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CASUALTY STUDY OF KER-1 LOOP DUMP VALVE

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By Authority of CG PR-2 CASUALTY STUDY OF KER-1 LOOP DUMP VALVE

DS Lewis, 12-10-98.

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Joseph P. Spampinato

PURPOSE

A study has been made to determine the adequacy of the KER-1 loop emergency dump valve in protecting the fuel elements against damage during a loop casualty.

INTRODUCTION

In a functional test of the radiation trip procedure of the KER-1 loop during a reactor outage, it was found that the indicated process water flow was much lower than expected. Subsequent inspection of the emergency dump valve showed that the dump port was considerably blocked with rust and scale, creating a flow restriction. As it was thought that inadequate cooling water flow could result if a similar situation occurred when the reactor was at normal power levels, a study was made of the loop and the adequacy of the valve to handle casualties.

The study was undertaken in two parts:

1. Calculation of the maximum dump valve port restriction allowable for the safety of the fuel elements under the conditions of a normal process radiation trip.
2. Determination of the ability of the dump valve to protect the fuel elements in the case of the worst casualty the loop might experience.

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The first case was relatively straight forward. For the second case, the casualty that was investigated was the inadvertent opening of the emergency dump valve during loop full power operation.

RESULTS AND CONCLUSIONS

Case 1 - Normal Process Radiation Trip

Figure 1

It was found that in the event of a normal process radiation trip the following sequence would take place.

TABLE I

<u>Time</u>	<u>Flow Path</u> (Fig. 2)	<u>Flow</u>	<u>T_c</u>	<u>T_d</u>	<u>Remarks</u>
0-	abcdef(gg')	60 gpm	372°F	527°F	Normal operation
0+	abcdef'g'	60	372	527	Radiation process trip
2.8 sec	abcdef'g'	60	372	527	Scram
106 sec	abcdef'g'	60	70	90	Emergency storage tank water reaches process tube
7 min	abcde'	60	70	90	Dump valve opens
7+ min	a'bcde'	90	70	80	Process water comes in

It is seen that in the normal process radiation trip sequence, a significant occurrence is the bypassing of the loop flow into the emergency storage tank. This forces cold water from the tank into the loop and after 106 seconds transport time, over the fuel element. From that time until some seven minutes later when the dump

valve opens, the fuel is cooled by cold water from the emergency storage tank. Once the dump valve opens, the loop pressure decays very rapidly and at some time shortly after seven minutes, the loop pressure is low enough to allow the entrance of process water.

Since the dump valve does not open until the loop is well cooled down, valve port restriction is harmful only from the standpoint of not allowing sufficient process water cooling flow to remove the decay heat after seven + minutes. Therefore, using as criteria a 475 psig process water pressure and process tube outlet enthalpy limited by prospective flashing in the line, it is concluded that the dump valve will allow adequate cooling flow with as much as 90 per cent flow restriction.

Case 2 - Inadvertent Opening of the Dump Valve

It was found that in the event of an inadvertent opening of the dump valve during full power loop operation, the following sequence occurs:

Figure 2

Time Secs	Pressure			Flow			Quality % by Wt.		Heat Generation	Remarks
	0	1	3	0	1	3	1	2	%	
				lb/sec	lb/sec	lb/sec				
0-	-	1400 psia	-	-	60 gpm	-	0	0	100	Normal Operation
0+	-	1400 psia	-	-	180 gpm	-	0	0	100	Emergency Dump valve opens
1 1/2	1035	1035	810	3.43	9.85	10	0	0	100	First Flashing occurs at valve
3	1035	1035	810	3.43	9.85	10	0	0	100	Scram
31	915	915	760	3.80	14	14	0	0	27	"Cold" water reaches valve
44	1150	1100	990	3.15	3.15	16	6.6	21	23	Two-phase mixture reaches fuel element
61	980	925	480	3.72	3.72	3.72	10	18	18	All two-phase mix- ture in loop
111	--	--	--	3.58	3.58	3.58	12	--	14	Pressurizer heaters go off. $P_p = 1400$ psia
133	780	600	415	3.43	3.43	3.43	12	--	13	$P_p = 1200$ psia
163	650	540	315	2.80	2.80	2.80	15	--	12	$P_p = 900$ psia
173	535	445	305	2.75	2.75	2.75	--	--	12	$P_p = 800$ psia

Using a calculated steam heat transfer coefficient, it was found that the surface temperature of an outside rod of a seven rod cluster fuel element with 21.2 KW/ft heat generation would not exceed 1100°F at any time during the casualty. Solid and I & E type fuel elements are shown to be relatively safe from damage. Furthermore, it is estimated that the valve port may be restricted as much as 30 per cent of full area and still pass sufficient flow to prevent damage to the fuel element.

Therefore, it is concluded the KER-1 emergency dump valve will adequately protect the loop with as much as 30 per cent flow restriction in the dump port.

ASSUMPTIONS

1. Process Radiation Trip Sequence

A. Normal process radiation trip sequence occurs

1. Reactor scrams
2. Pressurizer blows down
3. Heat exchanger bypass valve closes
4. Heat exchanger cooling water on full
5. Loop flow control valve opens full
6. Process tube outlet flow bypassed to emergency storage water tank.

B. Loop depressurization rate is timed such that no flashing occurs at any time in the loop.

2. Inadvertent Opening of Dump Valve

A. Two-phase pressure drops may be calculated by Martinelli-Nelson method (Reference 3).

B. Pressurizer is maintained at operating pressure until low pressurizer water level switch turns off heaters.

C. Loop pumps neither aid nor hinder two-phase flow.

D. Loop flow control valve may be considered as an equivalent length of pipe.

E. The pressurizer surge line heat exchanger has negligible effect.

F. There is negligible flow resistance in the dump valve drain line.

G. Effect of heat stored in loop piping and components is neglected.

ANALYSIS AND DISCUSSION

Case I

A process radiation trip sequence on a KER loop is initiated when the radiation monitor on the outlet side of the process tube gets an indication of excess radiation. The resulting signal triggers the following five functions simultaneously:

1. Reactor scram
2. Loop blow down by bleeding steam off pressurizer
3. Maximizing of loop heat removal by:

- a. Closing heat exchangers bypass valve
 - b. Turning heat exchanger cooling water on full
4. Opening of loop flow control valve to full open
 5. Bypassing of the process tube outlet water to the emergency storage tank to collect the free fission products.

It has been calculated that the pressurizer blowdown time from operating pressure to 50 psi above process water pressure (when dump valve opens) is seven minutes. Furthermore, the depressurization is so timed as to avoid flashing anywhere in the loop.* In order to determine the flow rate through the valve, it is necessary to determine the conditions of the water in the loop when the valve opens.

The time necessary for a slug of water to travel from point to point on the loop with a flow rate of 60 gpm is shown in Table III. Loop piping data is taken from Reference 13.

TABLE III

<u>Section</u>	<u>Size</u>	<u>Length</u>	<u>Time</u>	<u>Running Total</u>
Heat Exchanger to Pump	2 1/2 in	23 ft.	4.2 sec	4.2 sec
Pump to Reducer	2 1/2	320	58.7	62.9
Reducer to Pigtails	2	123	14.3	77.2
Pigtails to Inlet	3/4	54	3.0	80.2
Outlet to Pigtails	3/4	54	3.0	83.2
Pigtails to Reducer	2	54	6.3	89.4
Reducer to Dump Valve	2 1/2	182	33.4	122.8
Dump Valve to Heat Exchanger	2 1/2	200	36.7	159.5 secs or 2.66 min.

Using as an approximation the value of transport time from dump valve to process tube inlet, the transport time between the emergency storage tank and the process tube inlet is less than 106 seconds or 1.8 minutes. Thus, if the increase in loop flow due to the opening of the flow control valve is neglected for conservatism in 1.8 minutes after the process radiation trip the cold water from the emergency storage tank will first reach the process tube. A loop water temperature of 100°F at the process tube inlet will be assumed; this figure is reasonable and probably conservative in light of the fact that the water has been subjected to the maximum heat removal capacity of the heat exchanger.

* Personal communication with Ralph Dulin.

In seven minutes, when the loop has nearly completed its blowdown, the reactor power level will have decayed to 8.8 per cent of maximum. However, due to transport time, the valve at this time is exposed to water which passed over the fuel at $t = 6$ minutes when it had a power level of 9.3 per cent. Using the latter figure and a flow rate of 60 gpm, a heat balance on the water and fuel yields a temperature at the valve of 113°F at $t = 7$ minutes. Thus, there will be cold water flow through the valve when it opens and the pressure in the loop will drop quickly to process water pressure. The flow rate under process water pressure will depend on loop pressure drop and valve orifice size and will be determined by the cold water equation

$$Q = CA \sqrt{2 g P/\rho} \quad (1)$$

Using an orifice coefficient of 0.6, process water pressure of 475 psia, and port area of $1.51 \times 10^{-3} \text{ ft}^2$, the flow through the valve will be, accounting for loop pressure drop, approximately 90 gpm.

It is evident that a clean valve is more than adequate to provide proper cooling to the fuel element. With flow restriction at the orifice, the cooling flow will be proportionately reduced. One limit will be that restriction which will decrease flow in the line to the extent that the specific enthalpy of the water leaving the process tube is high enough to cause flashing at or just past the dump valve. The pressure drop due to this flashing will decrease the flow still further and possibly lead to fuel overheating.

If the temperature at which the flashing first might occur is conservatively set at 212°F and the heat generation is conservatively taken as that at $t = 4$ minutes, the minimum flow rates required to avoid flashing is determined to be 9 gpm. Since the full area flow rate is 90 gpm and flow is directly proportional to flow area, the valve may have as much as 90 per cent flow area blockage and still function adequately in a normal process radiation trip.

Case 2 - Inadvertent Opening of the Emergency Dump Valve

Case 2 consists of a study of the effects on the loop of opening the emergency dump valve to the atmosphere during (loop) full power operation. In the study, the loop is considered to be unattended and all corrective actions are considered to come about as the result of tripping automatic controls. The casualty is followed from the time the valve opens until the loop pressure decreases enough to allow the entrance of process cooling water.

Because of the nature of the casualty and of the loop, the study consists mainly of following the progress of discrete slugs of water through the loop. The loop depressurization is marked by four distinct flow phases:

1. Loop blowdown from operating pressure to hot leg saturation pressure. This flow phase is characterized by liquid water flow throughout the loop and through the valve.
2. Blowing out of the hot leg. A critical flow is established at the valve and the hot leg is "pushed out" by a slug of sub-cooled water followed by the water-steam mixture from the pressurizer.
3. Blowing out of the sub-cooled water. After the sub-cooled water reaches the valve, the flow increases greatly. Two-phase pressure drops are neglected until after the pressurizer outflux reaches the fuel and are considered thereafter.

4. All water-steam flow until process water comes in. This phase covers the loop flow conditions from the time the last solid water is expelled through the valve, through the pressurizer depressurization, until the loop pressure has dropped enough for the process water to enter the loop.

It should be noted that each discrete flow phase was calculated as if steady state conditions existed. For the first three phases, this assumption is very near actuality, with minor pressure variations being caused by varying pressure drops as the slug interfaces traverse the loop. The fourth phase is truly a transient phase and the steady state assumption is nothing more than a simplification. However, since the critical (for fuel element damage) flow phase is the third phase, the assumption does not affect the conclusions drawn by this study and yet allows a quick estimate of loop depressurization time.

Phase 1 - Loop Blowdown to Hot Leg Saturation Pressure

At $t = 0-$, the loop is operating normally under the conditions shown on Figure 3.

Figure 3

At $t = 0+$, the dump valve opens and the loop starts to depressurize; the loop can now be represented schematically by Figure 4.

Figure 4

Where volumes A and B represent the volumes of loop water between the valve and the heat exchanger and between the heat exchanger and the pressurizer connection to the loop, respectively. The loop will depressurize at a rate dependent on the net weight outflux of water through the dump valve; the difference between the weight outflow through the valve and the weight inflow from the pressurizer must be made up by the liquid water expansion with subsequent loop depressurization.

The loop water at operating pressure will have a high degree of subcooling; hence it is possible to accurately approximate the flow through the valve at this time by the cold water equation as plotted on Curve 1. The pressurizer outflow versus loop pressure for constant pressurizer pressure is calculated in Appendix I; the results are plotted on Curve 2.

Flashing will first occur in the loop when the pressure at the valve reaches the saturation pressure of 527°F or 860 psia. Considering the loop volume, pressure, and temperature at operating conditions, it is estimated that the loop must discharge 20 lbs of water in expanding from 1400 psia to the pressure where flashing first occurs. Reference to Curve 1 shows that at an average pressure of 1130 psia, the cold water flow through the valve is 160 gpm or 17 lb/sec in terms of water at 527°F. Curve 2 shows that the pressurizer outflow has a value of about 4 lb/sec at 1100 psia loop pressure. Thus, the net outflow is:

$$W_{net} = 17 - 4 = 13 \text{ lb/sec}$$

and considering the liquid expansion, the time that the first flashing will occur at the valve is approximately:

$$t = \frac{M_{exp}}{W_{net}} = \frac{20 \text{ lb}}{13 \text{ lb/sec}} \approx 1 \frac{1}{2} \text{ sec.}$$

One fact considered was that the pressurizer outflow is a steam-water mixture when it enters the loop. This would ostensibly complicate the calculation by destroying the validity of the liquid water expansion assumption. However, at the junction of the loop and the pressurizer surge line, the pressurizer outflow will mix with the liquid water expansion flowing from Volumes 3 and 4 of Figure 4. The mixing of the pressurizer water-steam mixture with the colder (372°F) expansion water results in the steam being condensed and the liquid water assumption being justified during the initial blowdown interval.

When the first flashing occurs, the rate of loop depressurization decreases considerably, and the flow caused by liquid water expansion stops. Then the steam from the pressurizer water is no longer condensed and must be considered.

Reactor Scram

In consideration of the preceding figures, it is evident that the reactor will be scrammed automatically in that initial blowdown period by one of two signals:

1. High flow, which is set at 69 gpm.
2. Boiling point suppression (8°C) and low pressure (1550 psia). (Both are necessary for scram).

Since the loop experiences high flow the instant that the valve is cracked, the reactor will get a high flow scram signal instantaneously. Sometime later, within 1 1/2 seconds, it will also receive a boiling point suppression - low pressure scram signal. It is important to note that the reactor will be scrammed automatically almost immediately after the casualty occurs by at least one signal.

Considering blowdown and scram delay times, it was assumed that the reactor scrammed at $t = 3 \text{ sec}$ after the casualty.

Cold Water Flow Thru Emergency Dump Valve
vs
Upstream Pressure

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CURVE 1

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Phase 2 - Blowout of Hot Leg

At the time flashing begins in the loop, a second depressurization and flow phase begins. Since the expansion of liquid water has stopped, the portion of the loop upstream of the pressurizer is not contributing any flow and hence the loop can effectively be represented by Figure 5.

Figure 5

- where Point 0 is the loop-pressurizer surge line junction
 1 is the beginning of the active zone
 2 is the end of the active zone
 3 is the valve.

For pressure drop analysis purposes, the various fittings and components in Line 0-1 and Line 2-3 were converted to equivalent lengths of pipe of active zone diameter per Reference 2. It should be pointed out that the main pumps and the main flow control valve are in the Line 0-1. It was assumed that the pumps neither hindered nor helped flow and that the flow control valve flow area remained constant (i.e. could be converted to a constant length of equivalent pipe). The author realizes that both these assumptions are open to question. Some justification may be made for the pump assumption if, it is considered that the pumps will continue to run throughout the duration of the casualty; nothing in the sequence of events shuts them off automatically. As far as the valve is concerned, little is known about its behavior with two-phase flow; hence, it is felt that the assumption is as reasonable as any other that could be made, despite its lack of justification.

If the effect of the events of the first blowdown phase on temperature distribution are ignored because of the short time involved, the temperature of the water in Line 0-1 is 372°F and in Line 2-3 is 527°F. This flow phase will be distinguished by the flowing of several different slugs of water in the loop:

1. Water at 527°F in Line 2-3, a part of which will be flashing near the valve.
2. Water at 372°F in Line 0-1.
3. A steam-water mixture from the pressurizer which will be the driving force behind all the flow.

There will be some mixing at the interfaces of each slug, but this is minor and each slug will be considered discrete. The problem will be to find the flow rate during this second phase. Since the beginning time of this second flow phase is to be taken as the time when the critical flow starts, which is assumed to be when flashing first occurs at the valve, the phase starts out with liquid water everywhere except near the valve.

The flow rate may be determined by matching the volumetric flow rate from the pressurizer with the volumetric flow rate of the slug of cold water as limited by the critical flow at the valve. The flow from the pressurizer will be dependent

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on the loop pressure at the pressurizer connection. The critical flow is determined from a critical pressure which in turn is related to the pressure at the pressurizer loop connection by the pressure drop in the line. Thus, it is seen that a trial and error solution is called for. Making use of F. E. Tippets critical flow curve (Reference 4), loop pressure data from Reference 2, and the pressurizer flow characteristics from Appendix III, the loop flow is calculated in Appendix IV for this second flow phase and is summarized below:

Volumetric flow rate: $.194 \text{ ft}^3/\text{sec}$

P_3 : 810 psia

Mass flow rate over fuel: 9.85 lb/sec

P_0 : 1035 psi

Pressurizer flow rate: 3.43 lb/sec

Pressurizer outsurge quality: 8.04 per cent

Since under normal operating conditions 60 gpm represents 6.4 lb/sec flow, it is evident from the above data that the coolant flow in this second flow phase will be substantially subcooled upon leaving the process tube. Thus, starting at the valve, this phase will be distinguished by a slug of hot flashing water at 527°F being pushed by a slug of water hotter than 372°F but substantially lower than 527°F , followed by a slug of water at 372°F and finally a slug of the water-steam mixture from the pressurizer.

In calculating the pressure drops, it was assumed that the flashing occurred linearly from the valve to the end of the process tube and that the pressure drop from the pressurizer connection (Point 0) to the process tube inlet (Point 1) were cold water pressure drops. Neither of these assumptions are strictly correct but since their correction would result in a change of only 25 psi in the loop pressures and a correction to the third decimal place of the volumetric flow rate, they were not corrected.

It was further assumed that the flows would remain constant at this rate until the hot water was blown completely out of the loop and the "cold" slug following reached the valve. This was justified by the fact that the increasing pressure drop in the steadily increasing water-steam slug from the pressurizer would balance the decreasing pressure drop in the decreasing flashing slug being ejected from the loop. Again, this is not strictly correct, but the extra refinement necessary was not merited by the increase in accuracy to be gained.

Hence, it is possible to calculate the time necessary for the hot water to be pushed out of the loop. From Reference 2, it was found that the volume of the loop from Point 2 to Point 3 is:

$$V_{23} = 5.55 \text{ ft}^3$$

With a non-flashing volumetric flow rate of

$$Q = .194 \text{ ft}^3/\text{sec}$$

the time necessary to dispose of its contents is

$$t = \frac{5.55}{.194} = 29 \text{ seconds.}$$

Thus, 29 seconds after the start of the second flow phase, or 30 1/2 seconds after the accident, the original hot flashing leg will have been blown out of the loop. The volume of colder, 372°F, water between the pressurizer connection and the process tube (Volume O-1) is 9.5 ft³; hence at this point, the steam-water mixture has not yet reached the fuel.

Phase 3 - Blowout of Sub-Cooled Water

Once the flashing water is blown out of the loop, there will be a substantial increase in flow through the valve and loop. Using the cold water equation as an approximation to flow through the valve and neglecting two-phase pressure drops, a new flow rate may be calculated by matching the volumetric flow rates of the valve and pressurizer flows as in Phase 2. The results of that calculation are:

$$P_0 \approx 915 \text{ psia}$$

$$P_1 \approx 915 \text{ psia}$$

$$\text{Pressurizer flow} - 3.8 \text{ lb/sec}$$

$$\text{Valve flow} - 14 \text{ lb/sec}$$

$$\text{Loop volumetric flow} - .284 \text{ cfs}$$

At this flow rate, the remaining "cold" water in Section O-1 will be emptied and the water-steam mixture will reach the fuel in

$$t = \frac{9.5 - 5.55}{.284} = 14 \text{ seconds}$$

additional. Thus, at $t = 1 \frac{1}{2} + 29 + 14 \approx 45$ seconds after the accident, the fuel elements will first be exposed to two-phase cooling.

At the conclusion of the preceding portion of Phase 3, the loop fluids consisted of a slug of water-steam mixture from the pressurizer connection to the active zone, and water a little above 372°F in the remainder of the loop. Up to this time, two-phase pressure drops have been more or less ignored; henceforth, they will be considered.

The reasons for choosing this point to consider two-phase drops are two-fold: (1) the water-steam mixture is now beginning to occupy a large portion of the loop and (2) the heat addition to the steam passing over the fuel will raise its quality such that the two-phase drop can no longer be ignored.

The calculations for this phase were similar to the preceding cases except for the following:

1. Martinelli-Nelson two-phase pressure drop correlation was used to determine two-phase pressure drops.
2. The volumetric flow rate of the steam-water mixture leaving the process tube was matched with the volumetric flow rate of water flowing through the valve. The results were as follows:

$$P_0 - 1150 \text{ psia}$$

$$X_2 - 21.1 \text{ per cent}$$

$$\text{Pressurizer flow} - 3.15 \text{ lb/sec}$$

$$\text{Volumetric flow} - .323 \text{ ft}^3/\text{sec}$$

It is noted that there is a considerable decrease in flow from the pressurizer once the steam hits the fuel. This is caused by the expansion of the steam-water mixture upon heat addition in the process tube. With the heat addition the quality and specific volume are raised, requiring a lower flow rate from the pressurizer to match the cold water volumetric flow rate.

The quality of the process tube exit two-phase mixture was calculated as part of the trial and error method since the quality is a function of outlet enthalpy and pressure. The outlet enthalpy was calculated by adding to the inlet enthalpy, the fuel decay heat generation at 45 seconds as given in Reference 6 divided by the flow rate. Thus, for heat balance purposes the two-phase mixture was considered homogeneous, and all the heat generated by the fuel was assumed to pass on to the mixture.

Based on the above figures, and considering them to remain fairly constant over the interval, the additional time for the last of the cold water to leave the loop is:

$$t = \frac{5.55}{.323} = 17 \text{ seconds.}$$

Phase 4 - Loop and Pressurizer Depressurization

The loop has now reached a point where, at $t = 45 + 17 = 62$ seconds after the accident, it is completely filled with a steam-water mixture. A calculable critical flow rate will immediately be re-established at the valve and a new set of flow conditions will have to be determined. Using the same methods as before, with Martinelli-Nelson drops applied throughout, the new conditions are:

P_0 approx. 980 psia

Pressurizer (loop) flow approx. 3.75 lb/sec

P_3 approx. 480 psia

Throughout these entire calculations, it has been assumed that the pressurizer water is maintained at 1400 psia saturation. This will be true as long as the heaters remain on and since no manual corrections are assumed, the heaters will remain on until the low-water level trip shuts them off. From data supplied by Ralph Dulin of IPD, it was calculated that the pressurizer could lose 396 lbs. of water before the heaters went off. A summation of the water lost up to this time yields:

<u>Phase</u>	<u>Flow</u>	x	<u>Time</u>	=	<u>Weight Lost</u>
1	3.43	x	29	=	100
2	3.80	x	14	=	53
2	3.15	x	<u>17</u>	=	<u>54</u>
			Sum		210 lb.

Thus, with an outflow of 3.72 lb/sec, the pressurizer will maintain pressure for

$$t = \frac{396 - 210}{.372} = 50 \text{ secs}$$

additional time.

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Finally, at $t = 112$ seconds after the accident, the pressurizer heaters go off and depressurization begins.

The rate of depressurization of the pressurizer was calculated by the following formula from Reference 12.

$$\frac{dP}{dt} = \frac{-(\lambda_{out} W_{out} - \frac{\sum \dot{Q}}{h_{fg}}) \rho v_{fg} + W_{out} \rho v_f}{V [0.89 + 6.5 \frac{v_f}{v}]}$$

It gave an average pressurizer de - pressurization rate of approximately 10 psi/sec. Loop flows were then calculated for pressurizer pressures of 1200, 900, and 800 psia assuming equilibrium in each case. The results are summarized below:

t_T	P_0	P_1	W	Pressurizer Pressure
112	--	--	3.58	1400 psia
134	780	600	3.43	1200
164	650	540	2.80	900
174	535	445	2.75	800

Since P_1 is the pressure at the entrance to the active zone, once it falls below 475 psia, process water will definitely enter the loop and the fuel elements will be process-water cooled from about 174 seconds on.

FUEL ELEMENT TEMPERATURE

In terms of heat balances alone, the fuel element is supplied with enough coolant at all times so that the process tube outlet quality does not exceed 25 per cent. Hence, if the two-phase flow were homogeneous, it is reasonable to assume that the fuel element would never be in danger of overheating. However, uncertainties in flow may exist (see Reference 9) such that a segment of the fuel element may be only steam cooled. This is verified experimentally in Reference 5.

With solid and I & E configuration fuel elements, this danger is minimized because of conduction within the fuel element. In applying the data of Reference 5 to the casualty being studied, the worst condition from a heat generation standpoint occurs at $t = 45$ seconds, when the two-phase mixture first reaches the fuel.

From Reference 6, the decay heat generation at $t = 45$ seconds (42 seconds after scram) is 23 per cent. Considering a full power peak heat flux of 575,000 Btu/hr-ft² (75 KW/ft² for a solid fuel element), the heat flux at 45 seconds is 132,000 Btu/hr-ft². The flow rate of 3.15 lb/sec gives a mass velocity of $.97 \times 10^5$ lb/hr-ft². Figures 6 and 9 of Reference 5 show that the top surface of a horizontal heated rod did not exceed 18°F ΔT with the same heat flux and quite similar mass velocity, quality, and pressure conditions. Figure 7 shows that for a mass velocity of $.59 \times 10^6$ lb/hr-ft², which corresponds to a mass flow rate of 1.8 lb/sec in the KER-1 process tube, the ΔT does not exceed 25°F for the same heat flux. Although these ΔT 's refer to surface temperatures, at this decay heat rate the fuel (radial) temperature profile should be substantially flat, and the core temperature will not be much higher.

Thus, it may be concluded that at no time during the accident will a solid or I & E fuel element be subjected to excessive temperatures.

ROD-TYPE CONFIGURATION FUEL ELEMENTS

Just as Reference 5 shows that there is no danger for solid and I & E elements, it also shows the possibility of overheating of rod-type fuel elements by demonstrating the effects of flow separation. Individual rods may be solely steam cooled because of separation of the phases. As an indication of the adequacy of steam cooling it is possible to calculate a steam heat transfer coefficient and determine the fuel surface temperature necessary to remove the heat generated.

Again, the most critical time in the casualty sequence will be at $t = 45$ seconds. It is at this time that the steam velocity is lowest due to high pressure and low specific volume and that the generated heat to be removed by steam is a maximum. A steam coefficient may be approximated by the Dittus-Boelter equation as given in Reference 10.

$$\frac{hD}{K} = .023 \left(\frac{DG}{\mu} \right)^{0.8} \left(\frac{C_p \mu}{k} \right)^{0.4}$$

Using the steam pressure and quality conditions at the entrance to the process tube at $t = 45$ seconds, correcting for the area occupied by water and considering a seven rod cluster type fuel element, the above equation yield a heat transfer coefficient of:

$$h = 217 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

Assuming the peak heat flux from the outside rod of a seven rod cluster fuel element to be 440,000 Btu/hr-ft² (15 x 1.41 KW/ft), at $t = 45$ seconds, the heat flux will have reduced to 101,000 Btu/hr-ft². Using the calculated h , this requires a ΔT of 467°F, which means that the fuel surface temperature will have an absolute value of 1033°F.

Again, because of the low value of heat generation, the fuel core temperature will not be much higher. On the basis of this study, it is concluded that in the event of KER-1 loop casualty consisting of the inadvertent opening of the emergency dump valve, the maximum fuel element temperature will not exceed 1100°F. (A critical fuel temperature may be considered to 1100°F where uranium undergoes a phase change resulting in a core volume change).

EFFECT OF DUMP PORT FLOW RESTRICTION

The above conclusion was based on a clean valve, but the results may be extended for a valve flow restriction. As the dump valve flow area is decreased, so thus does the rate of loop depressurization and therefore the time interval between scram and the time that the steam-water mixture reaches the fuel elements is increased. Thus, as long as the flow area is enough to allow enough cooling water over the fuel to prevent vaporization in the process tube, the fuel will not have any danger of overheating. A conservative limit is 30 per cent blockage, which is that area which will pass critical hot leg flow equivalent to 60 gpm. Restriction of the flow more than 30 per cent will make the process tube outlet water hotter than the hot leg water temperature and possibly lead to a condition of greatly reduced flow.

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Rough calculations using 70 per cent of the dump valve area showed that the pressurizer steam-water mixture would first reach the fuel in 70 seconds after the accident, at which time the heat generation is down to 17 per cent of full power. At this time in the depressurizing sequence, it can be shown that there is little decrease in steam heat transfer coefficient, so the limiting factor will be the process tube outlet water temperature.

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APPENDIX I

Nomenclature

A	Area	Ft^2
C_p	Specific Heat	$\text{Btu/lb } ^\circ\text{F}$
D	Diameter	Ft
G	Mass Velocity	$\text{lb/sec} - \text{ft}^2$
h	Specific Enthalpy	Btu/lb
K	Thermal Conductivity	$\text{Btu/ft-hr } ^\circ\text{F}$
P	Pressure	Psi
q	Heat Flow	Btu/sec
Q	Volumetric Flow Rate	Ft^3/sec
ν	Specific Volume	Ft^3/lb
V	Volume	Ft^3
W	Weight Flow Rate	lb/sec
X	Fraction Steam by Weight, (Quality)	
	Viscosity	lb/ft-sec

APPENDIX IIReferences

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APPENDIX III

CALCULATION OF PRESSURIZER OUTSURGE

SUMMARY

The pressurizer outsurge will be dependent upon pressurizer pressure and the two-phase pressure drop in the pressurizer surge line. To determine how the flow rate varies with loop pressure for constant pressurizer pressure, the procedure will be as follows:

1. For a constant value of saturated pressurizer pressure, assume a loop pressure.
2. Calculate the isenthalpic quality of saturated pressurizer water at loop pressure.
3. From Martinelli-Nelson curves (Reference 3), find values of $\frac{(\Delta P / \Delta L)_{TPF}}{(\Delta P / \Delta L)_O}$
4. Calculate flow required to give necessary pressure drop from

$$G = 10^2 \times \sqrt{\frac{\Delta P}{C \frac{(\Delta P / \Delta L)_{TPF}}{(\Delta P / \Delta L)_O} + 2.16 r_2}} \quad \text{lb/sec-ft}^2$$

where P is the difference pressurizer and loop pressure

$$C = 1.551 \text{ for } P_P = 1400 \text{ psia}$$

$$= 1.497 \quad " \quad = 1200$$

$$= 1.450 \quad " \quad = 1000$$

$$= 1.403 \quad " \quad = 800$$

The results of these calculations are tabulated below and plotted on Figure 1.

P_P	P_L	X	$\frac{(\Delta P / \Delta L)_{TPF}}{(\Delta P / \Delta L)_O}$	r_2	G	P_P	P_L	X	$\frac{(\Delta P / \Delta L)_{TPF}}{(\Delta P / \Delta L)_O}$	r_2	G
1400	1300	2.15	1.6	.010	6.32	1200	1100	2.2	1.5	.013	6.63
	1200	4.2	1.9	.016	8.19		1000	4.4	2.0	.019	8.11
	1000	8.24	2.5	.025	10.08		900	6.5	2.3	.021	9.27
	900	10.2	3.0	.030	10.28		800	8.6	2.9	.029	9.53
	800	12.1	3.2	.033	10.93		700	10.7	3.5	.035	9.70
	700	14.1	3.7	.039	10.99		600	12.8	4.0	.041	9.93
	600	16.1	4.1	.043	11.12						
	500	18.1	4.6	.049	11.15						
1000	940	1.4	1.6	.010	5.06	800	760	1.0	1.6	.011	4.20
	900	2.2	1.9	.015	5.99		700	2.5	2.0	.017	5.93
	800	4.6	2.3	.021	7.69		640	4.0	2.5	.022	6.71
	700	6.9	3.0	.028	8.25		580	5.5	3.0	.029	7.18
	600	9.2	3.8	.035	8.47		500	7.6	3.5	.035	7.76
	500	11.6	4.6	.042	8.59		400	10.4	4.6	.046	7.81

ANALYSIS

Two-Phase Pressure Drop

The outflow from the pressurizer will start out as saturated water in the pressurizer and flash to steam as its pressure drops through the surge line. The two-phase pressure drop may be calculated by the Martinelli-Nelson equation

$$\Delta P = \Delta P_0 \frac{\left(\frac{\Delta P}{\Delta L}\right)_{TPF}}{\left(\frac{\Delta P}{\Delta L}\right)_0} + \frac{r_2 G^2}{f}$$

where ΔP_0 is the liquid pressure drop.

The liquid pressure drop by the Darcy friction equation is

$$\Delta P_0 = f \left(\frac{L}{D}\right) \frac{v^2}{2g} \quad \text{Ft H}_2\text{O}$$

or in terms of mass velocity

$$\Delta P_0 = .0155 f \left(\frac{L}{D}\right) \frac{G^2}{\rho^2} \quad \text{Ft H}_2\text{O}$$

for $f = .023$

$$\Delta P_0 = 2.48 \times 10^{-6} \left(\frac{L}{D}\right) \frac{G^2}{\rho} \quad \text{Psi}$$

or

$$\Delta P_0 = C (G \times 10^{-2})^2 \quad \text{Psi}$$

where $C = \frac{2.48 \times 10^{-2}}{\rho} (L/D)$

so that the two-phase pressure drop equation becomes

$$\Delta P = (G \times 10^{-2})^2 \left(C \frac{\left(\frac{\Delta P}{\Delta L}\right)_{TPF}}{\left(\frac{\Delta P}{\Delta L}\right)_0} + 2.16 r_2 \right) \text{ psi}$$

Surge Line L/D Ratio

The pressurizer surge line consists of the following piping and fittings:

<u>Item</u>	<u>Size</u>	<u>Schedule</u>	<u>L/D¹</u>	<u>No. of Pieces</u>	<u>Σ (L/D)</u>
Reducer	2 x 1"	160	.35/023	1	15
90° Ell	1"	160	30	2	60
Tee	1"	160	60	2	120
90° Miter Bend	1"	160	59	2	118
40' Pipe	1"	160	40 x 12	--	589
			.815		902'

1. Reference 14.

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Also, pressurizer outsurge water must pass through a heat exchanger. As it is assumed that there is no pressure differential across the pump, there will be no secondary flow and hence no heat transfer in the heat exchanger. The heat exchanger flow area consists of annulus formed by 1 1/2" and 1" Schedule 80 pipes and has a calculated L/D ratio of 1830, based on surge line pipe diameter. Thus, the total L/D for the complete pressurizer surge line is $(L/D)_T = 1830 + 905 = 2735$.

The values of C may now be calculated for saturated water at 1400, 1200, 1000, and 800 psia.

APPENDIX IV

CALCULATION OF FLOW RATE DURING HOT LEG BLOWOUT

The flow rates for all flow phases are calculated by a trial and error method which entails the matching of the flow rates entering and leaving the loop; for the second flow phase, the volumetric flow rates at the pressurizer connection and at the valve will be matched.

The flow phase starts when a critical flow is established when the loop pressure drops to approximately hot leg saturation pressure at the valve. Hence, a good starting point will be to assume that a critical flow exists at saturation pressure at the valve.

Saturation pressure for 527°F is 860 psia. From the Tippetts Chart (Reference 4), the critical mass velocity of saturated water at 860 psia is

$$G_c = 6.6 \times 10^3 \text{ lb/sec-ft}^2$$

The full dump valve port area is

$$A = 1.51 \times 10^{-3} \text{ ft}^2$$

so that the critical flow rate is

$$W_c = 10 \text{ lb/sec or}$$

$$Q_c = 13.36 \text{ ft}^3/\text{min} = 103.7 \text{ gpm}$$

From Reference 2, the calculated loop pressure drop from the pressurizer connection to the valve is 77.4 psi at 60 gpm.

Hence, at 103.7 gpm, the pressure drop will be approximately

$$\Delta P = 77.4 (103.7/60)^2$$

$$\Delta P = 230 \text{ psi}$$

This requires a pressure at the pressurizer connection of $860 + 230 = 1090$ psia. From Curve 1, it is seen that at 1090 psia, the pressurizer flow will be 3.33 lb/sec which, at a quality of 6.8 per cent, is $9.12 \text{ ft}^3/\text{min}$. Thus, the assumed flow rate is too high.

A flow rate of $.194 \text{ ft}^3/\text{sec} = 11.65 \text{ ft}^3/\text{min} = 87.5 \text{ gpm}$ will be assumed. This represents a critical mass velocity of $G_c = 61.89 \times 10^2 \text{ lb/ft}^2 \cdot \text{sec}$ at the valve. From the Tippetts Chart, this flow will occur with a critical pressure of 810 psia and quality of 1 per cent at the valve.

Since some flashing occurs, the two-phase pressure drop will now be accounted for. Assuming, conservatively that the flashing occurs linearly between the valve and the center of the process tube, the Martinelli-Nelson pressure drop becomes

$$\Delta P = 0.0168 (G_c \times 10^{-2})^2 \left[1.195 \frac{(\Delta P/\Delta L)_{\text{TPF}}}{(\Delta P/\Delta L)_0} + 2.16 x_L \right] \text{ psi}$$

where the coefficient is a conversion factor to put the critical mass velocity in terms of loop pipe area.

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$\Delta P = 150 \text{ psia}$

From Reference 2, the pressure drop in the remaining part of the loop at 60 gpm is 40.5 psia. Hence the drop at the assumed flow rate is

$$\Delta P = 40.5 \left(\frac{87.5}{60} \right)^2$$

$$\Delta P = 85 \text{ psi}$$

making the pressure at the pressurizer connection 1035 psia. From Figure 1, this gives a weight flow rate from the pressurizer of 3.43 lb/sec. At the connection pressure, this represents a volumetric flow rate of .194 ft³/sec which is exactly what was assumed and the calculation is complete.

In terms of water at 372°F, this volumetric flow rate represents a weight flow rate of 1.85 lb/sec over the fuel elements.

The flow rates for the remaining flow phases were calculated in a similar manner with slight variation in pressure drop calculation techniques.

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