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MSIV-CLOSURE ATWS MITIGATION OF SBWR WITH THE STANDBY LIQUID CONTROL SYSTEM

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ABSTRACT

An Anticipated Transient Without Scram (ATWS) initiated by inadvertent closure of the Main Steam Isolation Valve has been analyzed using the RAMONA-4B code of Brookhaven Laboratory (1994). The Simplified Boiling Water Reactor (SBWR) operating in natural circulation is designed with many passive safety features. This analysis demonstrates the effectiveness of the heat-removal system during an ATWS, followed by shut down of the reactor through injection of boron into the reactor core from the Standby Liquid Control System (SLCS).

INTRODUCTION

The new design of light-water reactor known as the Simplified Boiling Water Reactor (SBWR) is a unique combination of several inherently safe operating features. Detailed description of the various emergency and non-emergency safety features are available in the SSAR (General Electric,1992). The present study will focus on Main Steamline Isolation Valve (MSIV) closure ATWS events and the related safety features for safe shutdown of the reactor. The analysis tool is the versatile RAMONA-4B code (Brookhaven Report, 1994), which is an upgraded version of RAMONA-3B (Wulff et al., 1984), modified for SBWR applications. The Isolation Condensers (IC) in the SBWR are designed to remove heat passively from the Reactor Pressure Vessel (RPV). The boron injection system coupled to the Standby Liquid Control System (SLCS) is a backup system available to the reactor in case of failure of the Alternate Rod Insertion (ARI) and the Fine Motion Control Rod (FMCRD) system. The IC and the SLCS system of RAMONA-4B will be utilized in this analysis for heat removal and shutdown of the reactor following an Anticipated Transient Without Scram (ATWS) initiated by the closure of Main Steam Isolation Valve.

Isolation of the reactor by the MSIV can be initiated by several setpoints, including high steam line flow, low steam line pressure, low water level within the downcomer of the RPV, or manual initiation by the operator. MSIV Closure is followed by a series of trips related to the operation and shutdown of the reactor. There are two MSIVs on each steam line (one inside the containment and one outside) from the steam dome leading to the main turbine through the turbine control valves. It takes approximately 4 seconds for full closure of these pneumatically controlled isolation valves. The closure of the MSIVs result in a pressure rise within the RPV, which leads to opening of the Safety Relief Valves (SRVs) at the preset pressures. Periodic opening and closing of the SRVs are typical of MSIV closure ATWS. Regulation of pressure within the RPV can be seen through the transient pressure results.

Increase in pressure within the RPV due to closure of the main steam line is controlled by the SRVs. Subsequent heat removal from the RPV is also accomplished by the initiation of the Isolation Condenser System, following 15% closure of the MSIV. These two systems in combination govern the system pressure following the ATWS. Loss of inventory to the suppression pool through the SRVs is reflected in the collapsed liquid level within the vessel. However, increase in system pressure, following MSIV closure, causes a core-wide void collapse. Because of negative void reactivity feedback, the void collapse leads to an increase in the thermal power of the reactor.

The SLCS is activated following loss of inventory (downcomer water level reaching Level 2) or high RPV pressure (7.76 MPa) sustained for a period of 150 seconds. This results in a rapid shutdown of the reactor due to high-pressure injection of concentrated boron solution. Reduction of the reactor power and shutdown of the reactor within 300 seconds from the initiation of the transient has been demonstrated in this study. The peak cladding temperature and maximum fuel temperature are found to remain less than 1200°C during the entire transient.

RAMONA-4B Code

In the RAMONA-4B code, individual components of a BWR and SBWR have been modeled. The core model includes 3D neutronics based on one- and half-group diffusion theory. Six delayed-neutron groups are used in the neutronics calculation. The void, moderator temperature, and Doppler reactivity feedbacks on core power generation are used to couple the neutronics to the core thermal hydraulics. In the natural-circulation system, the neutronics feedback feature is exceptionally useful, since the core flow rate is strongly coupled to the core thermal power. A two-phase drift-flux model for nonequilibrium, nonhomogeneous flow through parallel channels is used to solve two phasic mass balance equations with mixture momentum and energy balance equations. A schematic diagram of the calculational model used in RAMONA-4B is presented in Figure 1.

A detailed description of the governing equations and the constitutive relations are given in (Wulff et al., 1984, Brookhaven Report, 1994). A description of the core neutronics modeling and governing equations of thermal hydraulics is also presented there. The models implemented into RAMONA-4B, relevant to the MSIV closure ATWS event of the SBWR design, are the Isolation Condenser System, local boron transport, and the Standby Liquid Control System. Modeling assumptions and other details of the IC system have already been reported [4]. Therefore, a brief description of the IC will be provided here.

The SLCS model is used to determine the flow rate of sodium pentaborate solution for injection into the RPV. The boron transport problem is solved through a local boron mass conservation equation within the RPV. A detailed description of the SLCS model will also be presented here.

Isolation-Condenser System

The isolation condensers (Ics) are designed to remove heat passively after the reactor is isolated and normal heat-rejection options are not available. Ics are heat exchangers used to release heat to large compartmentalized tanks called the PCCS/IC pools. Make-up water to the pool ensures that the tubes are always covered and a constant level of water is maintained in the pool. The Ics are initiated automatically by any one of the following three events:

1. 15% closure of the MSIV,
2. High pressure within the RPV,
3. Low level (Level 2) within the RPV.

The Ics are activated by opening of the motor-operated condensate return valves. The liquid within the tubes drains at the beginning. The empty tubes are then available for internal condensation. Steam enters the Ics directly from stub tubes connected to the steam dome. Condensation of steam from the reactor continues within the tubes while the temperature of the pool water increases, resulting in nucleate pool boiling on the tube outer surfaces. Continuous condensation of steam within the Ics helps in maintaining a reduced pressure in the RPV.

In the RAMONA-4B code, the IC is modeled as a single control volume with variable cross sections due to the upper header, lower header, and multiple vertical tubes. Steam entering through the upper header is condensed and returned by gravity-induced flow to the RPV. Transient mass and energy balance equations are used to solve for pressure and enthalpy within the IC, while the momentum change in the IC is assumed to be negligible. Steam inflow and condensate outflow from the IC are determined from quasi-steady-state momentum balances applied to the inlet steam line and the condensate return line. Influence of the isolation condensers on a BWR's system pressure regulation has been demonstrated earlier [Khan et al., (1993)]. The cycling frequency (opening at the high-pressure setpoint and closing at the low-pressure setpoint) of the SRVs, is found to reduce with the usage of the Ics. Similar influence on the SBWR system is expected to occur.

Standby Liquid Control System

The Standby Liquid Control System (SLCS) is a safety-related system designed for manual or automatic initiation of boron injection into the RPV. This system comprises the following:

(1) High-pressure accumulator containing concentrated boron solution,
(2) Injection line with control valves,
(3) Control System coupled to the reactor operating set points.
(4) Cover-gas pressure-regulation system.

In the RAMONA-4B code, the SLCS system has been modeled based on the geometric and operating specifications given in the SSAR for SBWR of General Electric (1992). The control logic for activation of the system has also been implemented within the guidelines. The SLCS system of SBWR is the source of a high concentration (12.5%) of sodium pentaborate solution available for hot or cold shutdown of the reactor in case of failure of the normal control-rod system.

A schematic diagram of the processes in the SLCS system is presented in Figure 2. The SLSC accumulator tank is modeled as a single control volume with pipe line for liquid draining. High-pressure injection of boron solution into the bypass region of the core is also modeled. Boron transport throughout the RPV is accomplished by solving the boron mass balance equation in each hydraulic channel.

SLCS Modeling Assumptions:

1. The accumulator tank of the SLCS is modeled as a single control volume.
2. The cover gas expands polytropically during draining.
3. The liquid is incompressible and the flow within the pipe is fully developed.
4. The fluid properties are averaged within each phase

across the interface.

5. There is no refilling during the period of draining.
6. The system is at a thermal equilibrium.
7. The control logic is fixed during a transient.

The accumulator tank is connected to the RPV through valves and control logic based on system operation setpoints. Actuation of the SLCS system is therefore integrated to the RPV operating conditions, and the pressure at the liquid return port is used as the boundary condition to the transient solution of flow.

Momentum balance between tank and RPV return port is given by :

$$\frac{dV_L}{dt} = \frac{1}{L}\left(\frac{P_1 - P_3}{\rho_L} + g\,(L_1 + L_2)\right) - \frac{1}{L}\left[0.5\left(\frac{C_f P_w L}{A}\, V_L^2 + (1+k_c)\, V_L^2\right)\right] \qquad (1)$$

where V_L, P_1, and P_3 represent velocity of boron solution at the entrance to the RPV, cover-gas pressure, and RPV return-port pressure, respectively.

Constitutive Relations

The wall friction coefficient C_f in Equation 1 is obtained as follows,

For laminar flow:

$$C_f = \frac{16}{Re} \quad ; \quad Re < 2500 \ . \qquad (2)$$

For turbulent flow:

$$C_f = \frac{0.079}{Re^{0.25}} \quad ; \quad Re > 2500 \ , \qquad (3)$$

where the Reynolds number is defined as,

$$Re = \frac{\rho_L D V_L}{\mu_L} \ . \qquad (4)$$

Polytropic expansion of cover gas

Nitrogen cover gas is maintained at a high pressure P_1, which is a user-specified quantity. Liquid draining from the control volume is accompanied by expansion of the cover gas during the period of a transient. Polytropic expansion of this cover gas is as follows:

$$\frac{dP_1}{dt} = -\frac{nP_1}{\alpha v_t} V_L A \ , \qquad (5)$$

where n is the coefficient of expansion of the cover gas, and the definition of the void fraction within the tank is $\alpha = v_G/(v_G+v_L)$. v_t and A represent total volume of the tank and the pipe flow area, respectively.

The rate of change of the void fraction within the tank is given by,

$$\frac{d\alpha}{dt} = \frac{V_L A}{v_t} \ , \qquad (6)$$

which is used to track the level within the accumulator.

Liquid flow rate to RPV

The liquid velocity and gas pressure are obtained from the simultaneous solution of the coupled differential Equations 1 and 5. Liquid flow rate to the RPV is calculated from

$$\dot{W}_L = A V_L \rho_L \ , \qquad (7)$$

$$\dot{W}_B = C_B \dot{W}_L \ , \qquad (8)$$

where
C_B = Boron concentration
ρ_L = Liquid density = $\rho(P_1)\, G_s$
G_s = Specific Gravity

Control Logic of SLCS Operation

The control logic of SLCS actuation in the SBWR has been implemented into RAMONA-4B. The time delay associated with the signal transmission, valve actuation, and others are user-specified inputs. For the SBWR design, ATWS-related actuation of the SLCS is as follow:

Automatic power range monitor not downscale (>6%) and either of the following persists for 180 seconds;

(1) P_{dome} > 7.76 Mpa
(2) Level < Level 2 (14.423m above RPV base)

TRANSIENT PROBLEM DESCRIPTION

RAMONA-4B code has been used to predict MSIV Closure ATWS of the SBWR using the following system operating conditions and boundary conditions.

System Operating Conditions:

Pressure:	7.205 MPa
Rated power:	2000 MW
Feedwater Flow Rate:	1080 kg/s
Core flow rate:	7560 kg/s
Core inlet subcooling	9.125 °C

MSIV Closure ATWS Boundary Conditions:

(1) Manual closure of MSIV within 4.5 seconds, beginning at time t = 0.
(2) Feedwater flow coastdown within 20 seconds, beginning at time t = 0.
(3) Isolation condenser automatically initiated.
(4) Alternate Rod Insertion (ARI) is assumed to have failed.
(5) Fine-Motion Control Rod (FMCRD) is assumed to have failed.
(6) SLCS is available for reactor shutdown at automatic setpoints.
(7) Control-Rod Drive (CRD) flow available to the RPV.
(8) Safety Relief Valves operating normally.

RESULTS

Inadvertent MSIV Closure ATWS

Transient calculation using RAMONA-4B code was performed to predict the performance of the SBWR following a closure of the MSIV. Automatic closure of this valve can be due to several abnormal operating conditions, which include low level within the RPV, high steam flow rate, or low pressure. In addition, manual initiation of the MSIV can also be made. The sequence of events following the closure due to any of these events are qualitatively similar in time. In this analysis, a manual closure of the MSIV was initiated at time 0.0 second. The feedwater flow was tripped simultaneously, which completed within 20 seconds. Closure of the MSIV was followed by automatic initiation of isolation condensers and the transient was ended by boron injection into the bypass region of the core from the standby liquid control system.

In order to perform the calculation with reasonable computational efforts, one quarter of the core was simulated with SBWR cross sections at the beginning of equilibrium cycle. Symmetry of the reactor core allows us to use this configuration without any loss of information. A total of 183 neutronic channels and 183 thermal-hydraulic channels were considered with 18 axial nodes in the core. Five uniformly distributed spacers are located along the axial height of the core. Figure 3 shows the transient pressure response during the ATWS. Because of the closure of the MSIV, the pressure rises rapidly from 7.2 MPa to 9.2 MPa within 25 seconds. This rise in pressure causes several trips to activate. At a pressure of 7.447 MPa, the signal for Isolation-Condenser activation is initiated, which has a signal transmission delay time of 1 second, and the liquid return line valve opening time of 0.5 seconds. At a pressure of 7.76 MPa, (with a power not less than 6% of normal), the signal for SLCS is activated with a delay period of 150 seconds. The signal transmission delay time is assumed to be 0.5 seconds, with a valve opening time of 1 second.

The Safety Relief Valves in the two banks are opened at pressures of 8.72 and 8.858 MPa. With the opening of all the SRVs, the system pressure reduces rapidly until 70 seconds into the transient. Reduction below the SRV closing setpoint of 8.513 MPa causes the first bank of SRVs to close. Since the reactor power is still high, steam generation causes the pressure to rise again. The cyclic operation of this bank of SRVs is evident from 55 to 150 seconds into the transient, during which period the low-pressure SRV bank remains open. This can be referred to as the first phase of the transient. Since the RPV pressure remains below 8.858 Mpa, the high-pressure SRVs remain closed during the following part of the transient. The pressure variations during the second phase of the transient ($t > 180$ seconds) is solely due to the low-pressure SRVs. As shown in Figure 3, cyclic operation of the low-pressure SRVs are observed from 180 to 280 seconds.

The steam and feedwater flow results are presented in Figure 4. The feedwater was tripped at time 0.0 second as a boundary condition. Automatic initiation of the IC has resulted in condensate flow into the RPV. In addition, a boundary condition for Control-Rod Drive (CRD) flow has been modeled. For the SBWR, this flow amounts to 5% of the rated feedwater flow of reactor is found to enter around 70 seconds into the transient.

Condensate flow from the IC into the RPV occurs in two stages. The tubes of the isolation condenser are full of liquid during normal operation of the reactor. During the early part of the transient, within 30 seconds, the liquid from the IC tubes and part of the return line drain into the reactor in the downcomer region. However, after the initial draining period, this flow rate is equal to the rate of steam condensation in the IC.

Since the MSIV is closed, the steam flow rate in Figure 4 represents the flow through the SRVs to the suppression pool. During the first phase of the transient (between 50 and 150 seconds), the steam flow rate equals to the sum of the two SRV banks. In the second phase, a lower flow rate from the low-pressure SRV bank is evident in Figure 4. According to Figure 5, with the feedwater trip, the liquid level in the RPV drops rapidly in the early part of the transient until 180 seconds.

The increase in pressure is accompanied by a core-wide collapse of voids during the first 20 seconds of the transient, as shown in Figure 6. Since RAMONA-4B accounts for void reactivity feedback, the reduced void fraction is accompanied by a positive reactivity insertion. Consequently, the fission power increases to a peak value at 2 seconds, as shown in Figure 7. Thermal power is found to reach its peak value at 20 seconds as well. After the initial collapse of the void fraction, reduction in the RPV pressure is accompanied by the increase in void fraction from 37.5% to 47.5%. The mean void fraction remains in this higher value during the time period of 70 to 170 seconds.

The SLCS system is designed as an additional backup for reactor shutdown in case of a failure of the normal SCRAM system during an off-normal operation. The accumulator tank is charged by a nitrogen cover gas to be maintained at a pressure of 14.78 Mpa. The flow rate of sodium pentaborate solution into the RPV decreases the pressure in the tank, while the power reaches the decay-heat level. After reaching the setpoint pressure of 7.76 MPa in the RPV, the SLCS was initiated with a delay time of 150 seconds. The fission power in Figure 7 is seen to drop off from 60% to 10% as a consequence of boron injection following this period. High-pressure injection of highly concentrated boron into the bypass region therefore effectively shuts down the reactor within the next 150 seconds as shown in Figure 7.The second phase of the transient consists of the boron-injection period and consequent shut down of the reactor. The vapor generation rate drops during this period, causing a core void-fraction reduction from 45% to 35%. Strong coupling between the flow and power in the natural-circulation system of the SBWR has resulted in the reduction of core inlet mass flow rate during the entire transient as shown in Figure 8. This reduction of the core inlet flow rate is accompanied by flow reversal in the hydraulic channels and the bypass channel. Since highly enriched sodium pentaborate solution has been injected into the bypass channel, boron transport to the core region is aided by the flow reversal. The path traversed by the concentrated boron solution from the injection points to the fuel region is thereby minimized.

Conclusions:

The SBWR safety features have been proposed by General Electric to achieve shutdown of the reactor following an MSIV closure ATWS event. Analysis using the RAMONA-4B code shows that, after the closure of the main steam line, system pressure increase is accompanied by core-wide void collapse. Void reactivity feedback causes a corresponding increase in fission power and subsequent vapor generation. The isolation condensers in conjunction with the SRVs regulate the system pressure by removing heat from the RPV to the IC pool and suppression pool, respectively. The cyclic operation of the SRVs is followed by injection of concentrated boron solution into the RPV from the standby liquid control system. Shutdown of the reactor within 300 seconds of the transient is predicted by RAMONA-4B calculations.

ACKNOWLEDGEMENTS

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Nomenclature

A	=	Return pipe area
C_f	=	Wall friction coefficient
k_o	=	Line loss coefficient
ρ_L	=	Solution density
L	=	Total pipe length
L_1	=	Liquid level in tank
L_2	=	Height of return pipe
P_1	=	Cover-gas pressure
P_3	=	RPV return port pressure
P_w	=	Perimeter of the pipe wall
V_L	=	Velocity of Liquid at RPV inlet

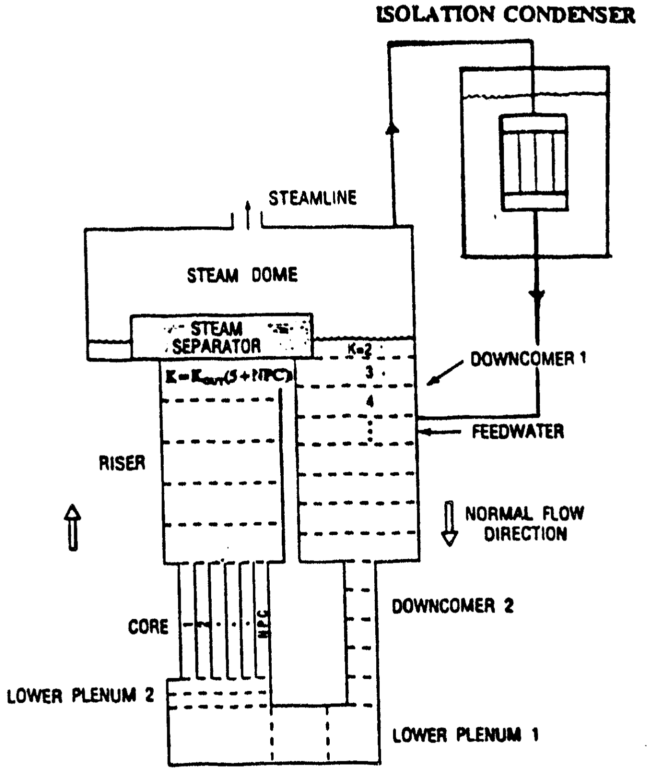

Figure 1. Schematic Diagram of RAMONA-4B Calculational Model.

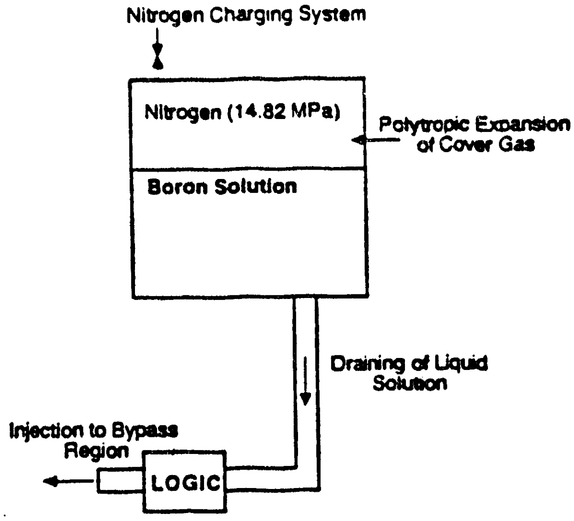

Figure 2. Schematic Diagram of the SLCS model

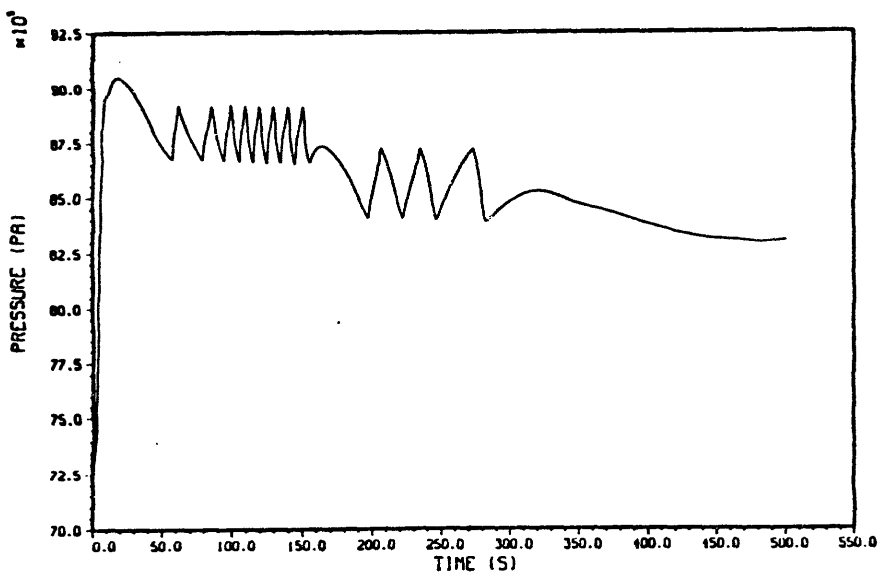

Figure 3. Transient Pressure of RPV During the ATWS

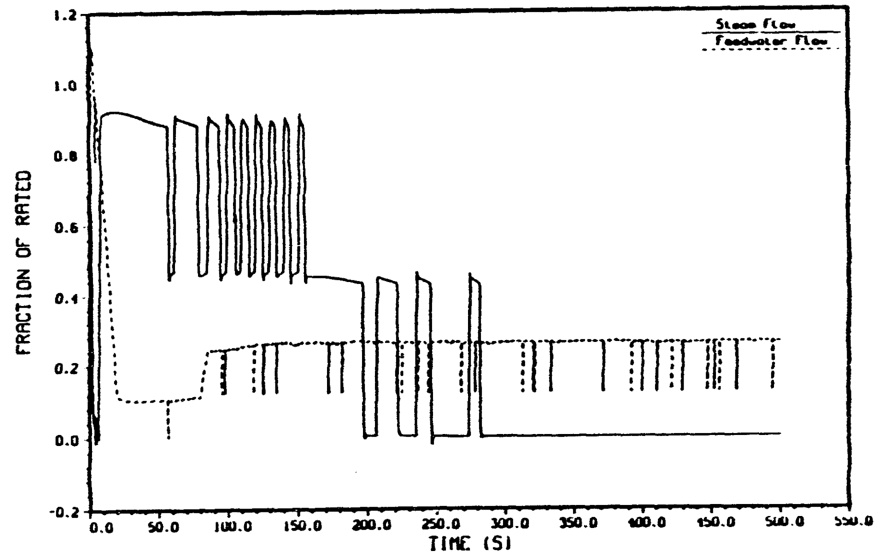

Figure 4. Steam and Feedwater Flow Rate During the ATWS

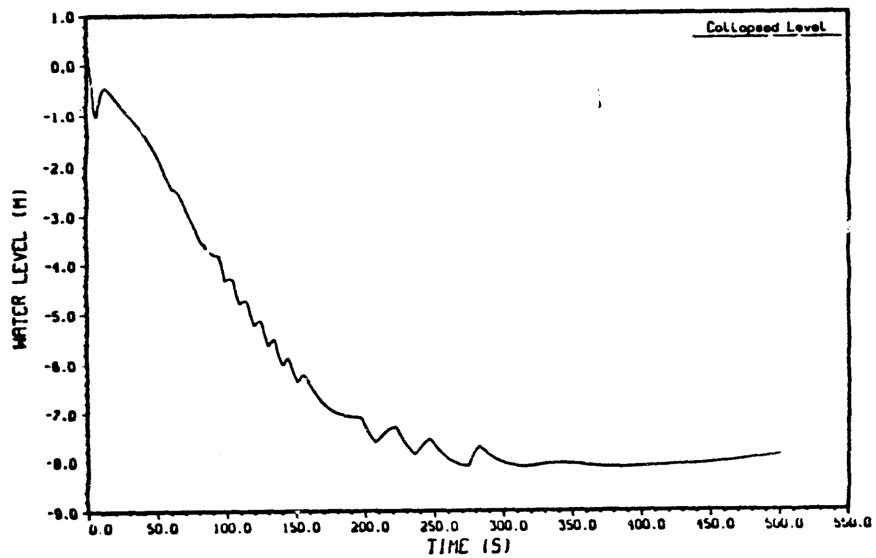

Figure 5. Liquid Level in Downcomer During the ATWS

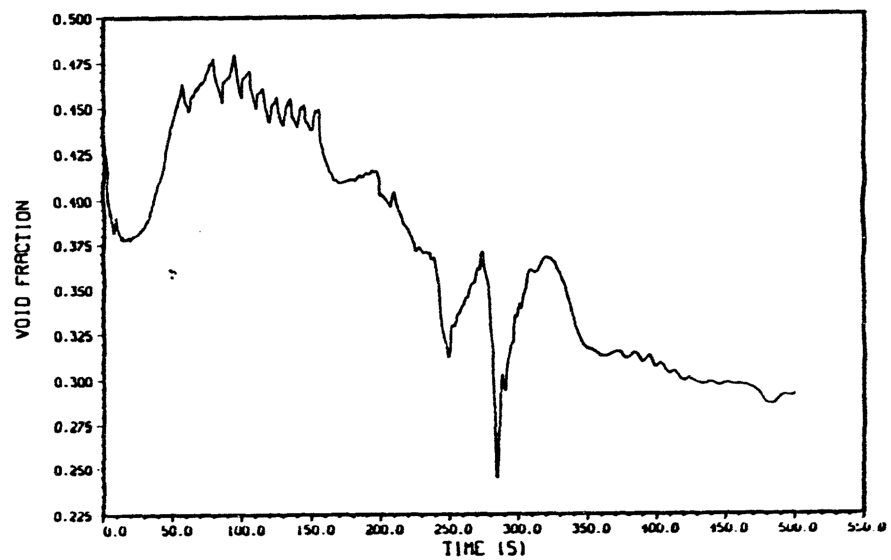

Figure 6. Void Fraction in RPV During the ATWS

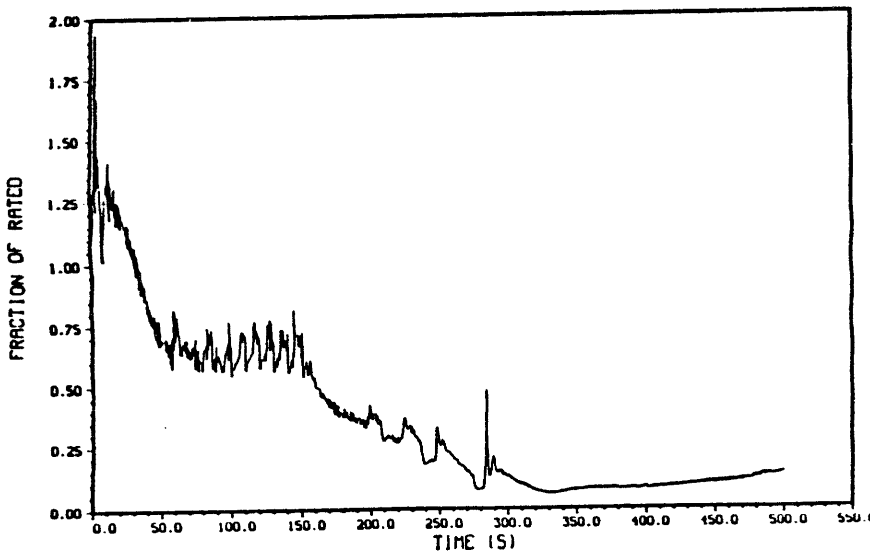

Figure 7. Fission Power During the ATWS

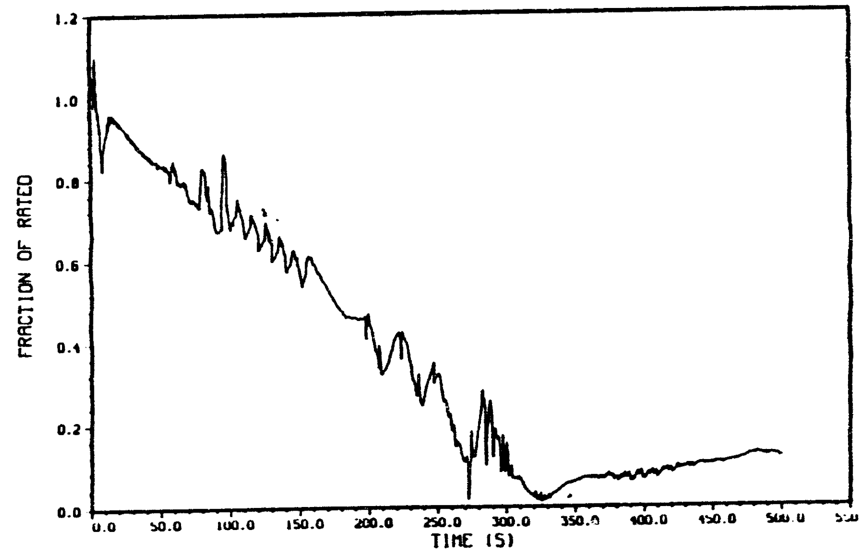

Figure 8. Core Flow Rate During ATWS

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