

# Analysis of abnormal operation procedures in sequences of loss of the RHRS at midloop operation

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## Abstract

Several studies indicate the importance that the sequence of loss of residual heat removal system (RHRS) at midloop operation has in the global risk of the plant. In this sense, several simulations of loss of the RHRS with closed and open primary system with the TRACE V4.160 code have been performed considering different availability of steam generators. This paper aims to analyze not only the thermal-hydraulic behavior of the plant after the loss of RHRS, but also the interaction of the simulation results with the abnormal operation procedures and with the event trees of the sequences of loss of RHRS at midloop operation. The simulation results show that the main parameters depends on primary vent and the number of steam generators available. After a detailed study of phenomenology and abnormal procedures some modifications have been proposed in these procedures.

## 1. Introduction

After a loss of RHRS at midloop level, other cooling mechanisms are required in order to avoid fuel damage or mitigate the severity of the accident. These mechanisms could be feed and bleed and reflux-condensation, in which the steam goes into the steam generators tubes, where it eventually condenses and drains back to the hot leg. The efficiency of these mechanisms depends on the configuration of the plant (open or closed primary system), the number of steam generators available and the residual heat level, Queral et al. (2006a) and Queral et al. (2006b).

During shutdown condition there are several possible vent configurations available, Fig. 1:

- no vent, primary closed,
- pressurizer manway open (PMO),
- one or two PORV open with relief tank dry and closed,
- one or two PORV open with relief tank dry and open to containment,
- one safety valve removed,
- vessel vent valve open, and
- any of the previous configurations with steam generator manways open (SMO) with two, four or six nozzle dams installed.

Regarding the PORV vents, it is usual that the plants operate with the relief tank dry and closed during midloop conditions. This implies that the configuration of the plant continues closed despite of the PORVs opening.

In this paper, the results of several simulations performed for different configurations are described; closed and open scenarios (one and two PORV open, pressurizer manway open and vessel vent valve open) and different availability of steam generators. The simulations have been performed with the TRACE (TRAC/RELAP advanced computational engine, NRC, 2003) model of Almaraz NPP (3 loop, Westinghouse design). It has been taken into

## Nomenclature

AP	abnormal procedure	RCS	reactor coolant system
CSN	Consejo de Seguridad Nuclear	RHRS	residual heat removal system
LPS	low power and shutdown	RWST	refueling water storage tank
NPP	nuclear power plant	SG	steam generator
PORV	power operated relief valve	TRACE	TRAC/RELAP advanced computational engine
PRA	probabilistic risk assessment		
PWR- <i>W</i>	pressurized water reactor, Westinghouse design		

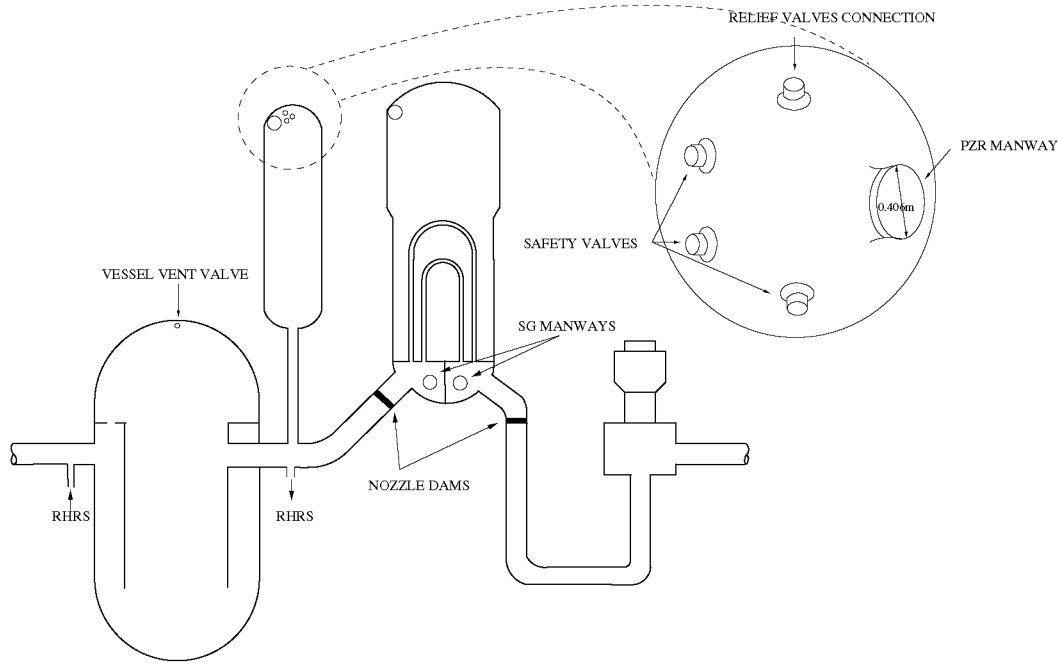


Fig. 1. Primary openings and nozzle dams position.

account the configurations of several plants. Thus, these analysis could be applied for a wide range of PWR-*W* (pressurized water reactor, Westinghouse design). In a second stage, the results of these simulations have been applied to the analysis of several abnormal procedures that correspond to different nuclear power plants. These analysis also include the event tree corresponding to the loss of RHRS at midloop conditions. This paper expands the work that was shown in a previous paper, Queral et al. (2006b), with a wider scope results (more plant configurations, such as primary closed, 2 PZR PORVs open, PZR

manway open and vessel vent) and proposing suitable changes in APs (abnormal procedures). Besides, it has been analyzed the impact of this proposals in the operator allowable times (see Table 1).

## 2. Simulation of loss of RHRS sequences at midloop level

The simulations have been performed with the TRACE model of Almaraz NPP, which has been described in previous papers, Queral et al. (2006b) and González et al. (2007). It has been considered different availability of steam generators in order to analyze the capability of the reflux-condensation as a mechanism of cooling for different configurations and the allowable times for other cooling mechanisms.

The initial conditions and hypothesis for the transients are:

- midloop level (mass inventory of almost 73,000 kg),
- initial pressure 1 bar, initial temperature 333.15 K,

Table 1  
Typical size of the primary vents in a generic Westinghouse plant

Vent	Area (m <sup>2</sup> )	Diameter
SG manway	0.1297	0.406 m
PZR manway	0.1297	0.406 m
PZR relief valves (2)	10 <sup>-3</sup>	0.035 m
PZR safety valves (3)	1.6 × 10 <sup>-3</sup>	0.045 m
Vessel vent valve	0.51 × 10 <sup>-3</sup>	0.025 m/with restriction of 1 cm

- 11 MW of thermal power,
- pressurizer is connected to loop 2,
- availability of steam generators as follows:
  - 3 steam generators full of water: 3SG,
  - 2 steam generators full of water and 1 full of air (loop 3): 2SG,
  - 1 steam generator full of water (loop 1) and the rest containing air: 1SG, and
  - all steam generators full of air: 0SG.
- secondary pressure: 1 bar, and
- no Auxiliary Feedwater available and no feed of coolant available.

The main variables of this kind of transients are the time to boil and to core uncover, the maximum pressure and the clad temperature. Table 2 shows these variables for the cases with 2 PORV open (*nSG-2P*), pressurizer manway open (*nSG-PM*) and closed scenarios (*nSG-C*).

In order to complete the different simulated scenarios (closed, 2 PORV and PMO), a sensitivity analysis with

other different scenarios has been performed. The simulated scenarios corresponding with these analysis are:

- sensitivity to the number of open valves: loss of RHRS at midloop level with 1 PORV open (*nSG-1P*),
- sensitivity to the valve location: loss of RHRS at mid-loop level with the vessel valve vent open (*nSG-VV*),
- sensitivity to primary mass inventory: loss of RHRS with 2 PORV open and the RCS level covering the hot and cold legs (*nSG-2P-L*), and
- sensitivity to a finite closed relief tank: loss of RHRS with 2 PORV open and the relief tank (in dry conditions) simulated (*nSG-2P-T*).

These results are also compared with the results obtained by other authors with RELAP5 models:

- R1: Ferng and Ma (1996). The simulation corresponds to 3 loop PWR-*W*, 11 MW of decay heat, initial hot leg temperature 328 K.

Table 2  
Simulations results for the loss of RHRS at midloop level

Cases	Time to boil (min)	Time to uncover	Maximum pressure (bar)	Time to 2/3 bar	Clad temperature at 10.000 s (K)	Time to HL level decrease
<i>Closed</i>						
3SG-C	10	no	3.8	45/85 min	414	Not
2SG-C	10	152	5.6	33/62 min	486	60 min
1SG-C	10	144	11.5	33/48 min	562	95 min
0SG-C	10	no	No limit	33/35 min		No
R1-2SG-C	10	no	6.3	26/46 min		
R1-1SG-C	10	no		26/46 min		
R2-3SG-C	6	no	3.6	83/230 min		
R3-4SG-C	5	20				
<i>2 PORV</i>						
3SG-2P	10	250	2.5	71 min/not	405	>170 min
2SG-2P	10	250	3.1	50/137 min	410	60 min
1SG-2P	10	114	6	31/65 min	1020	95 min
0SG-2P	10	114	12.4	27/42 min	1020	>170 min
<i>PMO</i>						
3SG-PM	10	80	1.4	not	1265	>170 min
2SG-PM	10	80	1.4	not	1383	60 min
1SG-PM	10	80	1.5	not	1412	60 min
0SG-PM	10	80	1.6	not	1744	>170 min
R2-3SG-PM	5.8	61	1	not		
R2-0SG-PM	5.8	49	1	not		
R3-4SG-PM	5	20				
<i>1 PORV</i>						
3SG-1P	10	165	3.1	70/150 min	460	>170
<i>Vessel vent</i>						
2SG-VV	10	>250	3.7	50/88 min	407	60 min
R2-3SG-VV	6	no	2.8	96 min		
R2-2SG-VV	6	no	3.3	80 min		
R2-1SG-VV	6	no	3.3	77 min		
R2-0SG-VV	6	331	4.9	42 min		
<i>2 PORV level covering legs</i>						
2SG-2P-L	10	>250	3.5	60/105 min	420	60 min
<i>2 PORV and relief tank simulated (dry conditions)</i>						
2SG-2P-T	10	153	5.4	33/66 min	485	60 min

- R2: Kim et al. (2000). The simulation corresponds to 3 loop PWR-*W*, 11 MW of decay heat, initial hot leg temperature 333 K.
- R3: Hassan and Raja (1993). The simulation corresponds to 3 loop PWR-*W*, 17 MW of decay heat, initial hot leg temperature 333 K.

All the sequences simulated with our model show that core reaches saturation in about 10 min after the loss of RHRS. However, lower values of time to boil, about 6 min, are obtained by other authors with RELAP5 models. This difference could be explained considering that the 3D vessel model of TRACE allows to simulate the natural circulation that appears inside the core during the heating before boiling; the natural circulation generates a large thermal mixing inside the core. However, the RELAP5 models have a one dimensional vessel model which does not allow to simulate the natural circulation inside a core at midloop conditions.

The pressure starts to increase, due to the steam formation, reaching an equilibrium pressure (except for the closed scenario and without steam generators), Fig. 2. The highest pressures correspond to the closed cases, and the lowest pressures to the pressurizer manway open (PMO) ones (slightly above one bar), Table 2. An intermediate situation corresponds to the 2PORV open cases. The reached RCS pressure affects considerably to the gravity feed effectiveness. The maximum pressure for gravity feed depends on the specific plant and its configuration, but this pressure is generally between 2 and 3 bar. The time available for the gravity feed for the open cases is considerably greater than in the closed scenarios, Fig. 2 and Table 2. In fact, in all PMO cases gravity feed is always possible. Also the 3SG-2P case never reaches the 3 bar limit pressure. The allowable time to gravity feed not only depends on the size of the opening, but also on the number of steam generators in operation.

With regard to core uncover, the time to reach this condition is highly dependent on residual heat, mass inventory

and RCS mass distribution. That is, it depends on the loss of mass through PORVs, the mass accumulated in the U-tubes and the pressurizer and, finally, the mass distribution in the hot and cold legs. The cases with less time to core uncover are the PMO cases due to large amount of inventory lost through the vent and also the amount of water accumulated in the pressurizer, Fig. 3 and Table 3. After the core uncover, the higher clad temperatures are also reached for the PMO scenarios, Fig. 4.

The real plant situation with 2 PORV open and closed and dry relief tank corresponds to a situation that is similar to the simulated closed scenarios, as it is proved in the sensitivity analysis, Table 2. The relief valves are connected to a pipe connected to the relief tank, which is generally drained in LPS conditions. Therefore, the results considered to be the most conservative ones are the most limitative ones between both cases, the closed and the 2 PORV scenarios.

In the following, the paper only considers two configurations, the PMO cases and the 2 PORV cases (restricted to the most limited results between closed and 2 PORV scenarios). This assumption is due to the fact that the Spanish NPPs generally operate with these vent configurations.

Regarding the sensitivity cases performed, the 2SG-2P-L case presents a higher time to core uncover than 2SG-2P due to more mass inventory in the first case. And in the 2SG-VV case, the inventory lost through the vent is lower

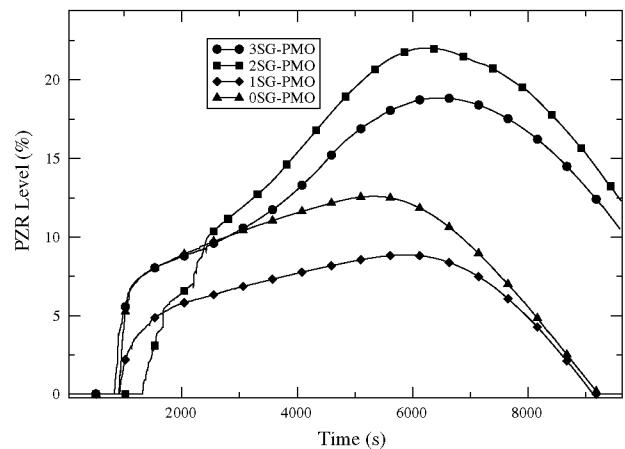


Fig. 3. Pressurizer collapsed water level. PMO scenarios.

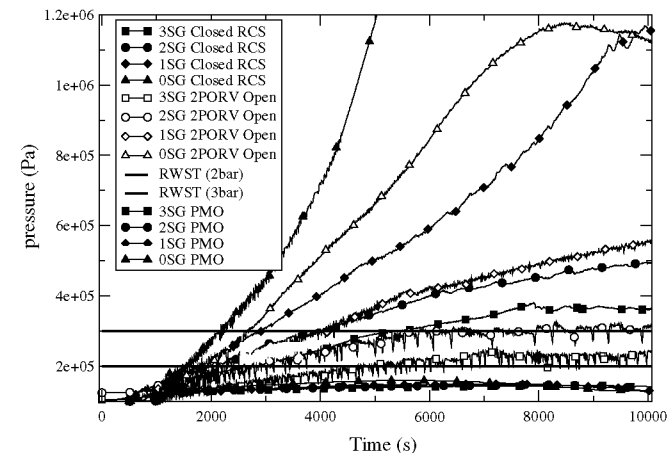


Fig. 2. Primary pressures.

Table 3

Lost mass through vent at 10,000 s

Cases	Mass lost through vent (kg)	Initial mass (%)
3SG-2P	4000	5
2SG-2P	5000	6
1SG-2P	11,000	14
0SG-2P	22,000	28
3SG-PM	26,900	35
2SG-PM	27,500	36
1SG-PM	30,200	39
0SG-PM	31,500	41

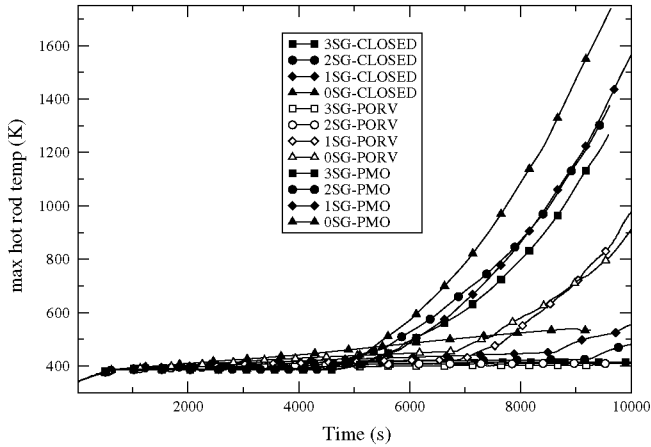


Fig. 4. Clad temperatures.

than the one of the cases with other vents. These considerations lead to a higher time to core uncover, Fig. 5. As we have shown, the 2SG-VV case corresponds to an interesting scenario, because there is a path for the pressure relief without water accumulation in the pressurizer.

With respect to the possibility that the plant has installed nozzle dams in the steam generators, the behavior of this situation could be similar to the cases with steam generators full of air in the secondary side (not operating) but with less free volume available, and as a result, the pressure reached in these cases could be higher. The typical value of the nozzle dams design pressure is about 3.5 bar. In this sense, only the PMO cases seem to provide enough certainty that this pressure is not reached any time. With regard to the other simulated transients, the worst case is 0SG-C, which reaches the design pressure of the nozzle dams in about 40 min, in contrast with the best possible case with nozzle dams and 2 PORV, 2SG-2P, that reaches a maximum pressure of 3.1 bar, almost the design pressure, in about 137 min. However, it should be necessary to perform simulations that consider these nozzle dams in order to analyze its impact.

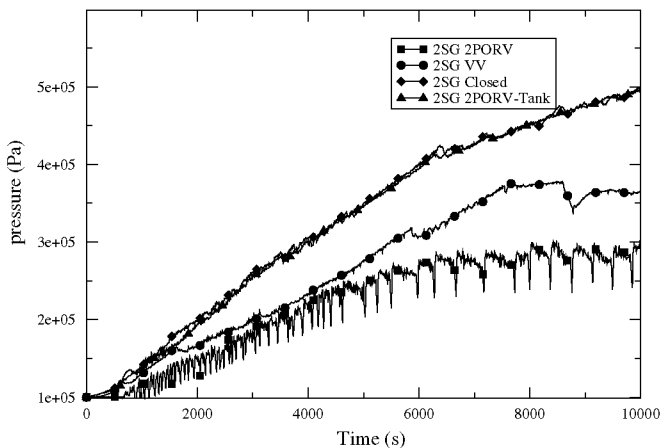


Fig. 5. Primary pressures. Sensitivity analysis: 2 PORV open, vessel vent open, closed RCS and 2 PORV with simulated relief tank.

### 3. Abnormal procedures of loss of RHRS at midloop conditions

During a sequence of loss of RHRS during midloop operation, the operator must take appropriate actions to keep the core cooled. These actions are included in a specific abnormal procedure. Therefore, the possible actuation of a particular cooling mechanism not only depends on its consideration in the AP, but also if it is possible according to the physical conditions of the plant. There are several kinds of AP in Westinghouse NPP, some of them are, NRC (1994), Ginna Station (2005): type 1, Fig. 6, type 2, Fig. 7 and type 3, Fig. 8.

There are several differences between these APs:

- In type 1 (AP1), the normal charge or safety injection, the gravity feed and reflux-condensation appear as alternative means of cooling after the loss of RHRS, no distinction of hot leg level and core outlet temperature are included. The RHRS recovery does not depend on the temperature and hot leg level.
- In type 2 (AP2), there is a step in which the hot leg level is checked. If the level is lower than a particular level value  $L_2$ , then the operator could use safety injection, gravity feed and reflux-condensation as mechanisms of cooling. However, if the hot leg level is higher than  $L_2$ , the procedure only reflects the reflux-condensation. The RHRS recovery is considered only if the hot leg level is higher than  $L_2$ .
- In type 3 (AP3), there is an initial step in which the core outlet temperature is checked. If the temperature is higher than the boiling temperature at atmospheric pressure, then safety injection could be possible. But, if this temperature is lower than the boiling temperature, then the hot leg level is also checked. Once the level is checked, three situations can take place. If the level is higher than  $L_2$ , there is not cooling mechanism considered. In opposition, if the level is between  $L_2$  and another reference level  $L_1$ , then the operator could use normal charge, and gravity feed. Finally, if the level is lower than  $L_1$ , the safety injection is considered. After these processes, the reflux-cooling is also considered in the procedure. The RHRS recovery is only possible if the hot leg level is higher than  $L_2$  and the core outlet temperature is lower than a particular temperature  $T_0$  (lower than atmospheric boiling temperature).

According to the simulations results, Table 2, it is important to highlight the following considerations:

- In AP1, there is not evaluation of the hot leg level and temperature, and therefore, all the cooling mechanisms could be possible whenever the plant conditions allow it. The gravity feed will be possible when the pressure is below the limit for the RWST.
- In AP2, there is an evaluation of the hot leg level and therefore all the cooling mechanisms could not always

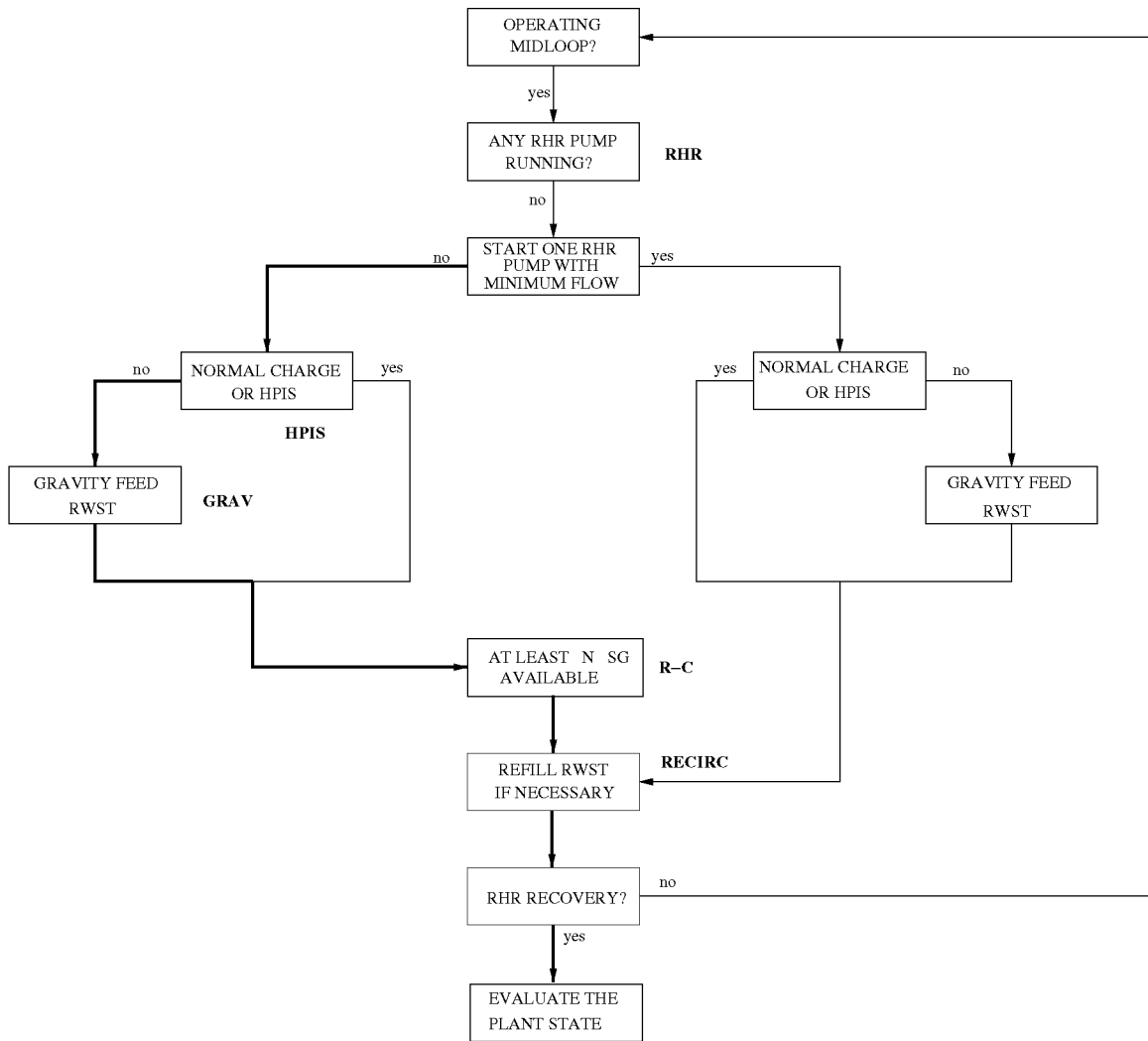


Fig. 6. Scheme of the procedure after a loss of RHR. Type 1 (Queral et al., 2006b).

be possible. It will depend on both, the plant conditions and if the AP allow it according to the hot leg level measurement. The gravity feed and the safety injection only will be possible when the hot leg level decrease from midloop level. The simulation results, Table 2, show that the hot level only decreases below midloop in 2SG and 1SG cases, but the gravity feed will be only possible when the pressure is below the limit for the RWST.

It must be taken into account that hot leg level measure depends on which hot leg the level is measured due to the possibility of having different levels in different hot legs. Only if the level measure in the hot leg with decreasing level is performed, the safety injection and the gravity feed could be possible. In general, the hot leg level is measured in the hot legs without connection with the pressurizer.

- In AP3, as in the AP2, the action of the cooling mechanism depends on the plant conditions and if the AP allows it according to, first the core outlet temperature and second the hot leg level measurement.

In this AP gravity feed is not possible because before reaching the boiling temperature (10 min) the hot leg level does not decrease in any case.

Taking into account these considerations, Tables 4 and 5 show the available times for the cooling mechanisms. The allowable times for the 2 PORV open real cases correspond to the most conservative between the simulated 2 PORV open cases and the simulated closed ones as it is reflected in Table 4. These allowable times depend on both, the physical plant conditions and the abnormal procedure:

- core uncover: CU,
- primary pressure: PP,
- the abnormal procedure in the step in which the hot leg level is evaluated: AP-L (AP2), and
- the abnormal procedure in the step in which the temperature is evaluated: AP-T (AP3).

In some cases, such as in AP2, 2SG and 1SG, the allowable times are limited by the measure of the hot leg level

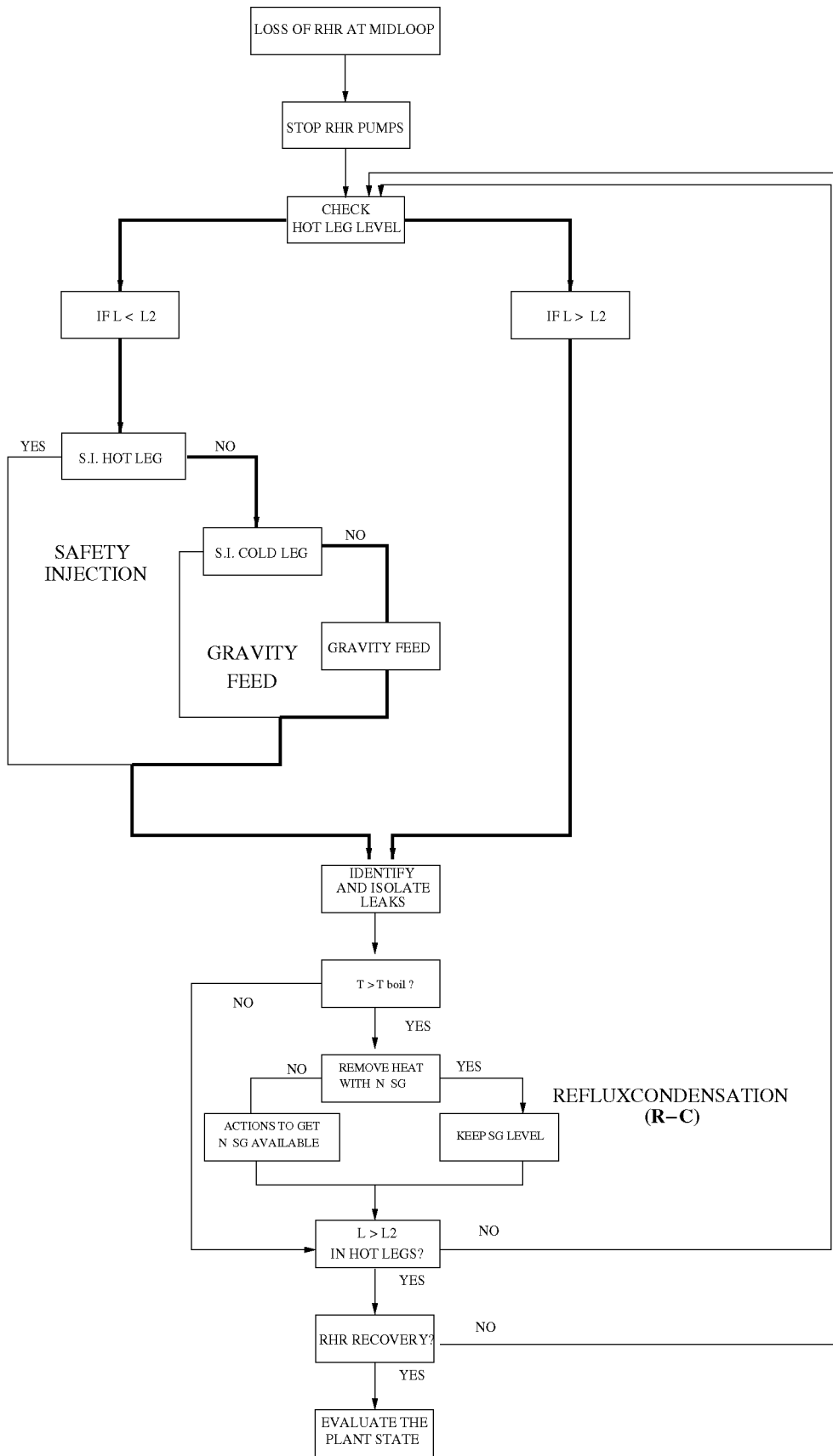


Fig. 7. Scheme of the procedure after a of loss of RHRs. Type 2 (Qeral et al., 2006b).

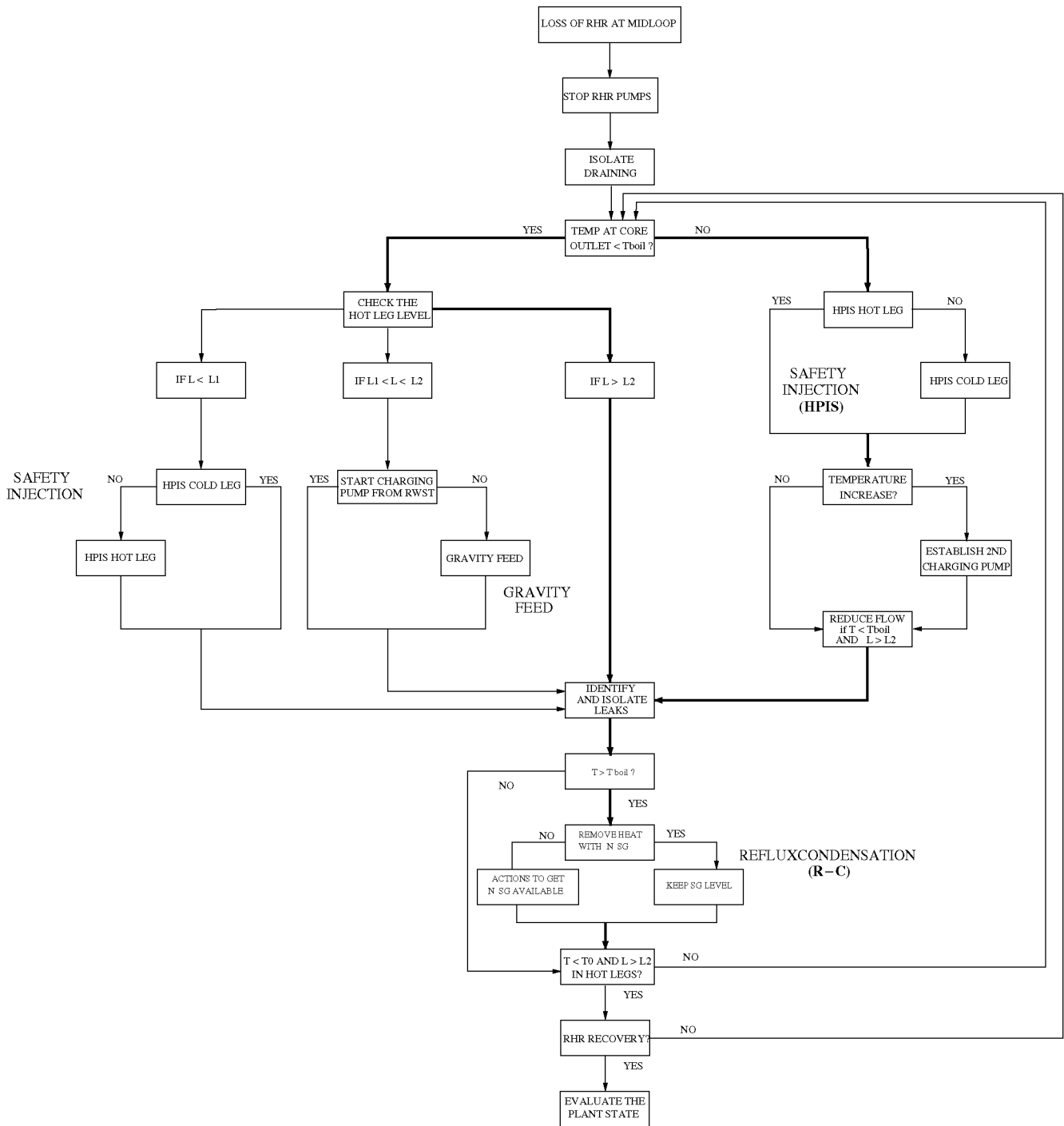


Fig. 8. Scheme of the procedure after a of loss of RHRs. Type 3 (Queral et al., 2006b).

(the gravity feed and safety injection only could be possible if the hot leg level decrease from midloop), by the time to core uncover for the safety injection and by the time to reach the limit pressure for the gravity feed.

#### 4. Event tree for the loss of RHRs at midloop conditions

In PRA (probabilistic risk analysis), the events delineation is performed by means of event trees. The headers of

the event tree must consider not only the physical limitations, but also the abnormal procedures. Therefore, the relationship between the event tree and the AP should be a close one.

Firstly, only the cooling mechanisms which are considered in the AP could be considered as a header in the event tree. Secondly, it must be checked if during the sequence simulations the necessary conditions to consider these mechanism are fulfilled. Meaning that, if some cooling



Table 4  
Available time for each cooling mechanism

AP	Recovery RHRS	Injection	Gravity feed (2/3bar)
<i>AP1</i>			
3SG	0–250 min (CU)	0–250 min (CU)	0–45/85 min (PP)
2SG	0–152 min (CU)	0–152 min (CU)	0–33/62 min (PP)
1SG	0–114 min (CU)	0–114 min (CU)	0–31/48 min (PP)
0SG	>170 min (CU)	>170 min (CU)	0–27/35 min (PP)
<i>AP2</i>			
3SG	0–250 min (CU)	No (AP-L)	No (AP-L)
2SG	0–60 min (AP-L)	60–152 min (AP-L; CU)	No (AP-L; PP)
1SG	0–95 min (AP-L)	95–144 min (AP-L; CU)	No (AP-L; PP)
0SG	>170 min (CU)	No (AP-L)	No (AP-L)
<i>AP3</i>			
3SG	0–10 min (AP-T)	10–250 min (AP-T; CU)	No (AP-T)
2SG	0–10 min (AP-T)	10–152 min (AP-T; CU)	No (AP-T)
1SG	0–10 min (AP-T)	10–114 min (AP-T; CU)	No (AP-T)
0SG	0–10 min (AP-T)	10–114 min (AP-T; CU)	No (AP-T)

2 PORV.

Table 5  
Available time for each cooling mechanism

AP	Recovery RHRS	Injection	Gravity feed
<i>AP1</i>			
3SG	0–80 min (CU)	0–80 min (CU)	0–80 min (CU)
2SG	0–80 min (CU)	0–80 min (CU)	0–80 min (CU)
1SG	0–80 min (CU)	0–80 min (CU)	0–80 min (CU)
0SG	0–80 min (CU)	0–80 min (CU)	0–80 min (CU)
<i>AP2</i>			
3SG	0–80 min (CU)	No (AP-L)	No (AP-L)
2SG	0–60 min (AP-L)	60–80 min (AP-L; CU)	60–80 min (AP-L; CU)
1SG	0–80 min (CU)	60–80 min (AP-L; CU)	60–80 min (AP-L; CU)
0SG	0–80 min (CU)	No (AP-L)	No (AP-L)
<i>AP3</i>			
3SG	0–10 min (AP-T)	10–80 min (AP-T; CU)	No (AP-T)
2SG	0–10 min (AP-T)	10–80 min (AP-T; CU)	No (AP-T)
1SG	0–10 min (AP-T)	10–80 min (AP-T; CU)	No (AP-T)
0SG	0–10 min (AP-T)	10–80 min (AP-T; CU)	No (AP-T)

PMO.

mechanism are not possible according to the AP and the sequences simulation, this mechanism should not be included as an event tree header.

The headers included in the event tree corresponding to the different AP considered in the previous section are:

- RHR: operation of the other train of RHR,
- VENT: existence of a vent,
- HPIS: recovery of inventory with charging pumps,
- GRAV: gravity feed from RWST,
- R-C: reflux-condensation, and
- RECIRC: long term cooling.

According to the simulations results, the order of the headers depends on the associated AP. Moreover, the order of both first headers, RHR and VENT, does not

vary. However, the order of headers HPIS, GRAV and R-C is not the same, it depends on the associated abnormal procedure. With the associated AP1, the order of the headers is HPIS, GRAV and R-C. With AP2, the order is R-C, HPIS and GRAV. With AP3 the order is HPIS and R-C (GRAV seems to be not possible). Finally, the last header, RECIRC, is included in the event tree for all AP. The event tree that considers all the AP is shown in Fig. 9.

The header's description is included in the following paragraphs:

#### RHR *Operation of the second train of RHRS.*

This header considers the possibility to startup the other train of RHRS. For each event tree there are the following considerations:

*AP1* The AP1 procedure always allows to try the start up of the other train of RHRS. Therefore, the allowable time for this header is the time to core uncover. It must be taken into account that it is not advisable the start up the RHRS without enough level in the hot legs.

*AP2* The AP2 procedure allows to start up the RHRS if there is enough level in hot legs (approximately midloop). Therefore, the allowable time to start up of the RHRS depends on the number of SG operating, in which hot leg the level is measured and the time to core uncover.

*AP3* The AP3 procedure allows to start up the other train of RHRS with enough level in hot leg and with a temperature lower than the boiling temperature. Therefore, the allowable time for this header is about 10 min.

#### VENT *Existence of a vent path.*

This header takes into account the possibility of the primary system opening. In open scenarios there is not R-C header due to the fact that this mechanism does not lead to long term cooldown.

#### HPIS *Recovery of inventory with charging pumps.*

In those situations in which the train of RHRS can not be started, the operator can feed the RCS by normal charge or safety injection. There are the following considerations:

*AP1* The AP1 procedure always allows this mechanism and therefore the allowable time is the time to core uncover.

*AP2* The AP2 procedure allows the injection if the hot leg level is below  $L_2$  (approximately midloop) and as result this header is later considered than R-C header. In this case the allowable time is conditioned to the time in which the hot leg level decrease from midloop and the time to core uncover.

*AP3* The AP3 procedure considers the injection after the boiling and before the boiling if the hot leg

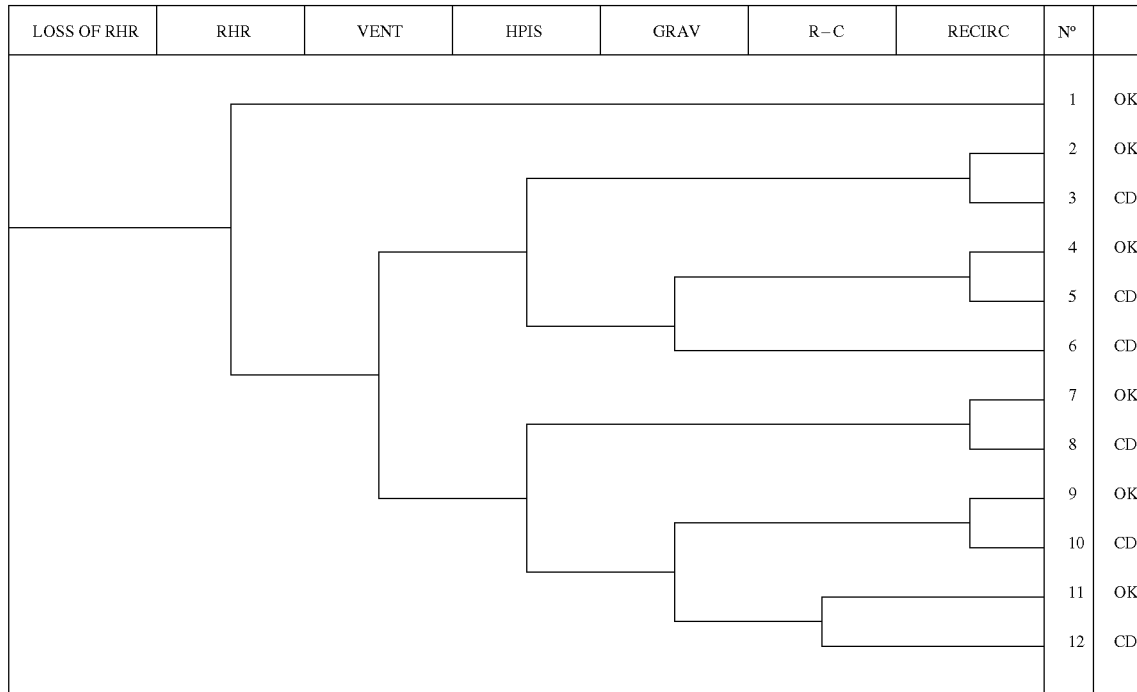


Fig. 9. Event tree for the loss of RHRS at midloop conditions.

level is lower than  $L_1$ . The last one conditions are not achieve in any case. Therefore, the allowable time for this header is from the boiling to the core uncover.

#### GRAV Gravity feed from RWST.

In practice, the last option to feed the RCS is the gravity feed. In general, the efficiency of this cooling mechanism highly depends on the primary pressure, not assuring the success of the cooling mechanism below the limit pressure. There are the following considerations:

*AP1* According to AP1, the gravity feed is always possible, only it is limited by the primary pressure (time to 2/3 bar) or the time to core uncover.

*AP2* The AP2 procedure allows the gravity feed if the hot leg level is lower than a particular level  $L_2$ . Taking into account this issue, and the time to reach the limit pressure, it seems that gravity feed is only possible for the cases 2SG-PM and 1SG-PM because the pressure keeps being low when the hot leg level decreases from midloop.

*AP3* The AP3 only considers the gravity feed before reaching the boiling temperature and with a hot leg level lower than  $L_2$ . However, there are not cases that fulfill these conditions and, therefore, in ET3 there is no header corresponding to gravity feed.

## 5. Proposed modifications in the abnormal procedures.

### Impact on the event tree

In this section, the abnormal procedures AP2 and AP3 have been modified in order to consider the safety injection and the gravity feed in the conditions in which they were not allowed, it is said, these procedures are modified in order to have the cooling mechanism only limited by physical conditions, and not by the procedure.

In AP2, after a period of time  $t_0$ , in which the hot leg level does not decrease from midloop but the loss of RHRS continues, it is convenient to include safety injection and gravity feed, Fig. 10. This period of time, much earlier than core uncover (see Table 2), depends on the size of the vent and it could be the following:

- In PMO cases:  $t_0$  should be less than 60 min (earlier than core uncover that amounts 80 min) for safety injection and gravity feed.
- In 2 PORV cases:  $t_0$  should be less than 20 min for gravity feed (earlier than limit time for gravity feed, which worse case is 27 min). However for safety injection 90 min could be enough (earlier than core uncover that amounts 114 min).

In AP3, after reaching the boiling temperature, the procedure does not consider the gravity feed if the safety injection fails (in case of Station Black Out, like Vogtle event, NRC, 1990). However, with large vents this mechanism

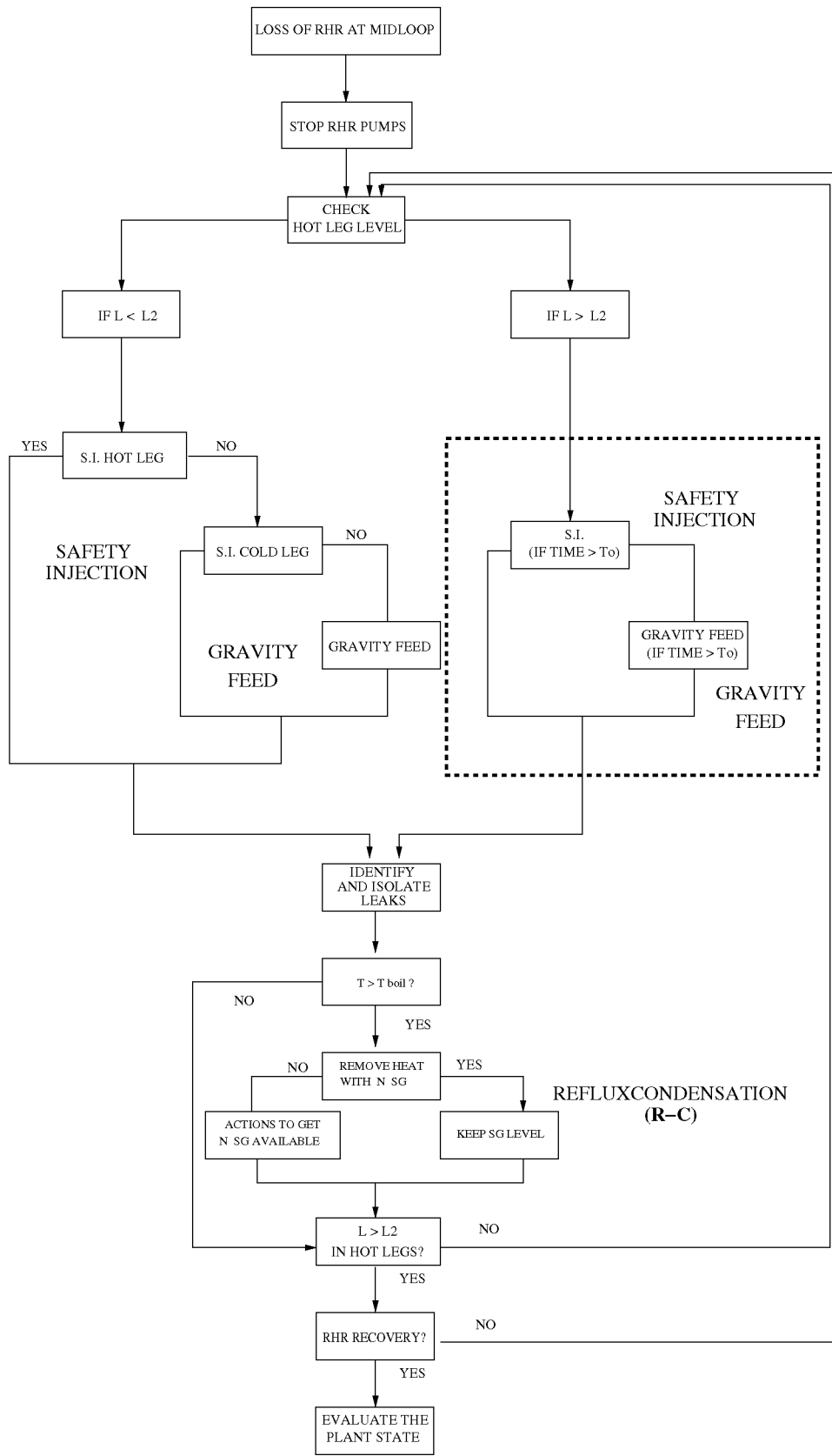


Fig. 10. Modification of the abnormal procedure AP2. AP2M.

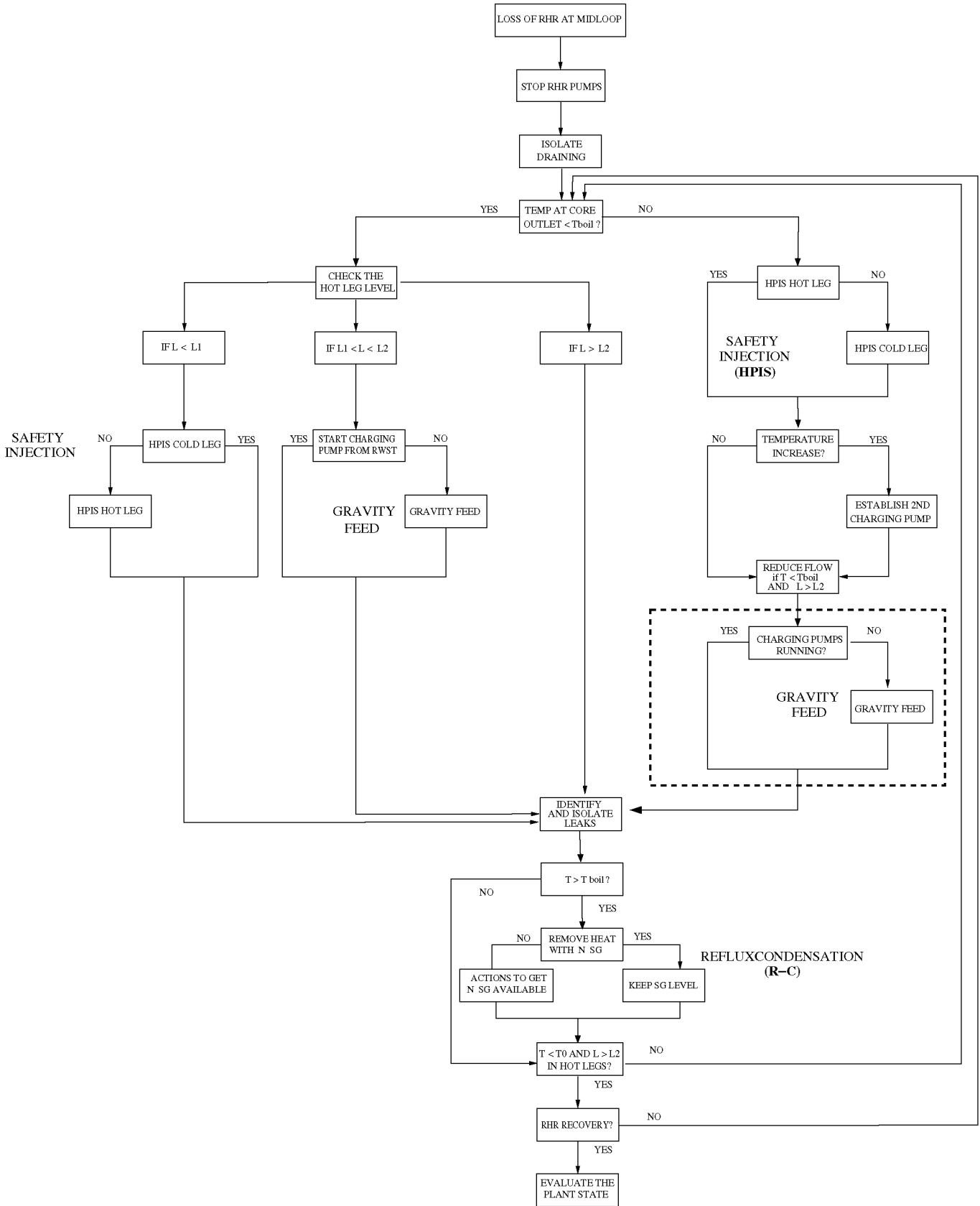


Fig. 11. Modification of the abnormal procedure AP3. AP3M.

could be an effective one and could avoid the core uncovery. Therefore, the gravity feed is considered in this modi-

fied procedure, Fig. 11. The allowable time for each mechanism is conditioned to the time to core uncovery.

Table 6  
Allowable time for the HPIS header

Case	2 PORV-O	2 PORV-M	PMO-O	PMO-M
3SG	No (AP-L)	250 min (CU)	No (AP-L)	80 min (CU)
2SG	60–152 min (AP-L; CU)	152 min (CU)	60–80 min (AP-L; CU)	80 min (CU)
1SG	95–114 min (AP-L; CU)	114 min (CU)	60–80 min (AP-L; CU)	80 min (CU)
0SG	No (AP-L)	114 min (CU)	No (AP-L)	80 min (CU)

Modified AP2.

Table 7  
Allowable time for the GRAV header

Case	2PORV-O	2PORV-M	PMO-O	PMO-M
<i>AP2</i>				
3SG	No (AP-L)	45/85 min (PP)	No (AP-L)	80 min (CU)
2SG	No (AP-L; PP)	33/62 min (PP)	60–80 min (AP-L; CU)	80 min (CU)
1SG	No (AP-L; PP)	31/48 min (PP)	60–80 min (AP-L; CU)	80 min (CU)
0SG	No (AP-L)	27/35 min (PP)	No (AP-L)	80 min (CU)
<i>AP3</i>				
3SG	No (AP-T)	45/85 min (PP)	No (AP-T)	80 min (CU)
2SG	No (AP-T)	33/62 min (PP)	No (AP-T)	80 min (CU)
1SG	No (AP-T)	31/48 min (PP)	No (AP-T)	80 min (CU)
0SG	No (AP-T)	27/35 min (PP)	No (AP-T)	80 min (CU)

Modified AP2 and AP3.

Other modifications that might be included are relative to the opening or closing the RCS vents according to the plant conditions:

### RCS closed

To open pressurizer PORVs and vessel vent valve (like in Korean procedures (Kim et al., 2000)) in order to extend the allowable time for gravity feed. If the pressure continues increasing and the gravity feed is not possible, it is better to close again the primary system for enhancing the reflux cooling and limiting the loss of mass inventory.

If there are installed any nozzle dams, it is not appropriate to close the RCS in order to protect their integrity.

### PMO

To close pressurizer manway in order to take advantage of reflux cooling and limiting the loss of mass inventory (like in some Spanish procedures). This consideration could only be done after new fuel reload because, in these conditions there is enough time to close the pressurizer manway before boiling (about 30 min).

### 2 PORV open

- With closed relief tank (dry).  
Open vessel vent valve (*the remaining procedure like in RCS closed case*).
- With open relief tank.  
This configuration is not used in general in power plants, but it could be interesting to analyze this config-

uration because it allows a higher vent than in the previous case and it could be closed quickly.

In order to develop procedures that consider all the possible cooling mechanism, the existing procedures have been modified. As a result of these modifications, the allowable time for each header have also increased. An important improvement is observed (original: case-O and modified: case-M), mainly in the GRAV header that now becomes possible, Tables 6 and 7.

## 6. Conclusions

The main conclusions of this analysis are

- A midloop model of Almaraz NPP with TRACE code has been performed, which shows a good behavior in the simulation of this kind of sequences. This model has allowed us to analyze the capability of the reflux-condensation mechanism and to understand the physical phenomena involved in this kind of transients.
- The simulation results show that the main parameters depends on primary vent and the number of steam generators available. In order to obtain allowable times large enough with respect to gravity feed and core uncover it is convenient to have at least two steam generators available. Among possible vents, it seems that vessel vent is quite appropriate because it is a good path vent for relieving pressure with a small inventory loss.
- The application of the results to the analysis of abnormal procedures with different configurations (steam generators and vent paths available) shows that the utilization of a cooling mechanism not only depends

on physical conditions of the plant, but also on the abnormal procedure. It is observed that not always the safety injection and gravity feed are possible according with the current abnormal procedure. This consideration must be taken into account in the event tree.

- In this paper, two kinds of abnormal procedures have been modified in order to consider the safety injection and gravity feed in the conditions in which they were not allowed by current abnormal procedure but, according with the plant configuration it could be beneficial to be considered. In this sense, the impact of the abnormal procedure modifications in the headers of the event tree is also analyzed. These modifications lead to a considerable improvement of the allowable times of the event tree headers.

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