delay times of 1 and 4 seconds are used for the near and far side streams, respectively. The equations for water enthalpy at the discharge point then take the form

$$h_{\text{near side}} = h(t - 1) \quad (8)$$

$$h_{\text{far side}} = h(t - 4) . \quad (9)$$

The reference time, $t = 0$, is taken to be when water first enters the bottom of the approach section from the near side.

The Runge-Kutta approximation

$$V(t + \Delta t) = V(t) + k_2$$

$$k_1 = \Delta t f[V(t), t]$$

$$k_2 = \Delta t f\left[V(t) + \frac{1}{2} k_1, t + \frac{\Delta t}{2}\right]$$

is used to solve Equation (7). The procedure at any particular evaluation of $f(V, t)$ is to:

1. Start evaluating the summation term of Equation (7) using P_{sat} equivalent to $h_{\text{near side}}$.
2. Continue the summation until a sufficient number of channels are used to pass the near side flow.
3. Now, using P_{sat} equivalent to $h_{\text{far side}}$, the summation is completed.

DECLASSIFIED

-16-

BNCC-55

The calculation is stopped when far side stream boiling occurs or when discharge of the entire near side stream is not possible because of choking. The latter would also give boiling since part of the near side stream would overflow. The calculation is also stopped when any large overflows occur.

Figure 1. Downcomer Approach Section and Entrance Elbow

DECLASSIFIED

-18-

BNCC-55

Figure 2. Slow Transient, Near Side Riser Hot

DECLASSIFIED

-19-

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The water level was not computed for this case since it would behave similar to Case 4.

Figure 3. Slow Transient, Far Side Riser Hot

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Figure 4. Fast Transient, Near Side Riser Hot

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Figure 5. Fast Transient, Far Side Riser Hot

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Figure 6. Fast Transient, Equal Riser Temperatures

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Figure 7. Observed Evidence of Cavitation During KE-Reactor Downcomer Inspection

Figure 8. Suggested K-Reactor Downcomer Modification
for Improved Entrance Elbow Flow

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END