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Thermal-Hydraulic Analysis of Total Loss of Steam Generator Feed Water in VVER-440

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1. Introduction

The analysis is carried out for a VVER-440/V270 with upgraded primary safety valves (replacement of the existing PRZ safety valves with Pilot Operated Relief Valves (PORV) of the type SEBIM (France))

The current analysis is focused on the scenario "Total Loss of SGs Feed Water" with application of the operator action of primary system "Feed and Bleed" in order to check the effectiveness of the installed pressurizer SEBIM valves and to verify that the operator can cool down the reactor system and cope with this accident. The calculations have been performed at the Institute of Protection and Nuclear Safety (IPSN) in Fontenay-aux-Roses with the computer code CATHARE 2 Version 1.3L_1. CATHARE is a French best estimate thermal-hydraulic program for accident analysis in the light water nuclear reactors, developed with the participation of the IPSN (Institut de Protection et Sûreté Nucléaire), CEA (Commissariat à l'Energie Atomique), Framatome and EdF (Electricité de France).

2. Description of the scenario

The chronology of the scenario "Total Loss of SG Feed Water" is the following:

The reactor is operating at the initial nominal power 100%.

At t = 0 sec. the loss of the SG feed water occurs.

The SG level starts to decrease rapidly because of the water evaporation and the steam flow to the turbine.

Due to the SG low level (0.4 m below the nominal) reactor scram occurs. The Emergency Feed Water fails to start.

As a consequence of the reactor scram turbine trip occurs with a delay of 10 sec. after the scram.

Without operator intervention the loss of the feed water leads to voiding of the SG secondary side, uncovering of the SG tube bundles and loss of the SG as a heat sink in order to remove the decay heat. The primary pressure remains high, significant primary mass inventory is released through the PRZ safety valves, the reactor core uncovers, fuel cladding temperatures increase and as the consequence the core melt takes place.

To cope with the accident the operator has to take measures in order to **remove the residual heat** and in the same time to ensure **sufficient primary coolant mass inventory**. This can be achieved by "Feed and Bleed" action:

- **Feed** by **safety injection** manual operation
- **Bleed** by opening **pressurizer safety valve**(s)

In proper time the operator can also trip the MCP in order to reduce the heat released by the pumps to the primary fluid.

3. Assumptions

3.1. Total Loss of SG Feed Water

It is assumed a **Loss of Main Feed Water of the SG at t=0 and failure of the Emergency Feed Water pumps**.

3.2. Reactor scram signal

The following signals for actuation of EP- 1 are used:

- "low level in 2/6 SG" (-0.4 m below the nominal level) or
- "low pressurizer level" (-2.56 m below the nominal level) or
- "low primary pressure" ($P1 < 9.32$ MPa) or
- "high primary pressure" ($P1 > 13.7$ MPa)

3.3. Loss of power

Normal power supply is assumed. Nevertheless, in some of the sensitivity studies loss of power is considered to take place at time of signal of reactor scram.

3.4. Heat sources

3.4.1. Axial core power distribution

The axial core power distribution is taken at the end of cycle as more conservative.

3.4.2. Reactor power law vs. time

Reactor power is assumed to remain at the initial level (100 % nominal), as long as the reactor trip signal defined in 3.2 has not been elaborated. After this time, a global power table is used, worked out by CATHARE calculation modeling the rod insertion with neutron kinetics with 6 groups of delayed neutrons (until 14.3 sec) and then ANS + 0% (A+B+C terms) power law is used.

3.5. Main coolant pumps

The main coolant pumps are inertial pumps of the type ZN-65-130 as the pumps of the reactors WWER-440/V213 (7100 m^3/h, $\Delta P=0.42$ MPa). In the basic case the operator stops the pumps when the SGs are no more effective and their mechanical coast down starts. In the cases with loss of power it is assumed that the MCP start their rundown with the reactor scram.

3.6. Pressurizer Safety Valves

According to the modernization programme two pilot operated relief valves are considered. They are of the type "TANDEM" of the French firm "SEBIM".

The PRZ Safety Valves have the followings characteristics:

PRZ first safety valve:

- opening set point: 14.4 MPa
- closing set point: 12.56 MPa

PRZ second safety valve:

- opening set point: 14.8 MPa
- closing set point: 12.56 MPa

Maximal steam flow rate through first PRZ safety valve = 30 kg/s at 14.4 MPa.

3.7. Emergency Core Cooling System

This system consists of:

- Emergency water tank (EWT) with borated water (12000 ppm, 800 m^3). The water is heated up to 55 °C in order to avoid cold thermal shocks to the reactor vessel.
- Two trains of 3 centrifugal HPSI pumps per train. The pumps of the first train are discharging in common collector and then injecting water into the six cold legs **upstream** of the MCP. The pumps of the second train are discharging also in common collector and then injecting water into the six cold legs **downstream** of the MCP.

Several scenarios have been calculated with the use of **one to four pumps**, actuated by the operator.

An assumption relies on the criterion for the operator to start one or more HPSI pumps when the core exit temperature increases to **320 °C** (see 3.8 Operator action).

The Safety injection flow rates of the HPSI pumps, delivered to the Reactor Coolant System, are function of the backpressure at the injection location.

3.8. Operator action

As a criterion to start the operation "Feed and Bleed" it is assumed the moment when the core exit temperature increases to the criterion of **320 °C** (about 20 °C margin to the saturation temperature at the PRZ SV opening pressure 14.4 MPa). The operator opens one or two pressurizer safety valves and starts one or more HPSI pumps. At the moment when the SGs become ineffective (low secondary side liquid mass: ~4%) he can stop the MCPs in order to reduce the energy, which they release to the primary coolant.

3.9. Secondary circuit

- **Turbine :**

  It is assumed that the stop valves of the two turbo-generators are closed 10 s after the reactor scram signal.

- **Main Feed Water**

  Main Feed Water is assumed lost at time t=0 sec.

- **Emergency Feed Water**

The Emergency Feed Water injection (on low SG level signal or station blackout)) fails.

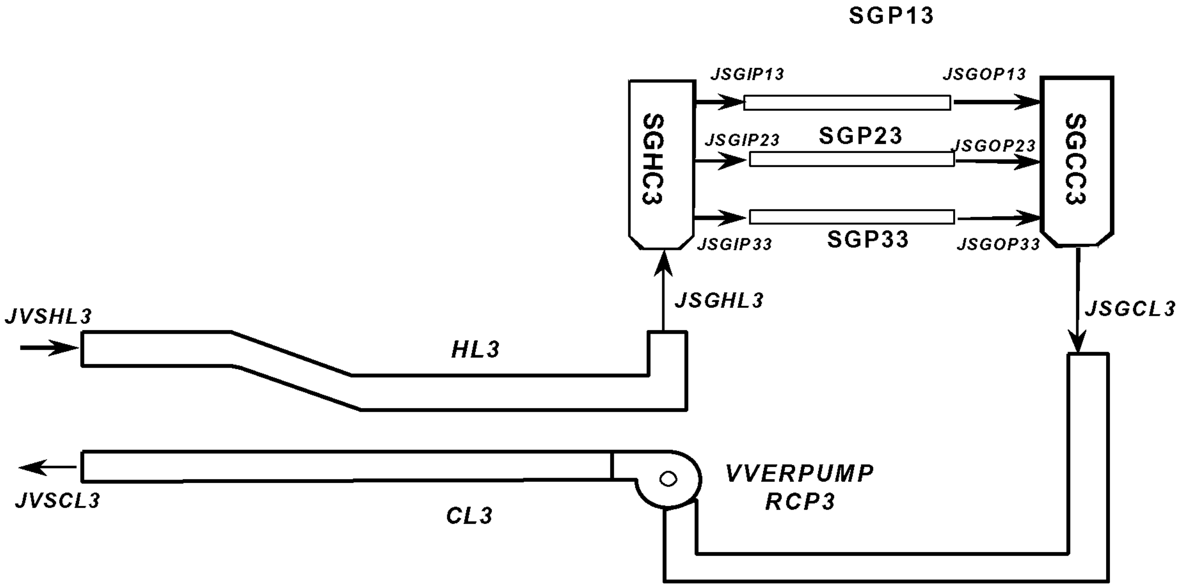
- **SG Safety Valves, Steam dump to the condenser (BRU-K) and Steam dump to the atmosphere (BRU-A) are available.**

4. The CATHARE input model

4.1. Primary circuit

The primary circuit nodalization scheme is shown in Fig 1. The circuit is modeled with axial elements, volumes and T-junctions. There are 3 single loops and one triple loop with the three loops lumped together. In one of the single loops the pressurizer is connected. In the reactor vessel the downcomer, core, bypass, upper plenum and dome are modeled. The scheme illustrates also the modeling of the hot and cold legs, pressurizer and PRZ surge line and the horizontal three tube bundles Steam Generators.

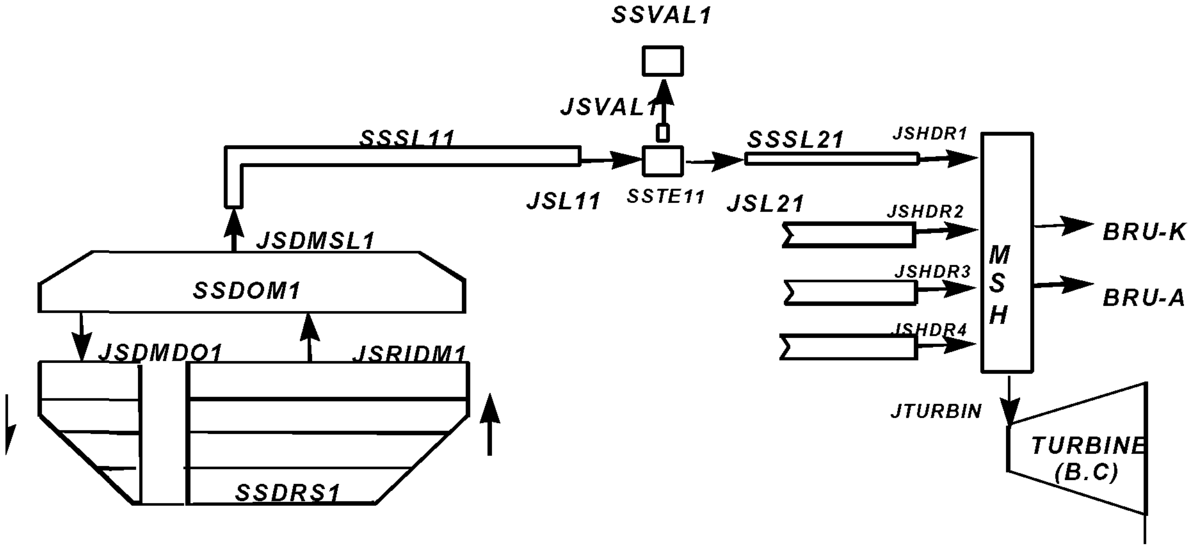
Fig. 1 CATHARE primary circuit nodalization scheme



4.2. Secondary circuit

The secondary side of the steam generator is represented with a recirculation model with a volume element SSDOM1 (2,3,4) and an axial element SSDRS1 (2,3,4) with downcomer and riser parts of the recirculation circuit. The thermal connection with the primary circuit is modeled in the riser part with three heat exchanging tube bundles. The steam lines to the turbine are modeled with axial elements and volumes for connection of the steam dump devices BRU-A, BRU-K and safety valves. The CATHARE secondary circuit nodalization is shown in Fig 2.

Fig. 2 CATHARE secondary circuit nodalization scheme (Loop1)



4.3. Regulation and safety systems

The CATHARE model for the TLFW calculations includes the following principal systems of the NPP:

- Pressurizer safety valves
- HPSI pumps
- Steam dump device to the condenser (BRU-K)
- Steam dump device to the atmosphere (BRU-A)
- Steam generator safety valves

The complete stop of the feed water flow to SGs is modeled by the closing of the "source" component for the feed water flow.

The closing of the turbine stop valves is modeled by replacing the pressure boundary condition at the turbine by a "blind" boundary condition (imposed velocities), which decreases the steam flow rate to zero within one second.

The PRZ safety valves opening and closing are modeled by imposing the full opening valve cross section or zero cross section respectively.

The same approach is used for modeling of the steam dump devices BRU-K and BRU-A and the delay time of 12 seconds for opening and closing is taken into consideration.

The HPSI pumps are modeled as "sources" injecting water into the cold leg with mass flow as a function of the primary pressure.

5. Results of the calculations

The Total Loss of Feed Water (TLFW) is a Beyond Design Basis Accident (BDBA).

As mentioned before complementary operator measures are necessary in order to cope with this accident. Without adequate operator intervention, this scenario leads to severe consequences. In order to quantify the parameters and illustrate the process a case **without "Feed and Bleed"** action has been calculated (**Case0**).

The basic case (Case34) calculated comprises the **"Feed and Bleed"** action by the operator with opening of **one PRZ safety valve**, starting **2 HPSI pumps** and stopping the **MCP when the SGs are no more effective**.

The basic case has been selected after a series of **sensitivity calculations**, which has been carried out to investigate the time available to the operator to apply the **"Feed and Bleed"** action and to find out the optimal cooldown of the reactor system in order to cope with the accident. They include calculations with combination of different PRZ SV opened, different HPSI pumps started and different time of trip of MCP without and with loss of power supply.

The transient calculations of TLFW have been performed according to the scenarios described in Chapter 2. Until the application of the "Feed&Bleed" action the chronology of the scenarios Case0 and Case34 is the same.

After the SG Main Feed Water shut-off the secondary mass inventory (Fig.4) and the SG level drop rapidly. At **t = 47.8 sec** the levels in the SGs are **0.4 m** below the nominal level, which induces the signal of reactor scram.

Following the reactor scram a strong primary pressure decrease and cooldown of the RCS take place (Fig.3, Fig.6). The PRZ level decreases (Fig. 5) with flashing of the liquid mass.

The turbine stop valves close 10 seconds after the reactor scram signal. This leads to secondary pressure increase up to the BRU-K opening setpoint of 4.95 MPa (Fig.3) and the steam dump to the condenser starts. After that the pressure regulation system keeps the pressure about the control pressure of 4.61 MPa (Fig.3).

As long as there is water in the SGs the parameters of the reactor systems remain quasi constant, the decay heat is removed by the secondary side (BRU-K remain open). The mass inventory of the secondary system is going down and at t = 7599 sec. (Fig.4) the SGs are no more effective (~ 4% liquid mass inventory) and the heat exchange from primary to the secondary side is not effective. The temperatures and the pressure of the reactor system start to rise (Fig.6, Fig.3). It is supposed that at this moment the operator stops the MCP in order to reduce the heat released to the primary fluid.

As a consequence of the misbalance between the decay heat and SG exchanged power, core heat up takes place. The primary pressure reaches the setpoint of the first PRZ safety valve (14.4 MPa at t=8738 sec). After that, the primary pressure is kept by opening and closing of the PRZ safety valve (Fig. 3).

5.1. TLFW without "Feed&Bleed" (Case0)

At **t = 11717 sec**. the exit reactor temperature reaches the **criterion of 320°C** for operator intervention (Fig.6). In **Case0** it is assumed that no operator action of **"Feed and Bleed"** takes place.

After this moment the periodical cycling (opening and closing) of the tandem "SEBIM" continues and primary pressure is kept between the pressure setpoints of the PRZ SV (14.4 /12.56 MPa). The decay heat is removed by the PRZ SV. With the opening of the PRZ SV and pressure decrease, vapor penetration into the PRZ through the surge line takes place and flashing of the liquid in the PRZ and primary system occurs as well (Fig.5.). Primary mass inventory and core liquid mass are going down (Fig.4). Upper plenum and PRZ levels are decreasing (Fig.5). Core void fraction is increasing (Fig.7).

At **t = 17820 sec**. the upper plenum is empty, its level is equal to zero, reactor core uncovering starts (Fig.7). Core dryout begins with a rapid rise of the fuel cladding temperatures (Fig.8), which reaches the **criterion of 1200 °C** at **t = 19320 sec**. So it is obvious that the NPP cannot cope with this accident without proper operator intervention.

The chronology of the events is summarized in the Table 1.

5.2. TLFW with "Feed&Bleed" (Basic case Case34: F&B-1 SEBIM, 2 HPSI pumps, MCP stop when SG not effective)

In the basic case at **t=11717** sec., when the exit reactor temperature reaches the **criterion of 320°** (Fig.6) the operator begins the action **"Feed and Bleed"** :

- **Bleed** by opening of **1 PRZ safety valve**
- and **Feed** by starting **2 HPSI pumps** (one pump of the first train injecting cold water upstream the MCPs and one pump of the second train injecting cold water downstream the MCPs)

At this moment the PRZ is full of water (Fig.5). With the opening of the SEBIM valve a fast pressure decrease occurs (Fig.3). The maximal total release flow of steam and liquid mixture through the valve is about 100 kg/sec. A flashing of the liquid in the PRZ and primary system can be observed. Primary system cooldown takes place (Fig.6). The heat transfer from primary to secondary circuit is completely stopped at t=13919 sec. The steam dump devices BRU-K close. The decay heat is removed only by the PRZ SV.

The primary mass inventory decreases (Fig.4). Minimal primary total and liquid masses are observed at t=14490 sec. After that the release through the PRZ SV is compensated by the cold water injection of the emergency pumps HPSI and the core masse increases.

The primary pressure becomes equal to the secondary pressure at t=17102 sec (Fig.3). Then further decrease of primary pressure can be observed. At the end of the calculation (T=20000 sec) the primary parameters take the values:

- primary pressure ~1.5 MPa
- primary temperatures ~120°C.

The chronology of the events is summarized in the Table 1.

5.3. Sensitivity studies

One of the **most important parameter** in the sequence Total Loss of SG Feed Water in order to avoid the severe sequences of the accident is the proper **time of operator intervention for starting the action "Feed&Bleed".** This moment is defined when the core outlet temperature is achieving a certain maximal value as criterion in order to have some margin to the saturation at PRZ SV opening pressure and to guarantee sufficient time to undertake remedy measures. In the current study this criterion is taken as **temperature of 320 °C**.

So the **sensitivity calculations** has been performed on these points:

- scenarios **with loss** of power
- scenarios **without loss** of power

This consideration leads to earlier or later MCP trip and earlier or later start of "Feed&Bleed".

Important to the evolution of the process is also:

- number of PRZ SVs opened (1 or 2)

- number of HPSI pumps actuated (1, 2, 3 or 4)

A summary of the sensitivity studies **without loss** of power is shown in the Table 2. The MCP are tripped by the operator when the SGs are no more effective (~4% mass inventory). The results show that operator action for "Feed and Bleed" on core exit temperature criterion above 320°C occurs at 11717 s and the cooldown rate varies from 32°C/h to 214°C/h depending on the number of open safety pressurizer valves and HPSI pumps started. Two additional calculations (Case38 and Case42) have been calculated with MCP trip at **20 min** or **one hour** after the reactor scram. The results are less favorable (around one hour) regarding the time of "Feed&Bleed" action compared to the previous cases. One calculation (**Case 46**) has been carried out imposing a delayed "Feed&Bleed" at t=17820 sec. (beginning of core uncovery and core dry out). Even in such extreme condition the core melt can be avoided, stopping the fuel cladding temperature rise with consecutive cooldown.

A summary of the sensitivity studies **with loss** of power is shown in the Table 3. The MCPs are tripped at the reactor scram. The results show that operator action for Feed and Bleed on core exit temperature criterion above 320°C occurs at 9119 s and the cool down rate varies from 66°C/h to 196°C/h depending on the number of open safety pressurizer valves and HPSI pumps started.

After the analysis of the calculated cases the **Case34** (**F&B-1 SEBIM, 2 HPSI pumps, MCP stop when SG not effective)** is proposed as a **Basic case** because it provides **longer time to the operator to intervene** (**3h 15min)** and a **reasonably fast cooldown** with a smaller void fraction in the reactor core and faster passage from two-phase flow to single-phase liquid core cooling.

It should be noticed that even in the cases of loss of power (**Case39, Case40, Case41**) sufficient time is available to the operator in order to cope with the accident (**2h 30min**).

6. Conclusions

For VVER-440 the accident with **Total Loss of Steam Generator Feed Water without operator intervention (Case0)** leads to **core dryout** which starts **4h 57min** after the beginning of the accident and at **5h 22min** the fuel cladding temperature reaches **Tclad=1200 °C (Case0)**.

The results of the **basic case** calculation (**Case34: F&B-1 SEBIM, 2 HPSI pumps, MCP stop when SG not effective**) show that the operator has at his disposal **at least 3 hours 15 min** to undertake measures for reactor cooldown by primary "**Feed and Bleed**" action:

- **Feed** by **safety injection** manual operation
- **Bleed** by opening **pressurizer safety valve**(s)

But even in the case of loss of power (**Case39, Case40, Case41**) sufficient time is available to the operator in order to cope with the accident (**2h 30min**).

The **Case46** with a '**Feed and Bleed**" action started at the time of core uncovery and begin of dry out, shows that even in such extreme conditions the core melt can be avoided.

For the accident TLFW regarding the criterion "**available time for operator action**" the reactors WWER-440 are more favorable compared to the reactors WWER-1000 and PWR because of the much bigger amount of primary and secondary liquid mass inventory related to the reactor power.

The CATHARE calculations of the TLFW with the assumptions taken into consideration show that the operator by the proper accident management action of "Feed and Bleed" can carry out reliable cooldown of the reactor system, avoid the dryout of the reactor core, the fuel cladding temperature rise and meltdown.

Table 1, CATHARE results of TLFW, Case0 and Case34 (Basic case)

Event	Case0 Operator action : No Feed&Bleed sec	Case34 Operator action : Feed&Bleed sec
Loss of SG Feed Water	0	0
SG low level (DHSG=-0.4 m) Reactor scram signal	47.8	47.8
Reactor scram	49.7	49.7
Turbine stop valve close (Delay after reactor scram signal 10 sec)	58.0	58.0
BRU-K opens (4.95 MPa)	61.2	61.2
SG non effective (~4% liquid mass) MCP trip	7599	7599
First opening and closing of the PRZ SV 1 (14.4/12.56 MPa)	8738/8746	8738/8746
PRZ full of water	11310	11310
Operator action: (TLIQUP>320 °C)	11717 No Feed&Bleed	11717 1 SEBIM open, 2 HPSIP start
Minimal primary liquid mass	--	14490 (129657 kg)
BRU-K steam dump stop	--	13919
Core dry out start	17820	--
Primary pressure = secondary pressure (3.63 MPa)	--	17102
Max. fuel cladding temp.=1200°C	19320	--
End of the calculation	19495	20000

Table 2 Feed&Bleed time and cooldown rate (°C/h) without loss of power

CASE N°	1 PRSZ SV 1 HPSIP	1 PRSZ SV 2 HPSIP	1 PRSZ SV 4 HPSIP	2 PRSZ SV 1 HPSIP	2 PRSZ SV 4 HPSIP	FEED AND BLEED TIME (s)	MCP TRIP TIME (s)
CASE32	32	--	--	--	--	11717	7599
CASE33	--	--	--	107	--	11717	7599
CASE34	--	87	--	--	--	11717	7599
CASE35			164			11717	7599
CASE36					214	11717	7599
CASE34NS		53				10555	NO TRIP
CASE37	35					10555	NO TRIP
CASE38	89					8066	1200
CASE42	--	56				7145	3600
CASE46*	--	142				17820*	7599

CASE46*: F&B is imposed at the beginning of core uncovery and dry out (t=17820 s)

Table 3 Feed&Bleed time and cooldown rate (°C/h) and with loss of power

CASE N°	1 PRSZ SV 1 HPSIP	1 PRSZ SV 2 HPSIP	2 PRSZ SV 2 HPSIP	FEED AND BLEED TIME (s)	MCP TRIP TIME (s)
CASE39	86	--	--	9119	SCRAM
CASE40	--	66	--	9119	SCRAM
CASE41	--	--	196	9119	SCRAM

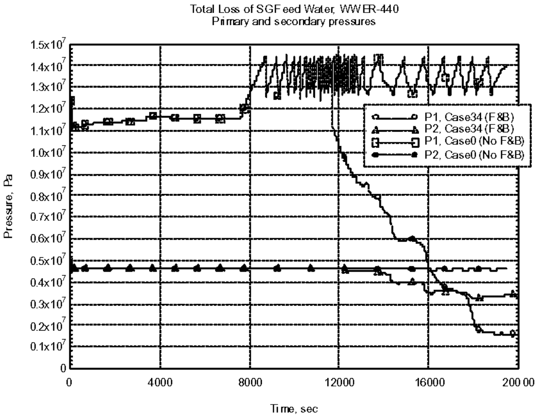


Fig. 3 Primary and secondary pressures

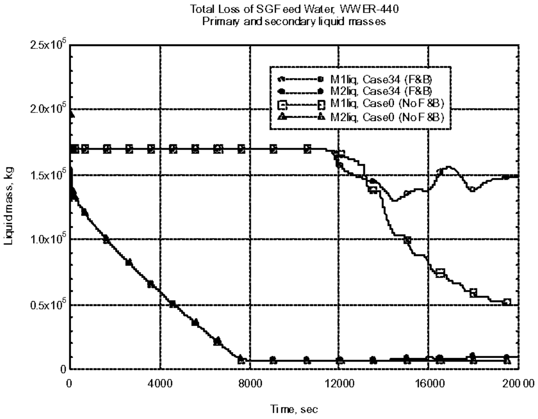


Fig. 4 Primary and secondary liquid masses

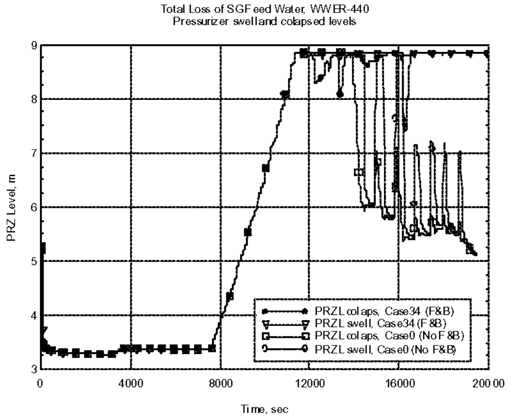


Fig. 5 Presurizer levels

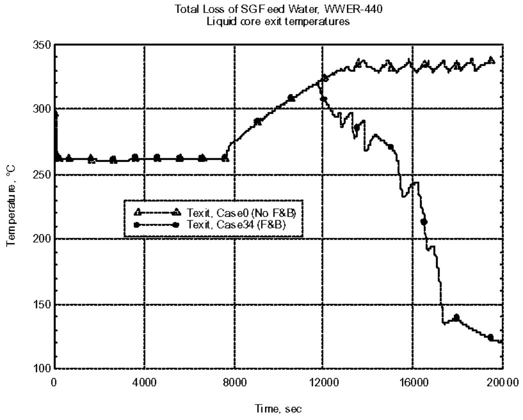


Fig. 6 Core exit liquid temperature

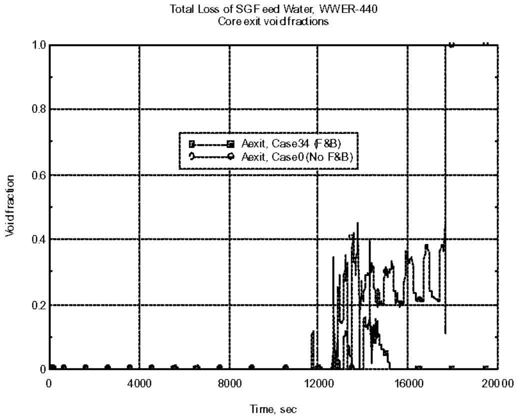


Fig. 7 Core exit void fraction

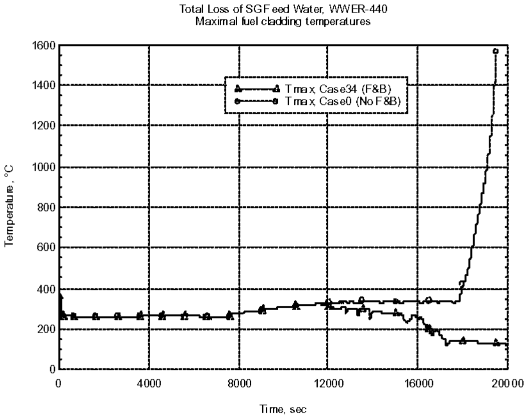


Fig. 8 Maximal fuel cladding temperatures