

Evaluation of Single Failure Effects During Loss of Coolant Accidents For A VVER-440 Reactor

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1. ABSTRACT

This paper describes the results of an analysis of loss of coolant accidents (LOCA's) for the Soviet designed, light water cooled and moderated reactors referred to as VVERs. The VVER unit selected for this analysis is designated as VVER-440 Model 213. This plant generates 440 MWe and is of current interest since fifteen are now operating and additional units are in various stages of construction within Eastern Europe and the New Independent States. In addition to the analysis of two base case LOCA's, this paper also presents the results of several sensitivity studies related to single failures in various plant systems that have been included in the design to mitigate the effects of LOCA's on plant and fuel system performance. Examples of the safety systems selected for these sensitivity studies include the scram system, the accumulators, and the high pressure injection system.

2. INTRODUCTION

Loss of coolant accident transients have been simulated for the Soviet designed, VVER-440 reactors using the RELAP5/MOD3 computer code (1). The VVER-440 selected for this analysis, designated as Model 213, has six primary coolant loops and generates 1375 MWth. Existing VVER-440/213 plants have two different surge line configurations: the conventional, single surge line between the hot leg and the pressurizer and a double surge line design. The design selected for this analysis was the double surge line configuration. Two different sized LOCA's have been analyzed: a 500 mm double ended break that is representative of the full shear of one main coolant loop and a single ended, 200 mm break that is representative of an

intermediate sized break comparable to the surge line. For each of these analyses, results are presented in terms of system pressure, fuel and clad temperature, reactor power, and core flow rate. Additional results are presented with the various sensitivity studies that have been performed related to single failures.

3. COMPUTER CODE DESCRIPTION

The RELAP5/MOD3 computer code has been used extensively for the analysis of pressurized water reactor LOCAs, abnormal occurrences, and anticipated transients without scram. The hydrodynamic model included in the code is a one-dimensional, two-fluid model for flow of a two-phase steam water mixture. The basic field equations include the continuity, momentum, and energy equations solved for each of the two phases. Heat transfer is modelled with the one dimensional heat conduction equation that is coupled with the hydrodynamic calculation through a number of surface heat transfer regimes. Process models are available for choked flow, branching, and representation of pipe ruptures. Component models can be used to represent pumps, valves, and accumulators. Considerable flexibility is available for the representation of very complex systems.

4. VVER SIMULATION MODEL

A detailed model of the VVER-440 plant has been developed for use with the RELAP5 code. This model, shown in Figure 1, consists of two main coolant loops with one loop representing the response of five VVER-440 loops and the second loop representing a single plant loop. Each loop contains models for steam generators, main coolant pumps,

and the associated piping. Overall, the entire plant is represented by 84 control volumes and 84 flow junctions. Specific areas of the modelling important for the current analysis are discussed in the following paragraphs. Data for the development of these models has been obtained from Reference 2.

Pressure Vessel Model: As shown in Figure 1, the reactor pressure vessel is represented by seven control volumes with additional nodalization in the heated core region as discussed below. The downcomer was split with individual connections to the lumped intact loop nozzles and the single loop nozzle connecting to the pressurizer. Individual control volumes are provided for the lumped nozzles, the intact nozzle, the lower plenum, and the outlet plenum.

Core Model: The core model developed for this analysis consisted of a single channel with five axial nodes. The heated core region was represented with three of these nodes; a chopped-cosine function was used to model the axial power distribution. Each axial core region is divided into 3 radial zones to model the fuel, gap, and clad regions of the fuel rods. The radial nodalization assigned four nodes to the fuel region, one node to the gap, and three nodes to the clad. Important results calculated from this model include the fuel center-line temperature and the inner and outer clad temperatures.

Neutronics Model: The neutronic response of the VVER-440 is not explicitly calculated in the current model. Core power is specified as a function of time with the power being held constant until the occurrence of a low core outlet pressure signal (9.2 MPa). Following this low pressure signal, designated as a first order safety signal or AZ-1 in VVER-440 design, the power is reduced to decay heat levels in thirty seconds. The assumption of constant power until the AZ-1 signal is considered conservative for this analysis since the loss of coolant accidents is expected to cause voiding in the core region and some subsequent power reduction prior to the low pressure signal.

Primary System Piping: The VVER-440 plant has two loop seals in each primary coolant system loop (the vertical pipe sections located upstream and downstream of the steam generator). These loop seals are particularly important for LOCA analysis since natural circulation flow through the loops can be impeded by the accumulation of steam in the seals.

Without natural circulation flow the water level in the core will quickly drop to the level of the inlet and outlet nozzles; further reductions in water level could be expected on a longer term due to boiling in the core region. In addition, the accumulation of water in the seals can have an important effect on the steam generator heat transfer. Thus, considerable detail has been included in the modelling of the hot and cold leg piping in each loop.

Steam Generator Model: The VVER-440 steam generators have horizontal once through steam generator tubes. The RELAP5 model represented the primary side with ten control volumes and ten heat slabs that transferred heat to the secondary system. Each of the heat slabs was sub-divided into 3 radial regions to allow the calculation of a temperature distribution through the walls of the steam generator tubes. This nodalization is considered adequate for the tube wall thickness of approximately .15 cm.

Secondary System Model: Each secondary steam system was represented by a single control volume that was sub-divided into three regions. All heat from the primary side was transferred to the middle, two phase region; feedwater flow entered the bottom region that was filled with liquid, subcooled by 15K. Turbine protection is provided by fast action isolation valves located at the end of the steam line. These valves have been modelled to close on a high steam pressure signal of 5.4 MPa. The closing time of the valves is 2.5 seconds. Since there is a possibility of steam line isolation during the transients, the steam generator safety and relief valves were also modelled. The safety valves were set to open at 5.7 MPa with a flow rate of 70 kg/s; the relief valves open at 5.5 MPa and the flow rate is 55kg/s.

Passive Safety Injection (Accumulators): Model V213 of the VVER-440 design includes four accumulators that provide a large source of coolant to the primary system following various LOCAs. These accumulators are arranged such that two deliver water to the downcomer region and the two deliver water to the outlet plenum. The initial operating pressure of the accumulators is 5.5 MPa.

Active Emergency Core Cooling System Models: This VVER-440 has three High Pressure Injection (HPI) Systems and three Low Pressure Injection (LPI) Systems. Each HPI system is connected to the cold leg piping; in the RELAP5 model, two systems are

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connected to the lumped, intact loop and one system is connected to the ruptured loop. The HPI systems are activated by a low core outlet pressure signal (10.9 MPa) with flow initiated following a thirty second time delay. The head/flow characteristic of the pumps is represented with the data Reference 2. The maximum flow rate per pump is 32. kg/s at atmospheric conditions.

Each LPI system has a high volume, low shutoff head pump. The maximum flow of 133 kg/s is reached at atmospheric conditions and the shutoff head is approximately .7MPa. Thus, this system is only effective in the long term analysis of primary system blowdown transients. Two LPI pumps deliver water to two accumulators and thus, to the downcomer and outlet plenum. The third LPI pump injects to both the hot and cold leg piping of a loop not connected to the pressurizer.

5. ANALYSIS RESULTS

5.1 Large LOCA Break Analysis

The large break LOCA transient was initiated by the instantaneous, double ended rupture of the 500 mm diameter main coolant pipe in the cold leg. The pressurizer surge flow is not sufficient to control primary system pressure and the outlet plenum pressure (Figure 2) decreases to the AZ-1 scram setpoint (9.2 MPa) in approximately 0.5 seconds. The rate of pressure decrease is reduced as saturated conditions are reached in the primary and significant voiding occurs in the outlet plenum. This initial depressurization is also sufficient to trip the HPI (at 10.9 MPa) and injection flow is initiated, following at 30 second time delay, at approximately 30.5 seconds. As discussed previously, the VVER-440 RELAP5 model include three HPI pumps with two pumps injecting to the intact loops and one pump injecting to the ruptured loop.

As discussed in the previous section, neutron kinetics have not been explicitly modelled; however, the effect of the reactor scram has been represented by reducing reactor power to decay heat levels over a thirty second time period. Thus, as shown in Figure 3, core inlet and outlet temperatures rapidly approach each other as power level decreases. At 9 seconds, the two temperatures are approximately equal. In addition, at 9 seconds, primary system pressure has decreased below the accumulator pressure (5.5 MPa)

and accumulator flow is initiated to both the downcomer and outlet plenum. The accumulator injection to the outlet plenum, a design feature of the V213 plant that differs from U.S. designs, allows the vessel to refill from the top in a reverse flow regime and causes the core outlet temperature to decrease more than the core inlet temperature (Figure 3).

As shown in Figure 4, the initiation of accumulator flow collapses the voids in the outlet plenum in approximately 12 seconds. The outlet plenum void fraction remains low until the accumulator inventory is depleted; however, at this time the primary system pressure is sufficiently low to permit the initiation of the LPI system flow. The LPI system provides a cyclical high volume source of inventory for the remainder of the transient and insures that no further fuel temperature transients occur.

The initiation of accumulator flow also effects the void fraction in the core. As shown in Figure 5, core void fraction increases quickly during the initial 15 seconds due to a reduction in core flow, decreasing system pressure, and the core heat generated. However, following the initiation of accumulator flow, the core voids are eventually collapsed and adequate core cooling is maintained for the remainder of the transient.

The clad surface temperature for two core regions is shown in Figure 6. The initial temperature rise caused by inadequate core cooling is terminated at approximately 20 seconds due to reverse flow cooling generated by the accumulator flow. This reverse core flow has caused the clad temperature in the lower core to be higher than the core exit. Following termination of the temperature rise the clad temperature is quickly reduced to below the initial value. At approximately 38 seconds, the high flow, low pressure injection system is initiated and the break flow rates are compensated for by the injection flows. Thus, no further clad temperature transients are anticipated. It should be noted that the peak clad temperature exceeds the temperature limit for fuel deformation of 1375 K indicating some fuel damage. The extent of this fuel damage will be evaluated in future work following the development of a more detailed core model.

5.2 Sensitivity Studies

The base case RELAP5 model has been used to perform several sensitivity studies that evaluate the effects of certain single failures in the VVER-440 design and a design modification in the accumulator

parameters. The single failures include the failure of either accumulator, the failure of one train of the HPI system, and delays in the initiation of the scram system. In addition, the effect of raising the pressure in the accumulator has also been evaluated. Each of these sensitivities is discussed in the following paragraphs.

Accumulator Failures: The effect of the loss of accumulator flow to either the downcomer or the outlet plenum has been evaluated individually. The loss of accumulator flow to the outlet plenum is more severe due to the loss of the reverse core flow from the outlet plenum to the core region. The peak clad temperature increased by approximately 250K for this transient. For the failure of the accumulator flow to the downcomer region, peak clad temperature increased by only 60K. This result is as expected since the cold leg causes reverse core flow and a significant amount of the downcomer accumulator flow is swept out the break. The transient clad temperatures are shown in Figure 7 for both cases.

Increased Accumulator Pressure: The previous sensitivity study indicated the effectiveness of the accumulator flow (particularly to the outlet plenum) in limiting clad temperature. Thus, the effect of raising accumulator pressure (and thus, reducing the initiation time) was evaluated. Two cases were analyzed: accumulator pressure increased by 1.4 MPa and 2.8 MPa. These results are shown in Figure 8 and indicate that the increased pressure and reduced initiation time are effective in reducing peak clad temperature. A pressure increase of 1.4MPa reduced the peak clad temperature by 75K and a 2.8 MPa increase resulted in a 140K temperature decrease.

HPI System Failure: The effectiveness of the high pressure injection system has been evaluated by analyzing the large break LOCA transient with one HPI system failed. These results indicate that there is no significant change in the peak clad temperature with one train of HPI removed. The accumulators provide a much greater contribution to the core cooling than the HPI and thus have a more significant effect on the peak clad temperature.

Delay in Scram Initiation: The reactor scram is initiated by low pressure in the outlet plenum. The effectiveness of this scram has been evaluated by analyzing the transient with a 10 second and a 20

second scram delay. These results are shown in Figure 9 and indicate that scram timing is very important in limiting the peak clad temperature. A scram delay of 10 seconds results in 350K increase in the peak temperature; in an extreme case, a delay of 20 seconds increases the peak temperature by 545K.

Break Size: As a final sensitivity study, an analysis was performed for a single-ended, 20 cm. rupture in the cold leg piping. The clad temperature for this transient is shown in Figure 10 and indicates that the combination of accumulator and high pressure injection flow maintain the clad surface temperature below the initial value for the duration of the transient.

6. SUMMARY

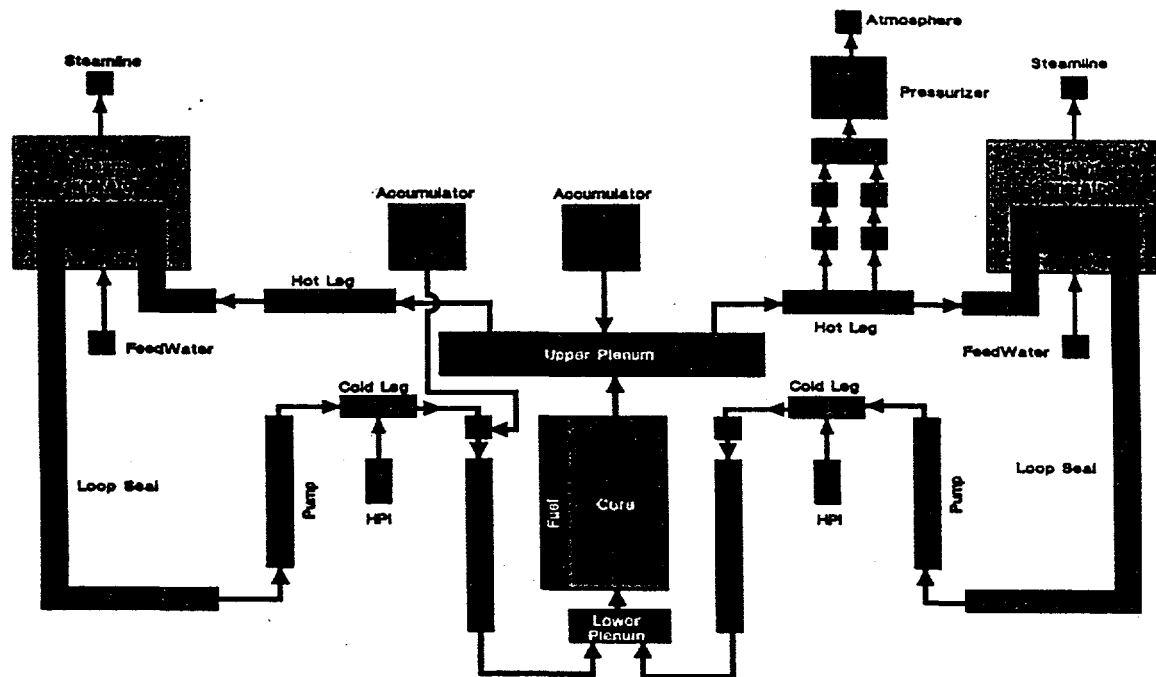
The analysis of loss of coolant accidents for the VVER-440 Model 213 reactor presented in this paper has indicated that following a full shear break of the cold leg piping some fuel damage will occur. Further details of the extent of this fuel damage will be determined during future analyses. However, the current analysis has shown the increases in peak clad temperature with increased accumulator pressure can be very effective in reducing the peak clad temperature during the transient; in addition, the importance of the timely initiation of the scram system was demonstrated by two sensitivity studies.

ACKNOWLEDGEMENTS

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REFERENCES

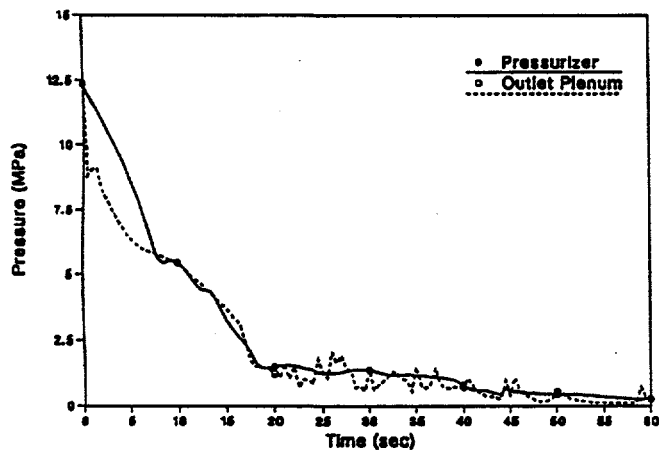
- [1] K.E. Carlson, et.al. , RELAP5/MOD3 Code Manual Volumes I and II, NUREG-CR-5535 (Draft), June (1990).
- [2] Central Research Institute for Physics. Specifications for a VVER-440 Type NPP with Pressure Suppression System, IDEA Workshop Report, February (1988).



VVER-440 Nodal Diagram

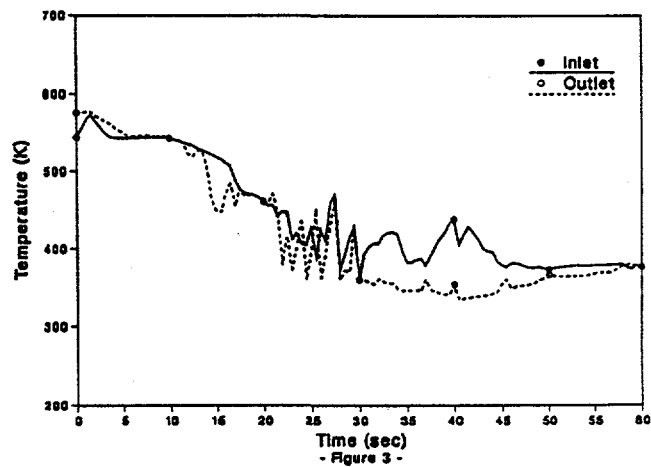
- Figure 1 -

VVER-440 LARGE BREAK LOCA - 50cm
Primary System Pressure



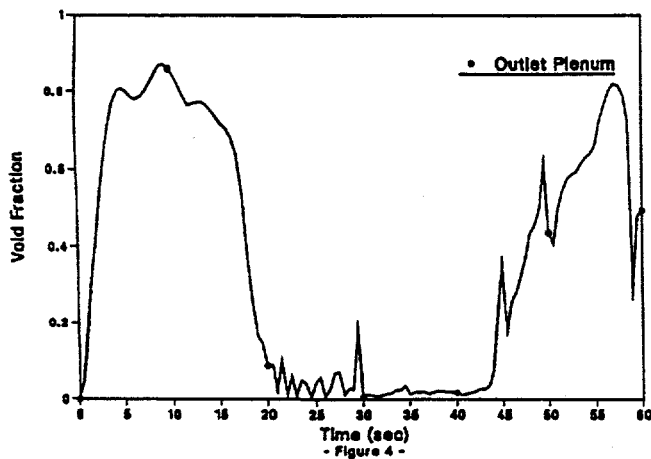
- Figure 2 -

VVER-440 LARGE BREAK LOCA - 50cm
Reactor Core Temperature



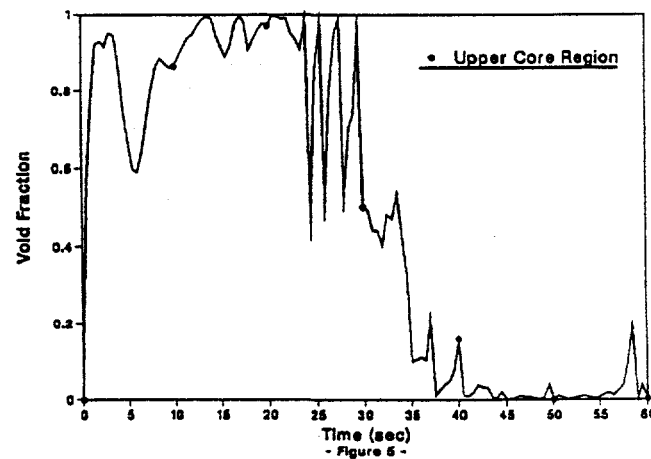
- Figure 3 -

VVER-440 LARGE BREAK LOCA - 50cm
Outlet Plenum Void Fraction



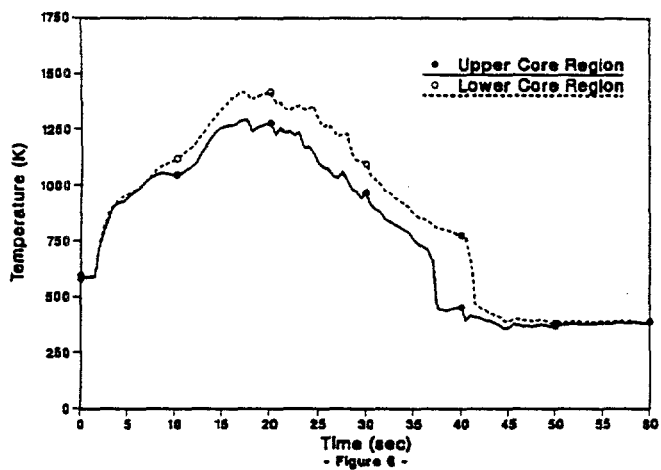
- Figure 4 -

VVER-440 LARGE BREAK LOCA - 50cm
Upper Core Void Fraction

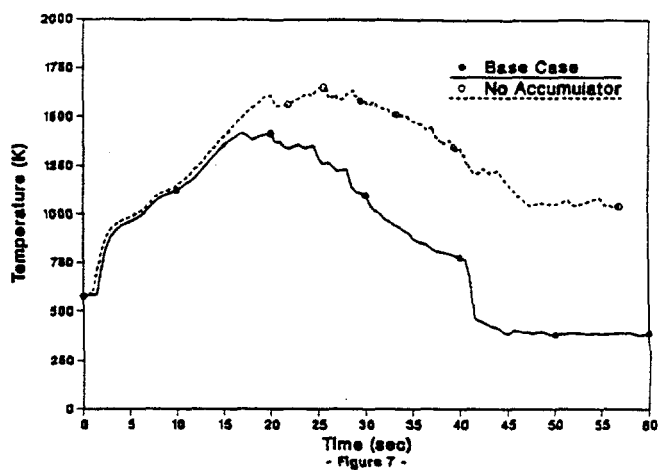


- Figure 5 -

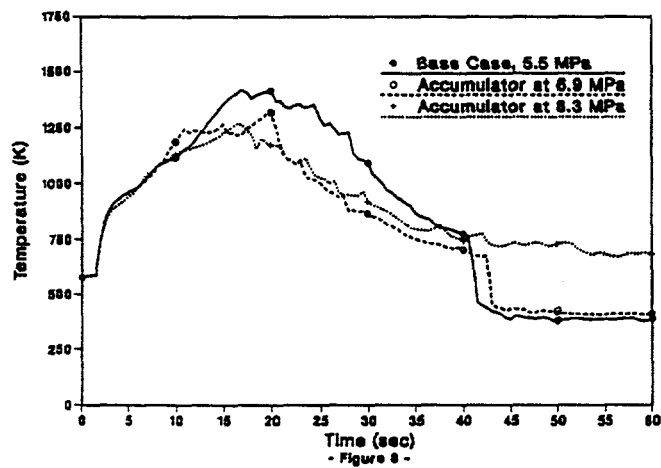
VVER-440 LARGE BREAK LOCA - 50cm
Clad Surface Temperature



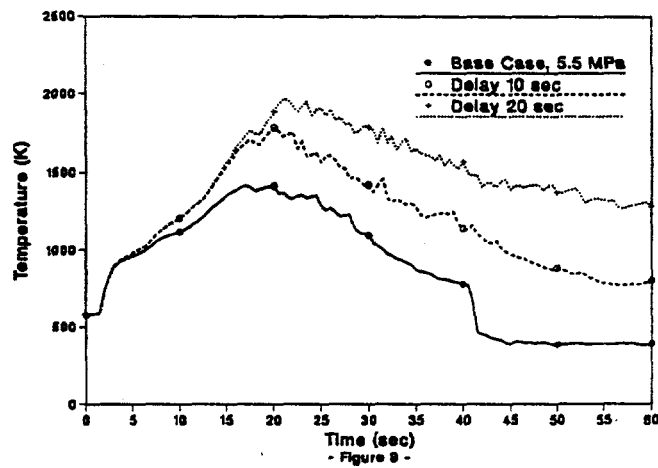
VVER-440 LARGE BREAK LOCA - 50cm
Clad Surface Temperature



VVER-440 LARGE BREAK LOCA - 50cm
Clad Surface Temperature



VVER-440 LARGE BREAK LOCA - 50cm
Clad Surface Temperature



VVER-440 MEDIUM BREAK LOCA - 20cm
Clad Surface Temperature

