UK EPR	Title: PCSR – Appendix 16 B – 4900 MW safety analyses used in Chapter 16
	UKEPR-0002-165 Issue 06

Total number of pages: 23	Page No.: I / III
Chapter Pilot: L. GICQUEL *Name/Initials* LG *Date 12-03-2012*	
Approved for EDF by: A. PETIT *Name/Initials* *Date 16-05-2012*	Approved for AREVA by: G. CRAIG *Name/Initials* *Date 15-05-2012*

REVISION HISTORY

Issue	Description	Date
00	First issue for INSA review	14.01.08
01	Integration of co-applicant and INSA review comments	29.04.08
02	Remarking with RESTRICTED classification	16.01.09
03	PCSR June 2009 update: – Clarification of text – Inclusion of references	24-06-09
04	Removal of RESTRICTED classification	10-06-10
05	Consolidated Step 4 PCSR update: - Minor editorial changes	30-03-11
06	Consolidated PCSR update: - References listed under each numbered section or sub-section heading numbered [Ref-1], [Ref-2], [Ref-3], etc - Minor editorial changes	16-05-12

For information address:

AREVA NP SAS
Tour AREVA
92084 Paris La Défense Cedex
France

EDF
Division Ingénierie Nucléaire
Centre National d'Equipement Nucléaire
165-173, avenue Pierre Brossolette
BP900
92542 Montrouge
France

TABLE OF CONTENTS

APPENDIX 16B – 4900 MW SAFETY ANALYSES USED IN CHAPTER 16

0. INTRODUCTION

This appendix contains the EPR Basic Design Report 99 section 19.2.1.3.6 [Ref-1] regarding the RRC-A sequence analysis of a “Small Break Loss of Coolant Accident without Low Head Safety Injection System”. This sequence has not yet been analysed in the framework of these PCSR studies. Therefore, once this analysis is performed, the present information will be deleted from the PCSR and replaced.

1. SMALL BREAK LOSS OF COOLANT ACCIDENT WITHOUT LOW HEAD SAFETY INJECTION SYSTEM (RRC-A)

1.1. IDENTIFICATION OF CAUSE AND ACCIDENT DESCRIPTION

The initiating event is a postulated small break located in the cold leg of the reactor coolant piping system. A small break is defined as a leak with an equivalent diameter of less than 5.0 cm or a cross section area of less than 20 cm^2.

The Risk Reduction Category A (RRC-A) event is identified by the combination of the initiating event and the total loss of a relevant safety system. The total loss of the low head safety injection system is assumed to be caused by a common cause failure. In accordance with the RRC-A guidelines, no additional failures (e.g. single failure or emergency power mode) are postulated in the required systems for reaching the final state of the transient.

After the event initiation, the break mass flow rate increases rapidly to its maximum in a fraction of a second, but decreases as the primary system pressure falls and the flow changes from single-phase sub-cooled liquid to saturated two-phase mixture, with increasing steam quality. The rate of depressurisation changes when flashing and boiling start in the core.

After reaching the reactor trip criterion “pressuriser pressure < MIN2”, the reactor and turbine are tripped automatically within a few seconds. The subsequent pressure transient in the primary and secondary systems depends on the partial cooldown action which is initiated after reaching the RIS [SIS] criterion “pressuriser pressure < MIN3”.

The total mass flow rate of the medium head safety injection system and the accumulators is able to compensate for the loss of coolant through the break and to replenish the primary coolant system.

The final state is reached by manual initiation of secondary side cooldown via the MS bypass station at 50ºC/hour until the pressure is reduced to 0.2 MPa abs.

In the long-term the primary coolant inventory and subcriticality are ensured by MHSI.

The heat removal from reactor coolant system and IRWST is ensured by the cooling chain EVU [CHRS] / RRI [CCWS] / SEC [ESWS].

Final State

It must be demonstrated that the final state (required for RRC-A analyses) can be reached, i.e.

- attainment of long term core subcriticality
- decay heat removal ensured
- activity releases under control with the integrity of radiological barriers

For this demonstration, the following decoupling criteria are considered:

- limited peak cladding temperature
- peak containment pressure below design pressure
- peak IRWST temperature below design temperature

The following systems are available to achieve these criteria:

- the 4-train MHSI compensates for the break flow in the short and long term and ensures long-term subcriticality (however one complete RIS [SIS] train is assumed to be lost due to the break)
- in addition to MHSI, the 2-train RBS [EBS] is available for ensuring subcriticality
- MHSI is effectively ensured by the partial cooldown at 100ºC/h via the MS bypass or the VDA [MSRT]s. It is actuated by the RIS [SIS] signal
- heat removal during the partial cooldown and the normal plant cooldown phase is achieved via the MS bypass station or the MSRTs and the AAD [SSS] (or the 4-train ASG [EFWS])
- the 2-train EVU [CHRS] provides heat removal in the long term from the IRWST to the SEC [ESWS]
- the four accumulators provide replenishment of the RCP [RCS] (however one complete RIS [SIS] train is assumed to be lost due to the break)
- containment isolation is available

1.2. METHODS AND ASSUMPTIONS

a) Methods

The thermal hydraulic response of the primary side, the secondary side and the connected containment system (inclusive IRWST) is simultaneously calculated with the coupled program system S-RELAP5/COCO (section 1 of Appendix 14A).

The major SB(LOCA) phenomena and the qualification of the models used in the computer codes S-RELAP5 and COCO are listed in Appendix 14A - Table 4 in section 1 of Appendix 14A.

b) Assumptions

The calculation is performed under best estimate initial and boundary conditions, as described in Appendix 16B - Tables 1 to 5. It is assumed that the postulated small break LOCA starts at normal operation conditions and no additional single failure nor preventive maintenance are considered, except the complete loss of the Low Head Safety Injection trains. RCV [CVCS] charging is not taken into account since it may be affected by the break.

With respect to safety system availability, three complete trains of MHSI and three accumulators are considered (one complete RIS [SIS] train is assumed to be lost due to the break). The transition to the final state with ensured long-term heat removal and stabilised primary coolant inventory is performed in the analysis as follows:

- the three available MHSI trains and three accumulators are able to prevent core uncovery, thus the radiological barrier ‘fuel rod cladding’ remains intact and there is no activity release

- the total capacity of three MHSI trains is sufficient to stabilise the primary coolant inventory and to ensure the long-term subcriticality of the core

- thirty minutes after occurrence of the RIS [SIS] signal, the secondary side plant cooldown at 50ºC/hour via the MS bypass station is initiated to bring the pressure down to 0.2 MPa (abs.). The secondary side AAD [SSS] ensures the SG feedwater supply.

- after approximately 4 hours when the cooldown to 2 MPa is terminated (end of calculation), the IRWST water temperature can be finally limited below its design value by actuation of the EVU [CHRS] / RRI [CCWS] / SEC [ESWS] cooling chain.

1.3. RESULTS AND CONCLUSIONS

The sequence of events and relevant system actuations of the RRC-A small break LOCA without low head safety injection are summarised in Appendix 16B - Table 6. The investigated time period is 4 hours. The calculation is terminated when the primary system and the containment/IRWST system have reached stabilised plant conditions with respect to primary coolant inventory and long-term heat removal via the SGs and the containment sump. The temperature increase of the IRWST is finally limited below the design value by actuation of the EVU [CHRS] / RRI [CCWS] / SEC [ESWS] cooling chain.

The main results are presented in Appendix 16B - Figures 1 to 7. Approximately 1 minute after break initiation, reactor and turbine trip are automatically actuated by the signal “pressuriser pressure < 13.2 MPa”. The RIS [SIS] signal “pressuriser pressure < 11.2 MPa” which starts the MHSI pumps and actuates the secondary side partial cooldown is activated 133 seconds after the beginning of the event. The injection rates of the Main Feedwater or the Start-up/ Shutdown system are able to hold the SG water level at normal conditions.

Five minutes (300 seconds) after the beginning of the event, the fluid at the outlet of the average core channel reaches saturated conditions and approximately 2 minutes later the pressure difference over the reactor coolant pumps decreases below 80% of its rated value and the pumps are automatically tripped.

At 424 seconds, the RCP [RCS] pressure decreases below the zero head of the medium head safety injection system, the three trains begin to inject into the primary coolant system and the loss of primary coolant will be partially compensated - see Appendix 16B - Figure 3.

Thirty minutes (1800 seconds) after the RIS [SIS] signal is activated, plant cooldown via the Main Steam Bypass Station is initiated by manual operator action. Within the next 1 hour 52 minutes (6720 seconds), the primary system pressure follows the resulting secondary system pressure gradient down to a minimum of 1.1 MPa at 2 hours 24 minutes 40 seconds (8680 seconds) - see Appendix 16B - Figure 1.

After the refilling of the primary system (see Appendix 16B - Figure 4), at approximately 2.5 hours (9000 seconds), single phase natural circulation restarts and the fluid mixing process leads to a balanced fluid temperature and boron concentration in the reactor coolant system.

The accumulators inject their total water mass within 1 hour 40 minutes (6000 seconds) and the primary coolant system is replenished to its initial coolant mass inventory. The accumulator injection stops the vapour break flow and the second pressure and temperature increase of the containment atmosphere is limited to well below the containment design limits (see Appendix 16B - Figures 6 and 5).

After accumulator depletion, the primary pressure increases to over 2.5 MPa (Appendix 16B – Figure 1) until the mass flow rates of the break discharge and MHSI are balanced (see Appendix 16B – Figure 3). The subsequent RCP [RCS] pressure history depends on the number of MHSI pumps in operation and the increasing primary pressure and break mass flow rate results in a third pressure and temperature peak of the containment atmosphere (see Appendix 16B – Figures 6 and 5) 3 hours 15 minutes (11,700 seconds) after the break.

An energy balance at 4 hours (14,400 seconds) shows the following distribution:

- total heat from reactor core and structure materials ≈ 45.7 MW
- energy removed via the steam generators secondary sides ≈ 32.7 MW
- energy released through the break to the containment atmosphere and to the IRWST ≈ 13.0 MW

The capacity of one EVU [CHRS] heat exchanger is 13 MW at an inlet temperature of 94°C. The analysis shows a temperature increase of the IRWST water up to 92.5°C during the time period of 4 hours considered. In order ensure MHSI operation in the long-term, further temperature increase can be prevented by actuation of 1 or 2 trains of the EVU [CHRS] which will limit the IRWST water temperature to below the allowed design value.

In the event no core uncovery occurs (see Appendix 16B – Figure 2) and the fuel cladding temperatures remain at saturated conditions without any cladding damage.

The primary and secondary side coolant inventory is stabilised and the long-term heat removal from the RCP [RCS] is ensured by the SGs and the EVU [CHRS] / RRI [CCWS] / SEC [ESWS] cooling chain. Subcriticality is ensured by injection of borated water from IRWST via the MHSI system.

In summary, in the 'SB(LOCA) with loss of LHSI' scenario, the final state is characterised by

- long-term core subcriticality ensured by boration via MHSI and/or RBS [EBS]
- decay heat removal ensured by SG and EVU [CHRS] / RRI [CCWS] / SEC [ESWS]
- activity release is under control since all barriers, i.e. fuel, RCP [RCS] boundary and containment maintain their full integrity.

APPENDIX 16B - TABLE 1

Initial and boundary conditions (1)

Event	Small Break Loss of Coolant Accident
Event-Category (PCC/RRC):	RRC-A - Prevention of Core Melt
Family of Events:	Loss of Primary Coolant Inventory (PCC-3+CCF, break size: 20 cm^2)
Safety Criteria: Radiological Limits	• Radiological Release not above PCC-4 Limits
Decoupling Criteria:	• Peak Cladding Temperature • Containment Design Pressure and Temperature
Purpose of Analysis	
• best estimate case	Verification of Non-Exceedance of Containment Design Limits
Shutdown Conditions:	
• final state	Stable Core Coolant Inventory and Heat Removal from the RCP [RCS]/IRWST ensured by EVU [CHRS] / RRI [CCWS] / SEC [ESWS] and SGs Subcriticality ensured by MHSI and/or RCV [CVCS] and/or RBS [EBS]

APPENDIX 16B - TABLE 2

Initial and boundary conditions (2)

Normal operating conditions for 4500MW are listed in Sub-chapter 14.1 - Table 3

Plant Parameter	Initial Value	Remark
Reactor/turbine power	100%	
Thermal reactor power	4900 MW	
Reactor cooling pumps power	41 MW	result of steady-state calculation
Thermal steam generator power (per SG)	1235 MW	result of steady-state calculation
Initial insertion of control rods	not relevant	
Initial power shape	top-skewed	
• Offset	10%	
Linear local peak power of hot rod	368 W/cm	result of steady-state calculation
Total RCP [RCS] mass flow rate	22244 kg/s	result of steady-state calculation
Total Core bypass	4%	closed hot dome
Coolant mixing in core	not relevant	
Average reactor cooling temperature	311.2°C	result of steady-state calculation
Pressuriser pressure	15.5 MPa	
Pressuriser level	7.0 m	
Feedwater/Main steam flow/SG	695.5 kg/s	result of steady-state calculation
Feedwater temperature	230°C	
Steam generator water level	16.0 m	result of steady-state calculation
Steam generator water mass	87.7 Mg	
Pressure of steam generator top	7.42 MPa	energy balance requirement

APPENDIX 16B - TABLE 3

Initial and boundary conditions (3)

Boundary Conditions: Containment	Best estimate	values used for analysis	Remark
Heat transfer between atmosphere and IRWST-water			
• heat transfer-area between atmosphere and IRWST	450 m^2	450 m^2	
• heat transfer coefficient between atmosphere and IRWST	100 W/(m^2K)	100 W/(m^2K)	
Containment free volume	80000 m^3	78000 m^3	
Initial conditions			
• water volume in IRWST	1900 m^3	1300 m^3	normally, as a conservative value 1800 m^3 could be assumed
• containment pressure	0.11 MPa	0.11 MPa	
• containment temperature	42°C	42°C	
• water temperature in IRWST	42°C	42°C	
• wall temperature	30°C	30°C	
Heat transfer area of containment walls and internal structures			
• containment wall	9572 m^2	9572 m^2	
• all other walls	26769 m^2	26555 m^2	
• all steel structures	27561 m^2	27010 m^2	
EVU [CHRS] heat exchanger capacity	13 MW	13 MW	per train

APPENDIX 16B – TABLE 4

Initial and boundary conditions (4)

Parameters concerning fuel management and reactivity feedback are listed in Sub-chapter 14.1 - Tables 4 to 8.

Boundary Conditions (kinetics and reactivity)	**Best estimate**	**Remark**
Burn-up state	BOC	
Bank reactivity		
• Initial bank reactivity acc. to rod pos.	not relevant	
• Partial trip	not relevant	
• Reactor trip	-5500 pcm	w/o stuck rod
Control rod dropping time	3.5 s	
Moderator R-feed back	not relevant	
Void reactivity	not relevant	
Fuel R-feed back	not relevant	
Boron R-coefficient	not relevant	
Boron concentration	not relevant	
Decay power	ORIGEN/S	see Table 6
Sum of delayed neutron fractions	731 pcm	

APPENDIX 16B – TABLE 5

Initial and boundary conditions (5)

The rules for the analysis of RRC-A studies are documented in Sub-chapter 16.1, section 2

Boundary Conditions (failure assumptions)	**Best estimate**	**Remark**
Emergency power mode	no	
Single failure F1A or F1B	no	
Maintenance	no	
Consequential failure	no	
Considered control and limitation systems (event specific):		
• Partial trip	not relevant	
• RCP [RCS] temperature control	not relevant	
• RCP [RCS] pressure control	yes	
– pressuriser normal spray	not relevant	
– pressuriser heater	yes	max. power: 2 MW
• Pressuriser level control (RCV [CVCS])	yes	
• Auxiliary spray via RCV [CVCS]	no	
• Turbine control	no	
• Steam dump control	yes	partial and normal cooldown
• MS relief control	no	
• SG level control (ARE [MFWS] and AAD [SSS])	yes	
• Start-up/Shutdown system	no	

APPENDIX 16B – TABLE 6

Sequence of Events [Ref-1]

Event	Criterion	Time/s
break initiation		0.0
reactor trip/ turbine trip	P-PZR < 13.2 MPa+1.2 s	62
pressuriser (PZR) low level (10 m^3)	L-PZR < 2.1 m	70
safety injection signal, partial cooldown	P-PZR < 11.2 MPa+15.9 s	133
saturated conditions at core outlet	$T_{fluid} \approx T_{sat}$	300
reactor coolant pump trip	Δp_{rcp} < 80% + 1.05 s	407
1st peak of containment pressure	P-Cont = 0.162 MPa	410
beginning of MHSI	P-RCS < 8.0 MPa	424
end of partial cooldown	P-Header < 5.5 MPa	1176
minimum relative RCP [RCS] water inventory	M / M_0 = 35%	1870
beginning of plant cooldown at 50ºC/h	$t > t_{SIS}$+30 min	1930
accumulator injection phase	4.5 MPa > P-RCS > 1.1 MPa	2705...8800
steam flow through the break is stopped	single phase break flow	3540
2nd peak of containment pressure	P-Cont = 0.213 MPa	4630
transition to single phase natural circulation with refilled SG-UT's		8000...9000
relative RCP [RCS] water inventory	M / M_0 = 100%	8575
minimum RCP [RCS] pressure reached	P-RCS = 1.1 MPa	8680
reverse SG heat transfer: SG to RCP [RCS]		9040...9800
3rd peak of containment pressure	P-Cont = 0.18 MPa	11700

Remark:
M/M_0 means: relative RCP [RCS] water inventory

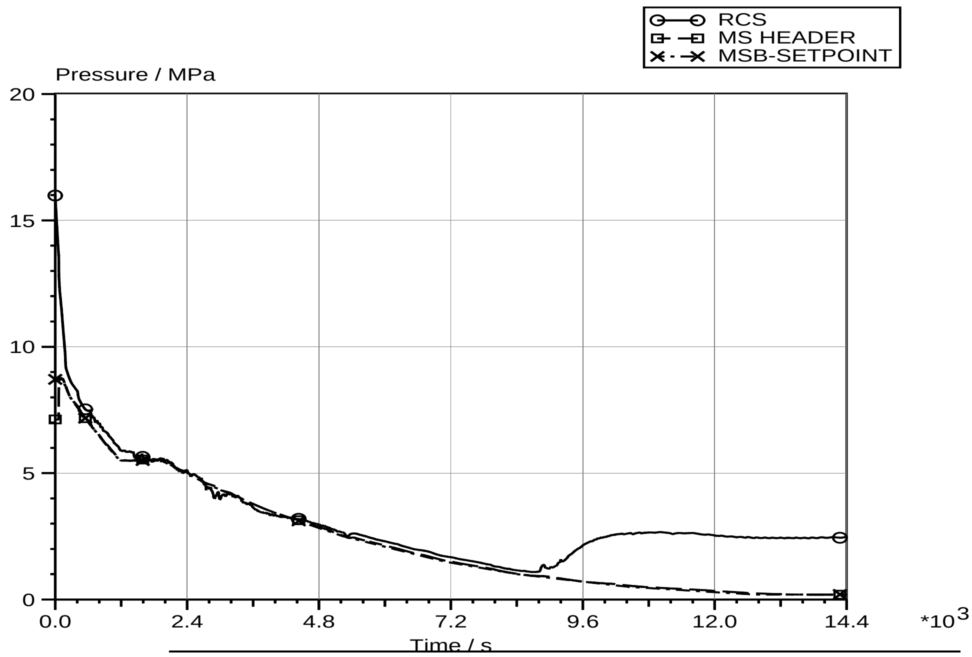
APPENDIX 16B – TABLE 7

Sequence of Events (see section 1 of Appendix 14A)

Plant conditions at end of calculation at 14400 s or 4 hours	**Value**
secondary pressure: end of cooldown	0.19 MPa
RCP [RCS] pressure	2.47 MPa
break flow ≈ MHSI flow	132.5 kg/s
boron concentration of core	2660 ppm
RPV outlet temperature	130°C
fluid temperature at break	120°C
containment atmosphere temperature	78.5°C
IRWST temperature	92.5°C
heat generation from RCP [RCS]	45.7 MW
heat transfer to SG secondary side	32.7 MW
energy release to the containment	13.0 MW

APPENDIX 16B - FIGURE 1

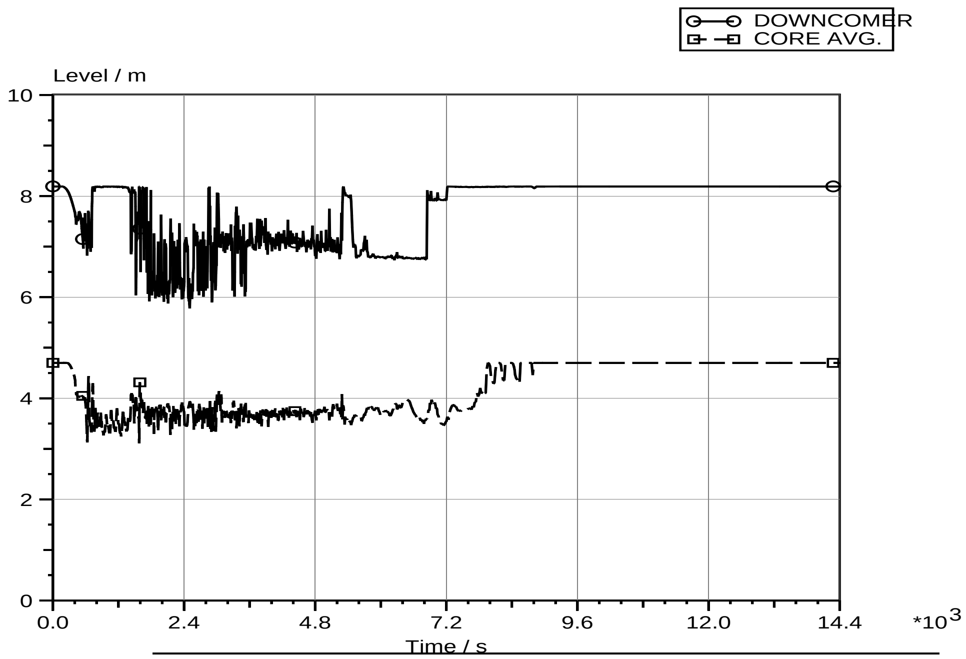
RRC-A: 20 CM2 SBLOCA (DN50) WITHOUT LHSI



PRIMARY SYSTEM AND SECONDARY SYSTEM

APPENDIX 16B - FIGURE 2

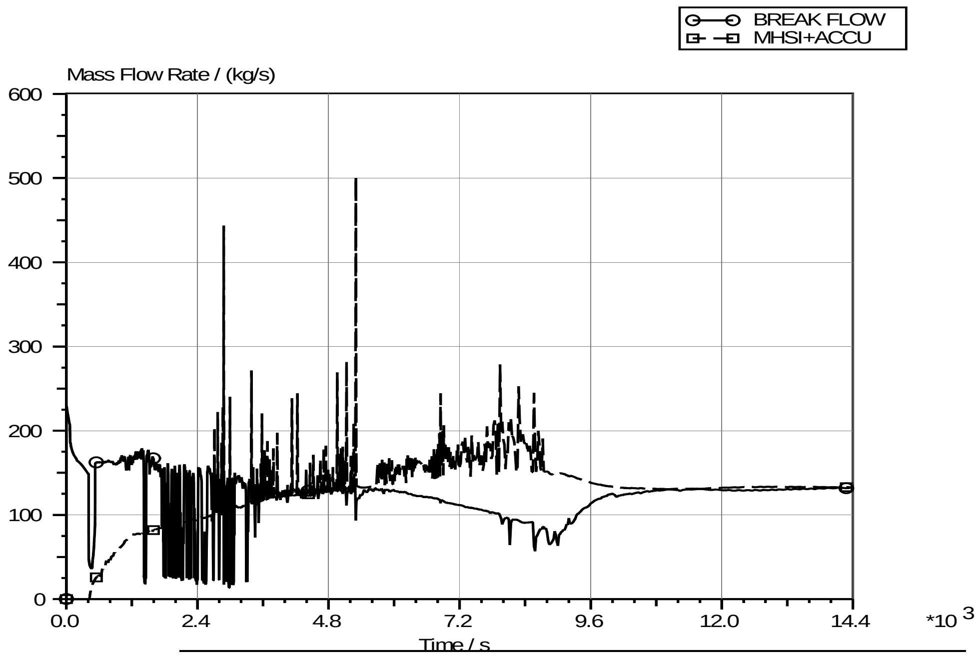
RRC-A: 20 CM2 SBLOCA (DN50) WITHOUT LHSI



COLLAPSED WATER LEVELS IN RPV

APPENDIX 16B - FIGURE 3

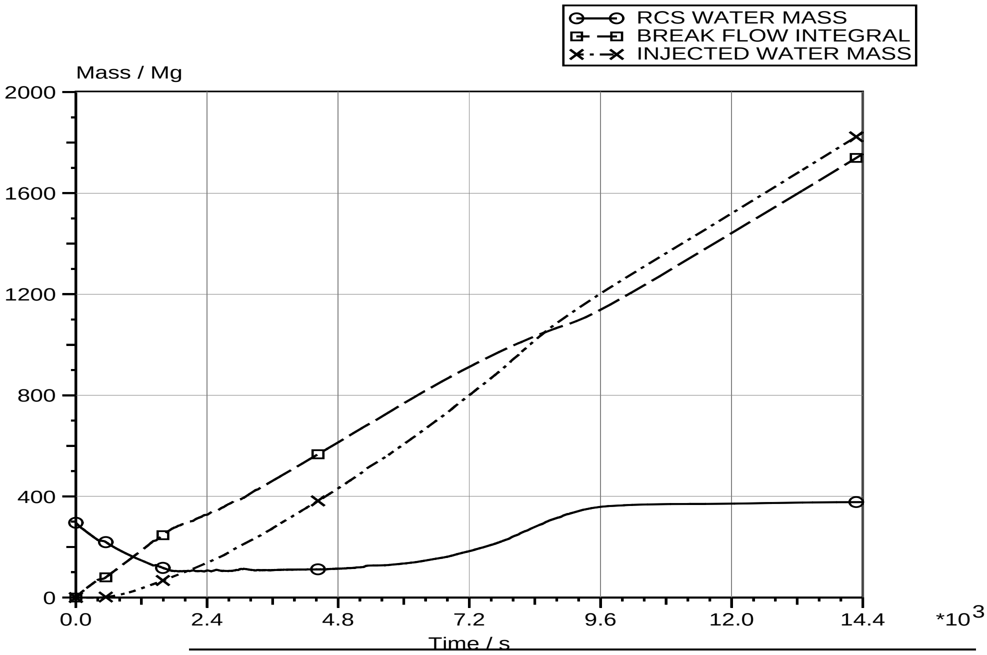
RRC-A: 20 CM2 SBLOCA (DN50) WITHOUT LHSI



BREAK FLOW AND RCS INJECTION FLOW

APPENDIX 16B - FIGURE 4

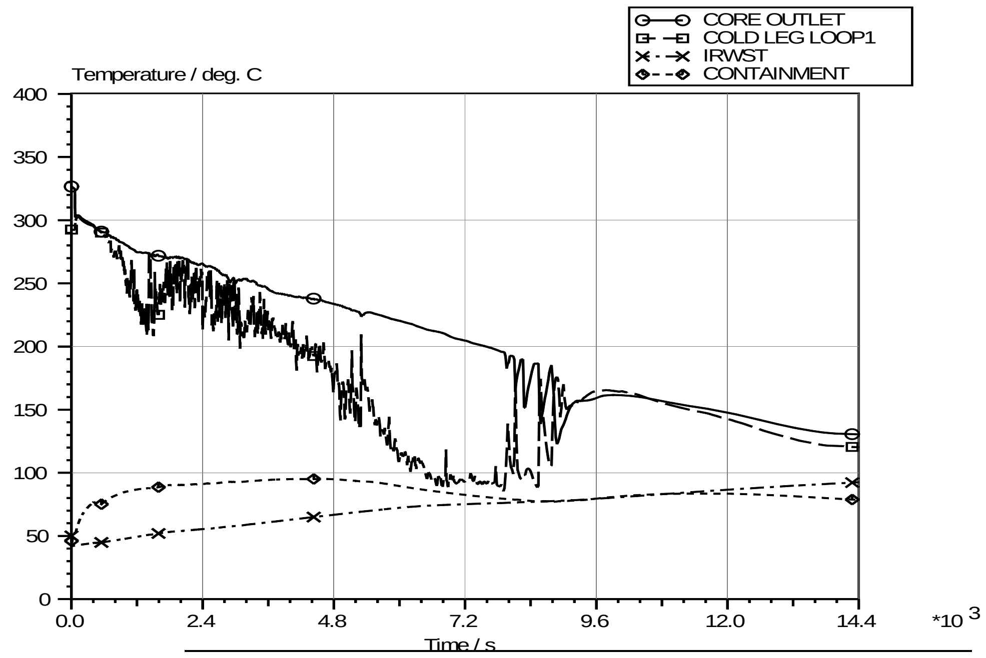
RRC-A: 20 CM2 SBLOCA (DN50) WITHOUT LHSI



MASS BALANCE OF REACTOR COOLANT SYSTEM

APPENDIX 16B - FIGURE 5

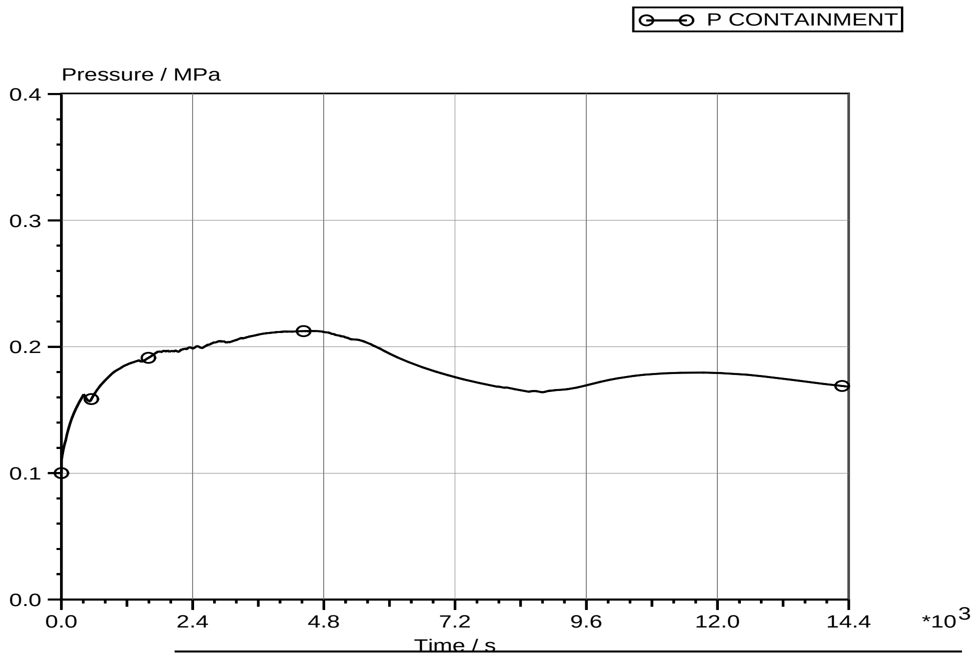
RRC-A: 20 CM2 SBLOCA (DN50) WITHOUT LHSI



CORE OUTLET, COLD LEG, IRWST, CONTAINMENT

APPENDIX 16B - FIGURE 6

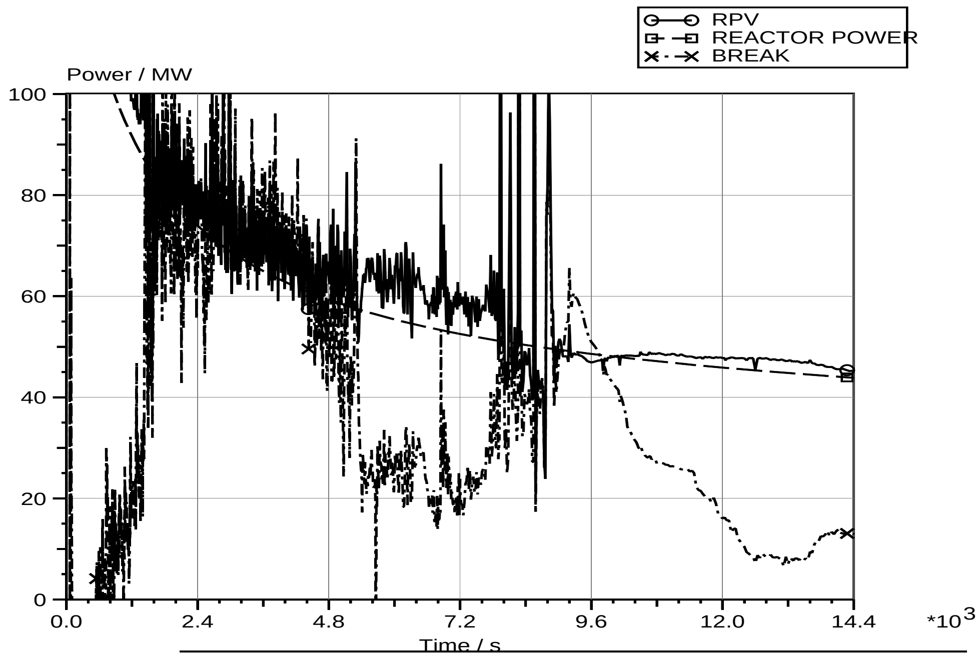
RRC-A: 20 CM2 SBLOCA (DN50) WITHOUT LHSI



CONTAINMENT PRESSURE

APPENDIX 16B - FIGURE 7

RRC-A: 20 CM2 SBLOCA (DN50) WITHOUT LHSI



ENERGY RELEASE FROM CORE, RPV AND RCS

APPENDIX 16B – REFERENCES

External references are identified within this sub-chapter by the text [Ref-1], [Ref-2], etc at the appropriate point within the sub-chapter. These references are listed here under the heading of the section or sub-section in which they are quoted.

0. INTRODUCTION

[Ref-1] Small Break Loss of Coolant Accident without Low Head Safety Injection System (RRC-A).
BDR chapter 19.2.1.3.6. EPR Basic Design Report, Revision D. AREVA . February 1999. (E)

APPENDIX 16B – TABLE 6

[Ref-1] Small Break Loss of Coolant Accident without Low Head Safety Injection System (RRC-A).
BDR chapter 19.2.1.3.6. EPR Basic Design Report, Revision D. AREVA . February 1999. (E)