

Analysis of a LBLOCA with FLEX actuations in a PWR-W

1. Introduction

Nowadays, nuclear safety is a discipline that still uses Fukushima-Daiichi accident lessons to improve, adapt and overcome the challenges created by a loss of safety-related systems. The loss of core cooling capability during the Fukushima-Daiichi accident led to a Severe Accident (SA) that included core melting, hydrogen combustion and reactor pressure Vessel Failure (VF), creating a landmark that changed the paradigm of nuclear energy worldwide (Vayssier, 2012).

After the accident, the international nuclear community engaged in a strong effort to apply the lessons learnt to other reactors in order to enhance the nuclear safety worldwide. Thus, in order to reduce the risk of loss of core cooling capability, the Diverse And Flexible Coping Strategies (FLEX) were developed and highlighted by the Nuclear Energy Institute (NEI), (NEI, 2018, 2012). FLEX strategies were originally developed after the “9-11” in the U.S. and were aimed as a support for the Emergency Operating Procedures (EOPs), Severe Accident Management Guidelines (SAMGs) and Anticipated Operation Procedures (AOPs) with the objective of establishing an additional coping capability to prevent fuel damage in the reactor and spent fuel pools, and to maintain the containment integrity by using both plant and FLEX equipment. Currently, FLEX Support Guidelines and other similar strategies have been implemented in most of the Nuclear Power Plants (NPPs) around the world, and in the U.S., they became mandatory for modification to licenses and construction permits after 2012 (NEI, 2016).

One of the pillars of these strategies is the use of portable equipment to provide means of obtaining power and water to maintain and/or restore key safety functions for all the reactors at one site, with a reasonable staging and protection of this equipment during a SA. In this sense, the FLEX strategies could be helpful to cope with SA like Fukushima thanks to the portable equipment, which can provide means of core cooling by injecting water to prevent or arrest its degradation

If the core is already degraded when implementing the FLEX procedures, their aim is to maintain the containment integrity during the accident, which involves preventing the reactor VF. If VF is avoided, the consequences of the SA can be strongly diminished and, as a result, a FLEX strategy has been developed named In Vessel Retention of molten corium (IVR) aimed at establishing cooling paths to keep the molten core within the Reactor Pressure Vessel (RPV) by establishing a number of internal, and/or external cooling paths, (Lim et al., 2017; W. Ma, 2016). In this sense, the IVR process can have a large impact on the accident progression in terms of long-term vessel coolability, timing of VF, conditions for ex-vessel fuel coolant interaction or the conditions for the molten core concrete interaction, (Seiler and Tourniaire, 2014).

As commented in (Braun et al., 2014), if the core has reached a slightly degraded state, the most critical action is to inject water into the Reactor Coolant System (RCS) or the RPV as the potential negative impact of this action during core melting is outweighed by the positive effects. However, core quenching may not be a straightforward action; the core quenching generates great quantities of steam, after the injection, and this steam can increase the Zircaloy oxidation, with its associated negative consequences. Nevertheless, thanks to the Passive Autocatalytic Recombiners (PARs) the hydrogen released can be managed and the hazard diminished.

Additionally, the temperature difference between the core and the water injected can induce fuel embrittlement and increase the release of fission products. In those scenarios, it is important to have a sufficiently high water flow rate to avoid this reaction, (Braun et al., 2014). One of the main activities focused in studying this phenomena was the QUENCH project, see (Steinbrück et al., 2010), for an extended record see (KIT, 2020).

As previously commented, the use of portable equipment permits the recovery and/or support of safety systems and Figure 1 provides an example of one of these strategies: external pumps injecting water into the RPV. The portable pumps considered for the FLEX strategies vary in

terms of pressure and flow rate capacity as there are certain accidents that would require specific characteristics, (CSN, 2014); Table 1 shows different specifications of portable pumps. For those scenarios, in which the injection safety systems have failed and some time has passed before the portable equipment is ready to inject, the core is very likely to be in a degraded state, and depending on its degradation stat and the pump flow rate, the water injection may not be able to prevent VF.

There are certain studies regarding this last topic; in a previous study of (Gómez-García-Toraño et al., 2017b), different accident timings and FLEX portable equipment injections are analyzed in a German Konvoi reactor with the ASTEC code during a MBLOCA. Complementary, (Wilhelm et al., 2018) includes depressurization strategies before portable equipment injection. Similarly, (Xiao and Wang, 2017) studied an SBO scenario with transfer to FLEX strategies at 8 and 24 h from the onset of the SBO in a PWR with the MAAP code.

Following this trend, the present study will assess the effectiveness of core reflooding as a Severe Accident Management (SAM) measure, investigated by means of analyzing a Large Break LOCA (LBLOCA) with Emergency Core Cooling System (ECCS) failure during the recirculation phase. Different scenarios will be analyzed, different timing for the recirculation failure, and different timing for FLEX injection and different portable pumps. This study is performed with the MELCOR 2.2 code in a three loop PWR-W with and focus on the processes generated by injecting water into the core after its degradation.

The present paper is divided in three additional sections. The next section is dedicated to the description of the MELCOR code and the models used for the analysis. Following, a depiction of the scenarios without any FLEX strategy are presented and then, the analysis of the FLEX strategies applied to the current case. Finally, some conclusions are drawn.

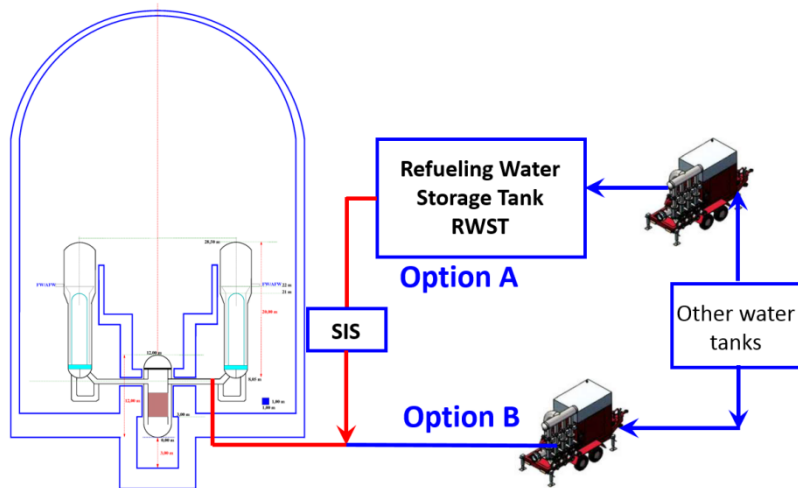


Figure 1. Example of different options for FLEX portable equipment injection.

Pump	Type	Head (bar)	Flow Rate (kg/s)	Reference
HH125	Low Head	10	45	(Rent, 2020)
AE16G	Low Head	6	100	(Peerless-Pump-Company, 2020)
M4031	Medium Head	20	4	(Lowara, 2016)
M6511pr	Medium Head	20	10	(Lowara, 2016)
M1001	Medium Head	20	15	(Lowara, 2016)
XH100	Medium Head	18	60–80	(Power-Prime, 2020)
M651h	High Head	51	22	(Park and Ahn, 2015)
M100h	High Head	46	40	(Lowara, 2016)
Hanul 3.4 firewater	Medium Head	14	22	(Park and Ahn, 2015)
BA80H D275	Low Head	9	36	(BBA, 2020)
BA-C150H41	Medium Head	20	36	(BBA, 2020)

Table 1. Specifications of different portable pumps

2. Computational Model

2.1. The MELCOR code

The MELCOR code is a fully integrated, engineering level computer code, capable of modeling SA phenomena in Light Water Reactors (LWRs). It was developed by Sandia National Laboratories (SNL) for the U.S. Nuclear Regulatory Commission. The MELCOR capabilities include the simulation of thermal-hydraulic behavior of the RCS and the containment, core damage progress including in-vessel melt progression and corium relocation, molten core concrete interaction, behavior of fission products, hydrogen generation and combustion, among others, (Humphries et al., 2017).

The MELCOR code contains models for core quenching after degradation but core quenching after degradation remains as one of the most computationally demanding and complex phenomena of a SA, being the focus of recent studies, (Gómez-García-Toraño et al., 2017a); therefore, the results obtained will have to be interpreted accordingly.

2.2. Models for quenching and initial calculations

The quench velocity is calculated with MELCOR. The quench velocity correlation implemented is that of Dua and Tien, (Dua and Tien, 1977). In this sense, MELCOR computes a quench velocity, distinct from pool water level according to the following relation:

$$Pe = [\bar{B} \cdot (1 + 0.4 \cdot \bar{B})]^{-0.5}$$

Where Pe is the dimensionless quench velocity or Peclet number, and \bar{B} is a dimensionless Biot number. This correlation has been used for the simulation of QUENCH, REWET-II experiments and the International Standard Problem 45, (Humphries et al., 2017), on which reasonable results were obtained.

As the complexity of the computational problem is large, it can be useful to develop some previous calculations about the mass flow needed to recover a degraded core, just to obtain the order of magnitude. The heat that is needed to be removed by the water injected is produced by the decay heat of the reactor (Q_{DH}) and extra heat generated by the Zirconium oxidation and hydrogen generation (Q_{Zr}). The heat removal capability of the injection water is determined by its flow rate (m) and specific heat capacity C_{liq} , C_{vap} phase change enthalpy h_{H2O} then in a simplified calculation, it is seen that:

$$\frac{Q_{DH} + Q_{Zr}}{\Delta T \cdot C_{liq} + h_{H2O} + \Delta T \cdot C_{vap}} = m$$

Applying typical values of a degraded core short after a recirculation phase injection failure (vapor reaches 1000 K, 100 kg of hydrogen can be generated, decay heat is close to 1% of 3000 MW) it is seen that the mass flow required for the heat removal is about 10 kg/s of water. This is in the same order of magnitude as what was obtained in the QUENCH program (Steinbrück et al., 2010).

2.3 PWR-W MELCOR Model

The MELCOR model used for the present study is a PWR-W with 3 loops. The model follows the best practice guidelines recommended in (Ross et al., 2014; SNL, 2012) in terms of core nodalization and core parameters. This model is an evolution of a previous PWR-W model developed in the UPM, (Martin-Fuertes et al., 1994; Ruiz-Zapatero et al., 2016). The model main characteristics can be found in Table 2, and the RCS nodalization is shown in Figure 2. The model

includes explicit representation of the entire RCS including each of the reactor loops, the pressurizer relief tank, the Steam Generators (SG), steam lines until the isolation valves, and associated safety and power-operated relief valves. The containment is divided into 51 control volumes where the 30 spray components are distributed. The reactor core is divided into six rings and 13 axial levels, with the lower three levels associated to the lower plenum. The RPV penetration failure temperature is set to 1273 K and the UO₂ starts to melt at 2500 K, (Ross et al., 2014).

Water injection provided by the FLEX portable pumps is modelled as a constant flow rate into the cold leg at a constant temperature. The recirculation phase of the safety and/or portable systems is modelled by extracting water from the containment sump and, at the same rate, injecting it in the cold leg at a constant temperature to recreate the heat exchanger present in the PWR-W model. The FLEX water injection, is located at the injection of the ECCS.

Control Volumes	Heat Structures	Core Axial Levels	Core Radial Rings	Cavities	Decay Heat
135	275	13	6	1	Table Function
RN Release Model	RN Classes	User defined NCG	Flow Paths	Hydrogen Burn	Containment Sprays
<i>Corsor-M with S-V ratio</i>	17	9	284	Disabled	30

Table 2. Main Characteristics of the PWR-W MELCOR model

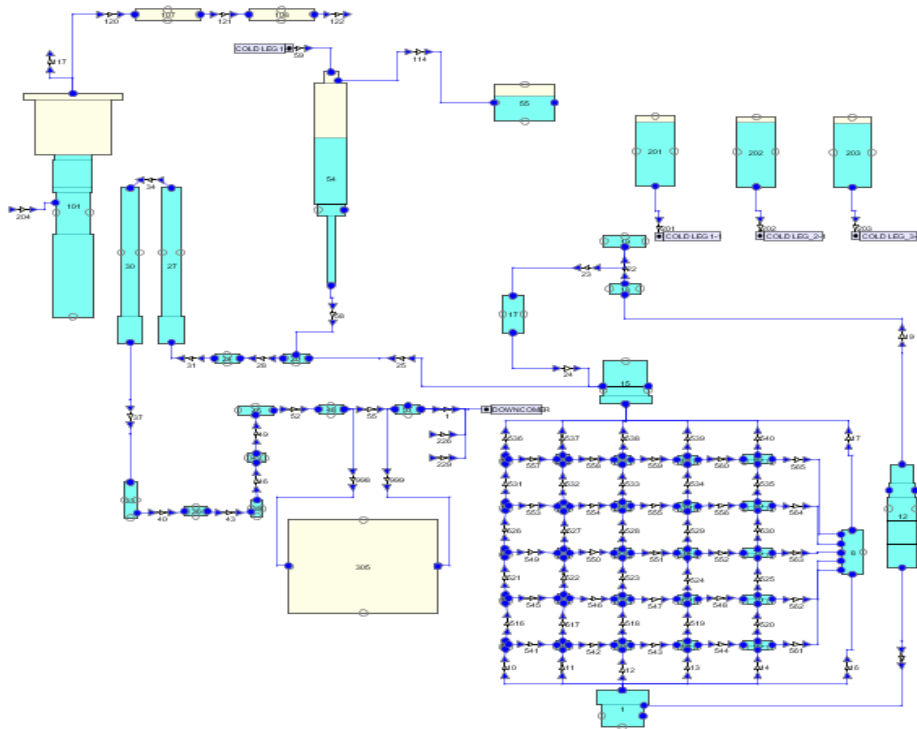


Figure 2. Control Volume and Flow Path Distribution of the PWR-W MELCOR model

3. ECCS failure during recirculation phase without FLEX strategies results

To study the effectiveness of FLEX strategies, a LBLOCA with failure of the ECCS during the recirculation phase at some point during the accident is selected. To assess the impact of different ECCS recirculation failure times, several cases are simulated, varying this time between 0 and 430 minutes after the recirculation starts, see Table 3. The sequences are identified as RF_XXX, where XXX is the time in minutes when the ECCS fails since the beginning of the recirculation.

The LBLOCA occurs 500 seconds after the beginning of the simulation and it is modelled as a guillotine break in the cold leg, reaching a discharge peak of 30000 kg/s. The LPSI and HPSI are available after the break, and they inject 127 kg/s and 22 kg/s per loop respectively. When the Refueling Water Storage Tank (RWST) reaches its depletion setpoint value with enough margin to avoid the pumps cavitation, the LPSI system changes from the injection mode to the recirculation mode; this occurs approximately 2500 seconds after the break.

Focusing on the RF_00 case (See Table 4), when the recirculation injection fails on demand the liquid level in the core starts to decrease until it reaches the bottom level, see Figure 3, while the temperature in the fuel starts to rise as soon as it gets uncovered, see Figure 4. After the fuel surpasses 2500 K, it starts to melt and when this material no longer exists in that cell, it is reported by MELCOR as a temperature of 0 K; then the molten material starts to candle downwards and re-freeze again, as seen in Figure 5. Molten corium starts to accumulate in the lower levels of the core, and after some time it reaches the RPV lower plenum, creating a molten pool. The molten corium starts to overheat the lower head and finally, the RPV can fail by exceeding the mechanical stress limits, or when the penetrations failure temperature is reached, spreading the corium into the basemat of the reactor cavity (Figure 6). In the present simulation the RPV fails because due to mechanical stress and after the corium reaches the cavity no further development of the accident is studied.

Comparing different recirculation failure time, Figure 7, the later the recirculation failure occurs, the later the core degradation process begins, this is due to the decay heat lowering as the SA progresses. Additionally, from the results obtained, summarized in Figure 8, it is seen that if recirculation fails on demand, the cladding melting appears at 3600 s (60 min), the relocation into the lower plenum at 5200 s (87 min) and the RPV fails 11600 s (194 min) after the recirculation mode failure. These timings are in agreement with previous studies on ECCS failure in the recirculation phase of a LOCA, (Gómez-García-Toraño et al., 2017b). Additionally, it is seen that the time between the initial core damage and VF timing is slightly increased as the recirculation failure is delayed in time. Moreover, the relocation of the corium into the lower plenum gets significantly delayed during the accident as the recirculation failure delays.

Case	Time
RF_00	Failure at demand
RF_10	Failure after 10 minutes of operation
RF_70	Failure after 70 minutes of operation
RF_130	Failure after 130 minutes of operation
RF_190	Failure after 190 minutes of operation

RF_250	Failure after 250 minutes of operation
RF_310	Failure after 310 minutes of operation
RF_370	Failure after 370 minutes of operation
RF_430	Failure after 430 minutes of operation

Table 3. Simulated Cases of recirculation failure without FLEX pumps

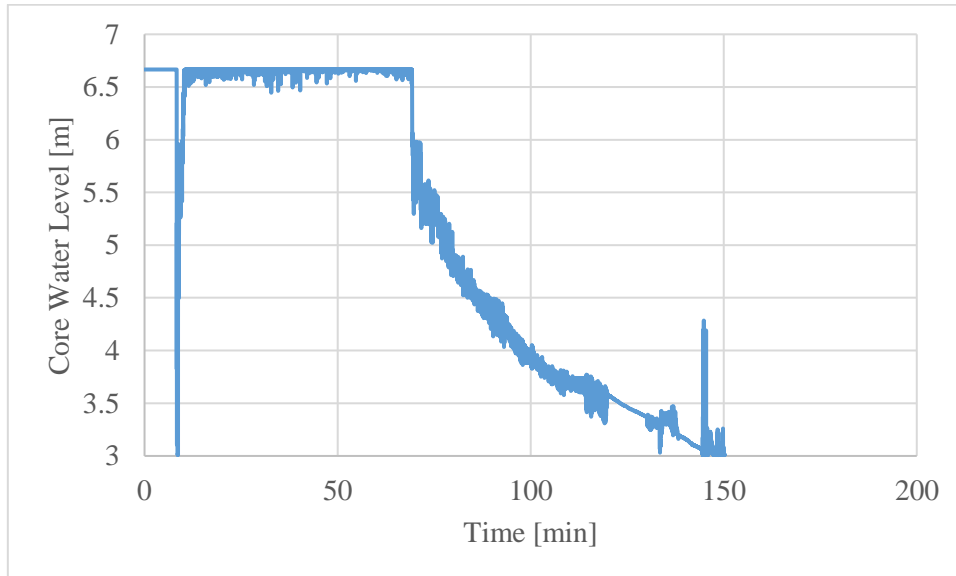


Figure 3. Core Water Level (case RF_00)

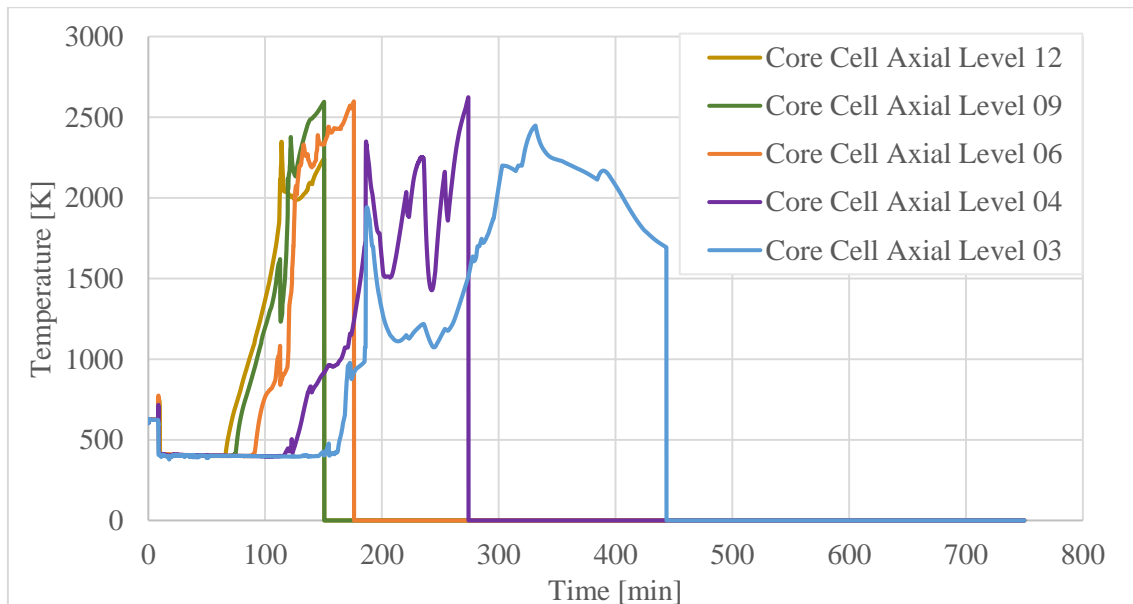


Figure 4. Core cell temperatures during the sequence (case RF_00)

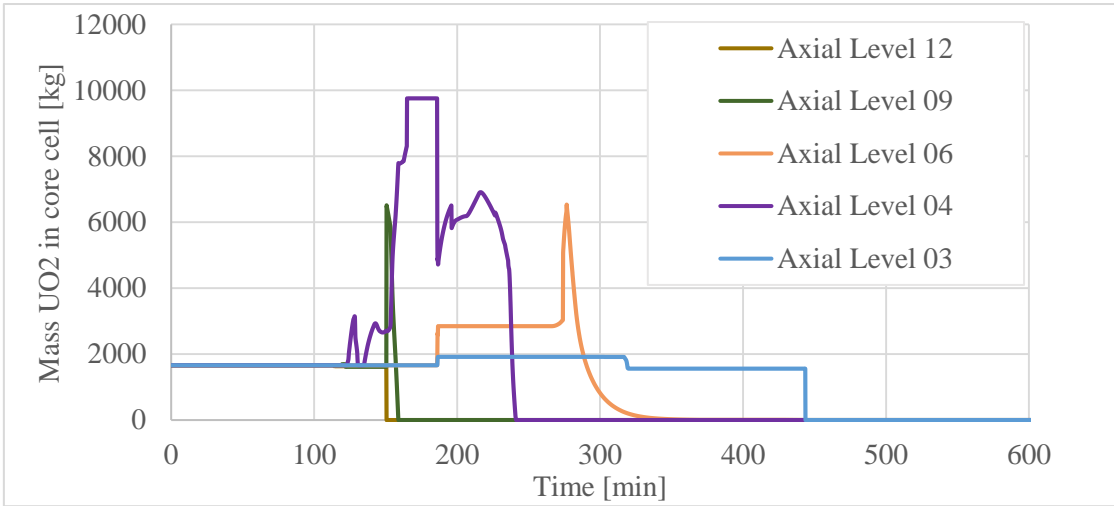


Figure 5. Mass of UO2 in core cells (case RF_00)

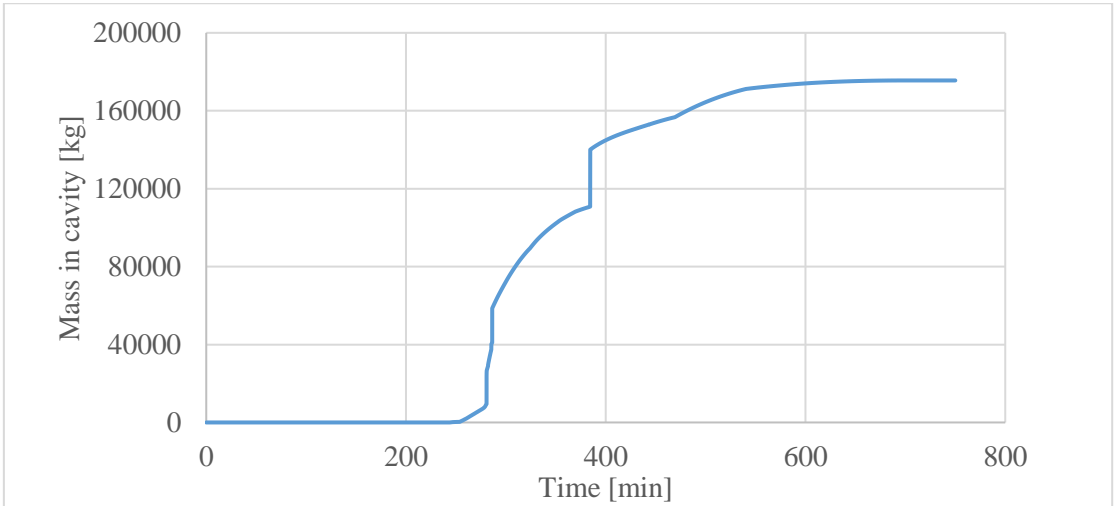


Figure 6. Mass of corium in cavity (case RF_00)

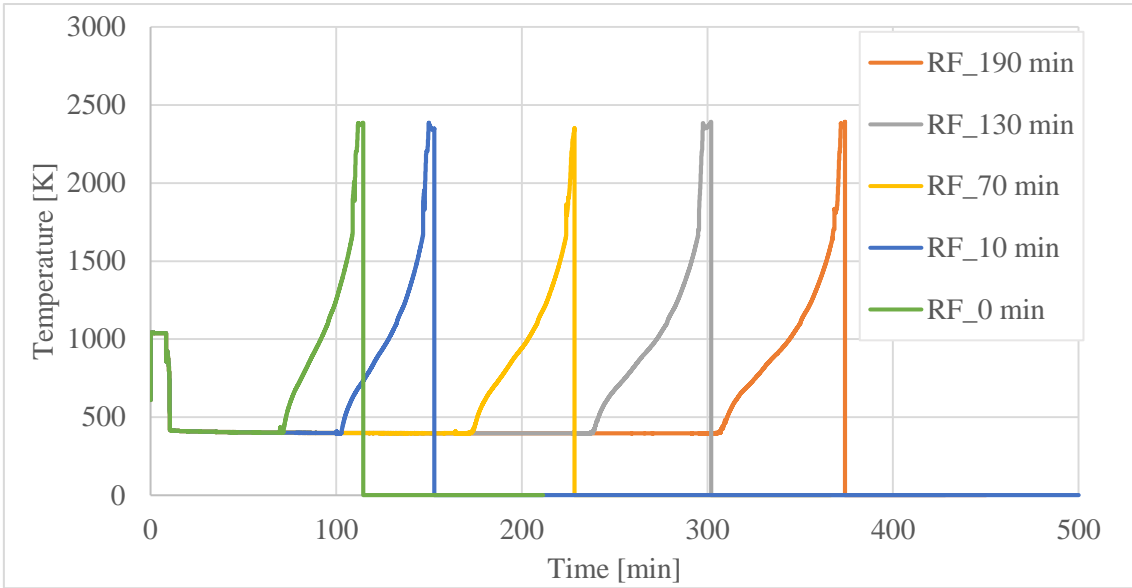


Figure 7. Core Temperature for different recirculation Failure timing.

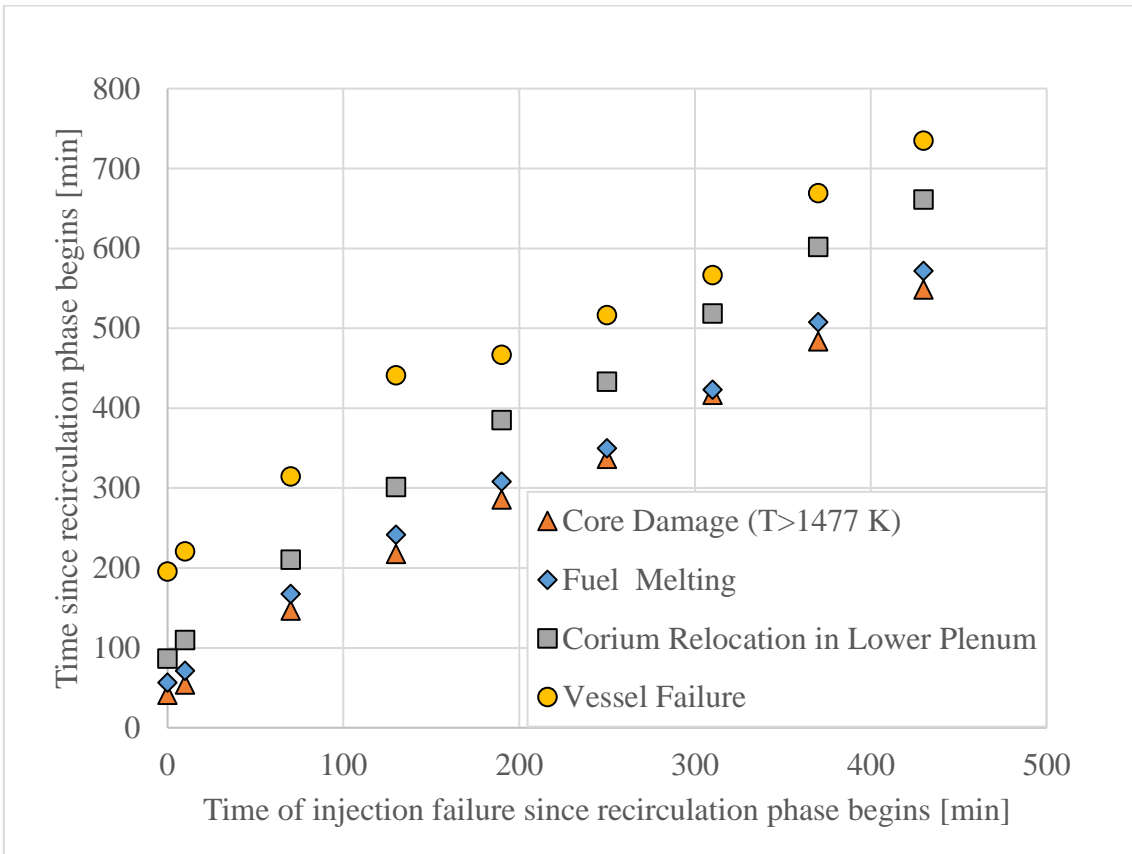


Figure 8. Summary of Core Damage States for all cases.

Time [s, (min)]	Event
0	Start of the simulation
500 (8.3)	Occurrence of the LBLOCA
501 (8.3)	Reactor Trip
514 (8.5)	Injection of ECCS
2986 (49.7)	Change to recirculation mode
2986 (49.7)	Injection failure
3940 (65.6)	Core uncover
5730 (95.5)	Surpassing embrittlement criteria (EC) PCT>1477 K
6610 (110.1)	Start of Core melting
9300 (155)	Core support plate failure
9400 (156)	Lower Core level full uncover
11760 (196)	RPV Failure

Table 4. Summary of the main events of the RF_000.

4. LBLOCA Recirculation failure with FLEX injection

After the initial study, the scenario is modified in the sense that a portable water injection pump is supposed to be available after certain time since the recirculation injection failure. The source of water for this injection is assumed to be large enough to last the full transient (e.g. external tanks). Different Recirculation failure timings are analyzed, together with different FLEX water injection timing and different mass flow rates. The sequences are identified with RF_XXX_FL_YYY_Q_ZZ, where XXX is the time when the recirculation is lost since the beginning of the recirculation phase in minutes (RF), YYY is the elapsed time between the recirculation failure and the beginning of the water injection with portable equipment in minutes (FLEX equipment, FL), and ZZ is the mass flow rate (Q) delivered by the portable pump in kg/s.

The different combinations of Recirculation Failure times and the onset of the FLEX water injection are shown in Table 6-8 with the legend explained in Table 5. In Table 5, the color indicates the core damage state when the FLEX injection begins, and the wording indicates the final state. The mass flow rate provided by the portable pump is assumed to be 20, 40 or 60 kg/s, to account for high, medium and low head pumps respectively as seen in Table 1. As an example, the mass flow rate from the ECCS in RF_130_FL_90_Q_60 can be seen in Figure 9.

Observing Figure 10, it can be seen that FLEX water injection is able to prevent core damage if the time interval between recirculation failure and FLEX injection is not extended. When water gets in contact with a degraded core, a rapid evaporation occurs, forming steam, with the potential to oxidize the cladding and produce hydrogen. For this reason, core reflooding must be performed with a sufficient water flow rate to quickly quench the full core, and avoid more Zr oxidation (Hermsmeyer et al., 2014; Queral et al., 2016). In this sense, if the core degradation is not too large, it would be possible to stop it.

In Table 6, it is seen how different core damage states are affected by the timing. If the recirculation has been functioning for a more than 70 minutes, the decay heat has decreased sufficiently to provide a larger margin to prepare the FLEX water injection. If the core is in a safe state prior to the FLEX water injection, it is seen that the core end state will remain safe.

Additionally, it can also be seen that under some circumstances, the FLEX water injection is not capable of stopping the accident progression. It is also confirmed, as in previous studies with

different PWR RPV designs, that if more than 25 tons of corium are relocated in the lower plenum, the VF is very likely, see (Broughton et al., 1989; Gómez-García-Toraño et al., 2017b). Moreover, code simulations show that after 270 min without injection, it is not possible to avoid VF.

Comparing the summary tables and attending at Figure 11, it is seen that the mass flow rate delivered by the portable pump (from 60 to 20 kg/s) hardly change the results. The fuel temperature quickly decreases when the water reaches the core, and only small differences can be seen if the recirculation fails in an early time. The hydrogen generated during the accident, however, varies slightly if the mass flow rate is not high enough, as seen in Figure 12. This is was expected, as the steam generated during the core quenching can provoke an increment in the oxidation of the unoxidized Zr, generating hydrogen in the process.

Figure 13 shows that the later the recirculation phase injection fails, the faster and easier it is for the FLEX water injection to cool down the core. However, attending at Table 6-8 it is seen that it is better to inject water into the RCS as soon as possible since the recirculation fails, instead of trying to delay the failure of the recirculation. Assuming a certain damage scenario, it is easier to reduce the hazard of the accident by graphically moving up than going right in the summary Tables 6-8.

Finally, in Figure 14 and 15, it is seen that the containment pressure is largely influenced by the timing of the FLEX water injection and the mass flowrate delivered by the portable pumps. When the LPSI and HPSI are lost (together with the sprays), if the decay heat is high enough, the pressure will rise slightly during a small period of time, and then it will start to decrease again until the FLEX injection is available. When the FLEX water injection starts, large quantities of steam are generated, increasing the pressure in the containment. At this moment, the pressure trend in the containment will be modified because of the steam generated. There are differences between the different portable pumps, if the flow rate is 20 kg/s, the pressure continues to increase after the water injection. This behavior is also observed even if the failure of the recirculation injection is delayed 430 minutes. However, if the FLEX flowrate is 40 or 60 kg/s, the pressure will have a decreasing trend in the long term as the core cooling capability is higher.

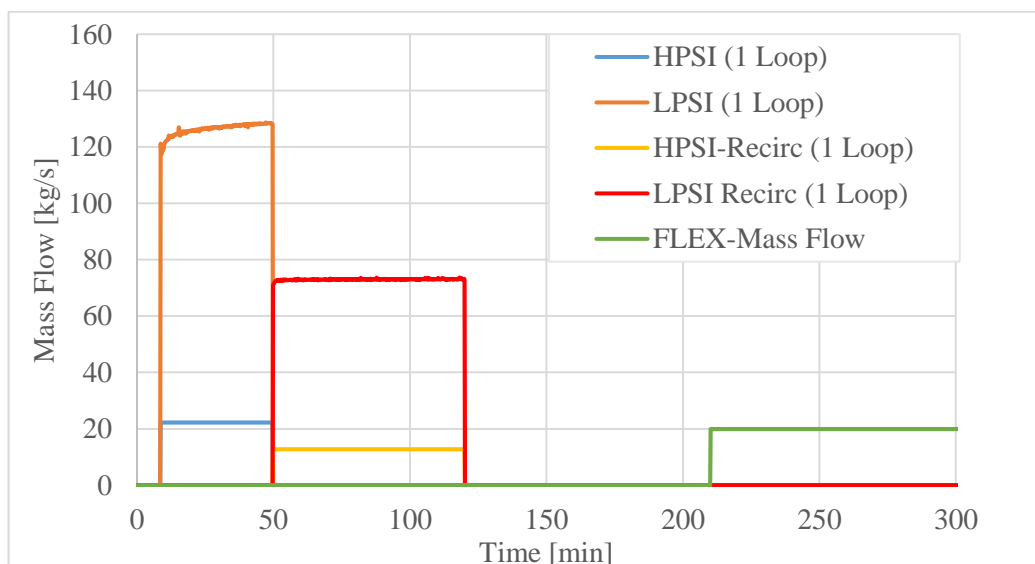


Figure 9. Safety Injection Systems mass flow in RF_70_FL_90_Q_20

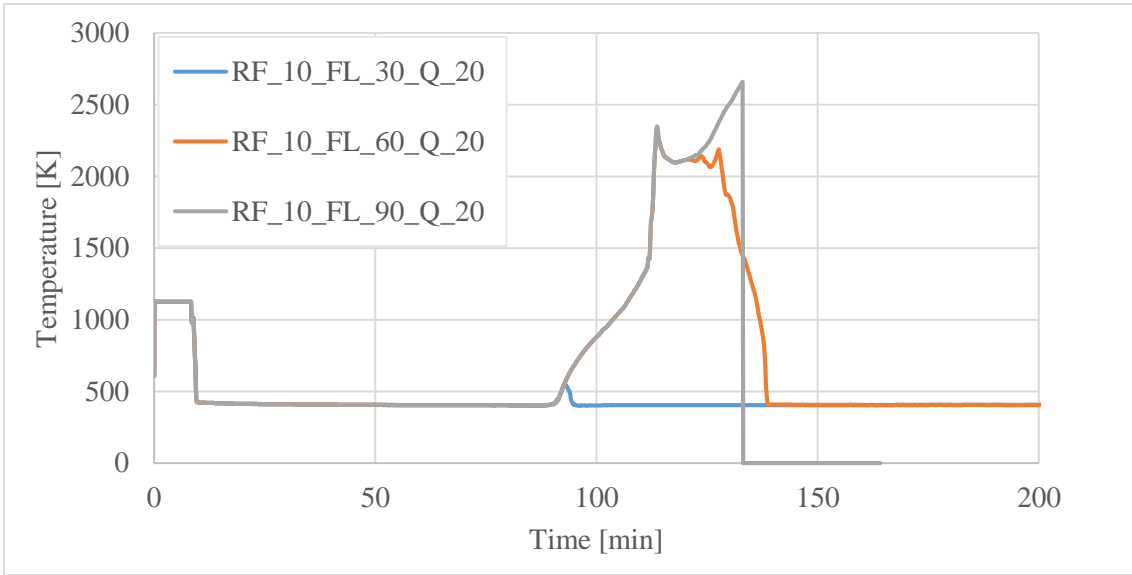


Figure 10. Core Temperature varying the FLEX water injection time after the recirculation failure in RF_10 cases.

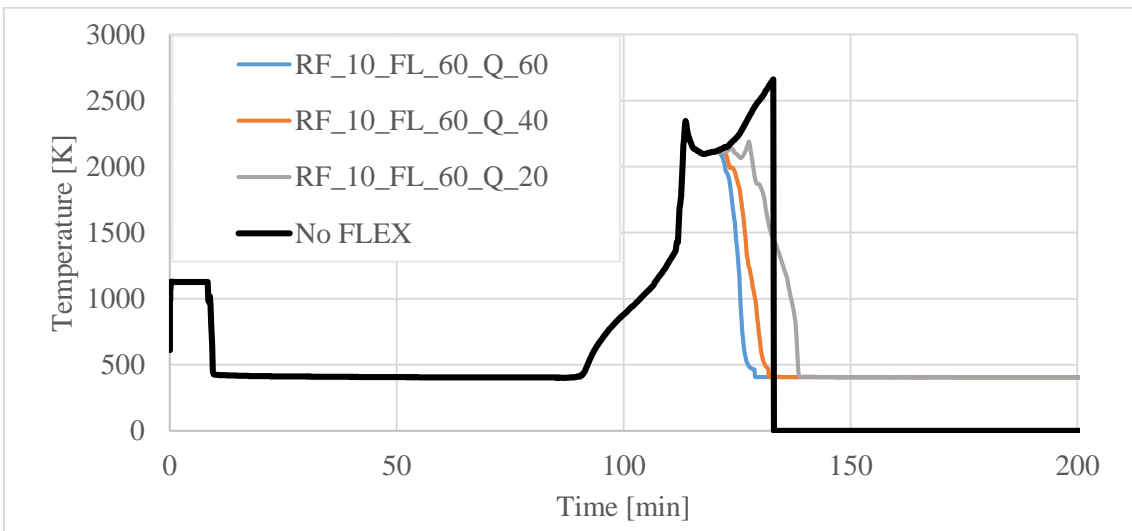


Figure 11. Temperature of core cell 209 for (RF_10_FL_60 cases)

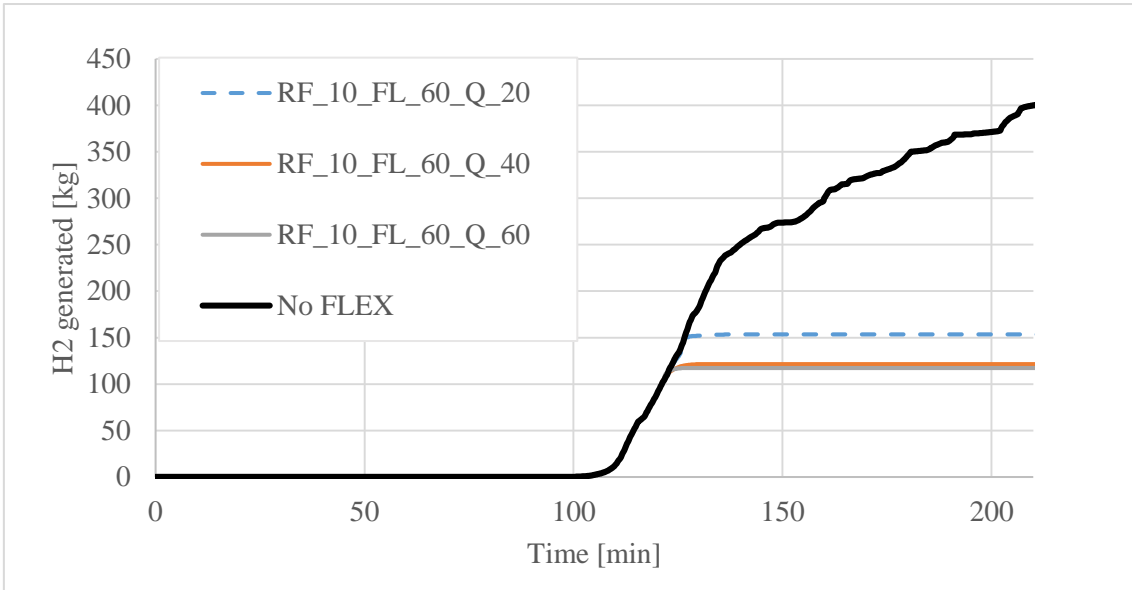


Figure 12. Hydrogen generated in core (RF_10_FL_60 cases)

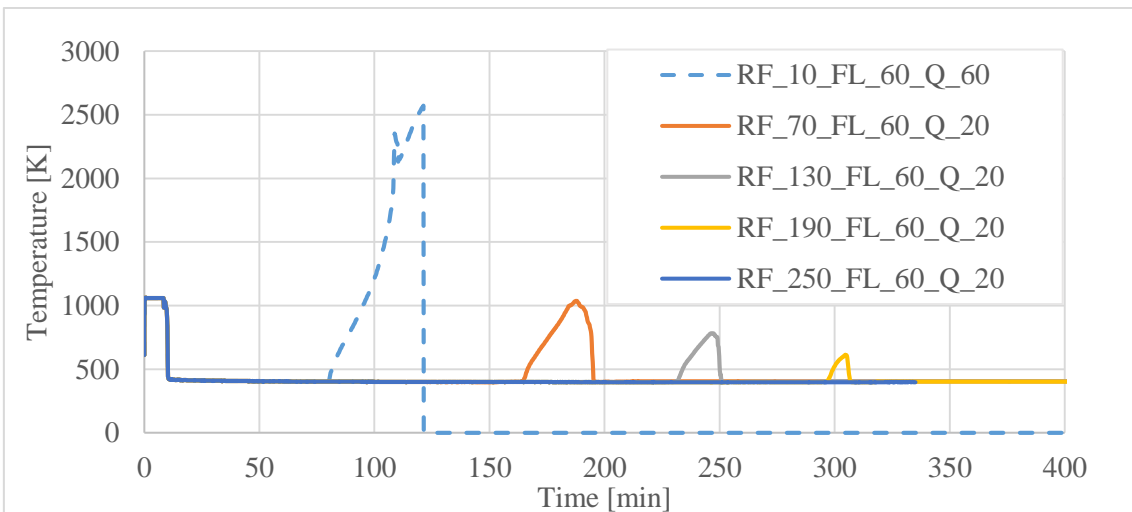


Figure 13. Temperature in Core axial level 212, for different timing of Recirculation Failure and FLEX water injection 60 min later.

Initial damage state when FLEX injection begins	Color
Safe State (SS).	Green
PCT > 1477 K (EC)	Yellow
Fuel Melting (FM)	Orange
Corium Relocation (CR)	Red
RPV Failure (VF)	Black

Table 5. Color Legend for Summary Tables of core initial states

G = 20
kg/s

		Recirculation failure since recirculation phase begins								
		0 min	10 min	70 min	130 min	190 min	250 min	310 min	370 min	430 min
FLEX water Injection time after recirc failure	30 min	SS	SS	SS	SS	SS	SS	SS	SS	SS
	60 min	FM	FM	SS	SS	SS	SS	SS	SS	SS
	90 min	CR	CR	FM	FM	FM	EC	SS	SS	SS
	120 min	CR	CR	FM	FM	FM	FM	FM	EC	EC
	150 min	CR	CR	CR	FM	FM	FM	FM	FM	FM
	180 min	CR	CR	CR	CR	CR	CR	FM	FM	FM
	210 min	VF	CR	CR	CR	CR	CR	CR	CR	CR
	240 min	VF	VF	VF	CR	CR	CR	CR	CR	CR
	>270 min	VF	VF	VF	VF	VF	VF	VF	VF	VF

Table 6. Core Damage State for different FLEX water injection and recirculation failure timings (G = 20kg/s)

G = 40
kg/s

		Recirculation failure since recirculation phase begins								
		0 min	10 min	70 min	130 min	190 min	250 min	310 min	370 min	430 min
FLEX water Injection time since failure	30 min	SS	SS	SS	SS	SS	SS	SS	SS	SS
	60 min	FM	FM	SS	SS	SS	SS	SS	SS	SS
	90 min	CR	FM	FM	FM	FM	EC	SS	SS	SS
	120 min	CR	CR	FM	FM	FM	FM	FM	EC	EC
	150 min	CR	CR	CR	FM	FM	FM	FM	FM	FM
	180 min	CR	CR	CR	CR	CR	CR	FM	FM	FM
	210 min	VF	CR	CR	CR	CR	CR	CR	CR	CR
	240 min	VF	VF	VF	CR	CR	CR	CR	CR	CR
	>270 min	VF	VF	VF	VF	VF	VF	VF	VF	VF

Table 7. Core Damage State for different FLEX water injection and recirculation failure timings. (G = 40 kg/s)

G = 60
kg/s

		Recirculation failure since recirculation phase begins								
		0 min	10 min	70 min	130 min	190 min	250 min	310 min	370 min	430 min
FLEX water Injection time since failure	30 min	SS	SS	SS	SS	SS	SS	SS	SS	SS
	60 min	FM	EC	SS	SS	SS	SS	SS	SS	SS
	90 min	CR	FM	FM	EC	EC	EC	SS	SS	SS
	120 min	CR	CR	FM	FM	FM	FM	FM	EC	EC
	150 min	CR	CR	CR	FM	FM	FM	FM	FM	FM
	180 min	CR	CR	CR	CR	CR	CR	FM	FM	FM
	210 min	VF	CR	CR	CR	CR	CR	CR	CR	FM
	240 min	VF	VF	VF	CR	CR	CR	CR	CR	CR
	>270 min	VF	VF	VF	VF	VF	VF	VF	VF	VF

Table 8. Core Damage State for different FLEX water injection and recirculation failure timings. (G = 60kg/s)

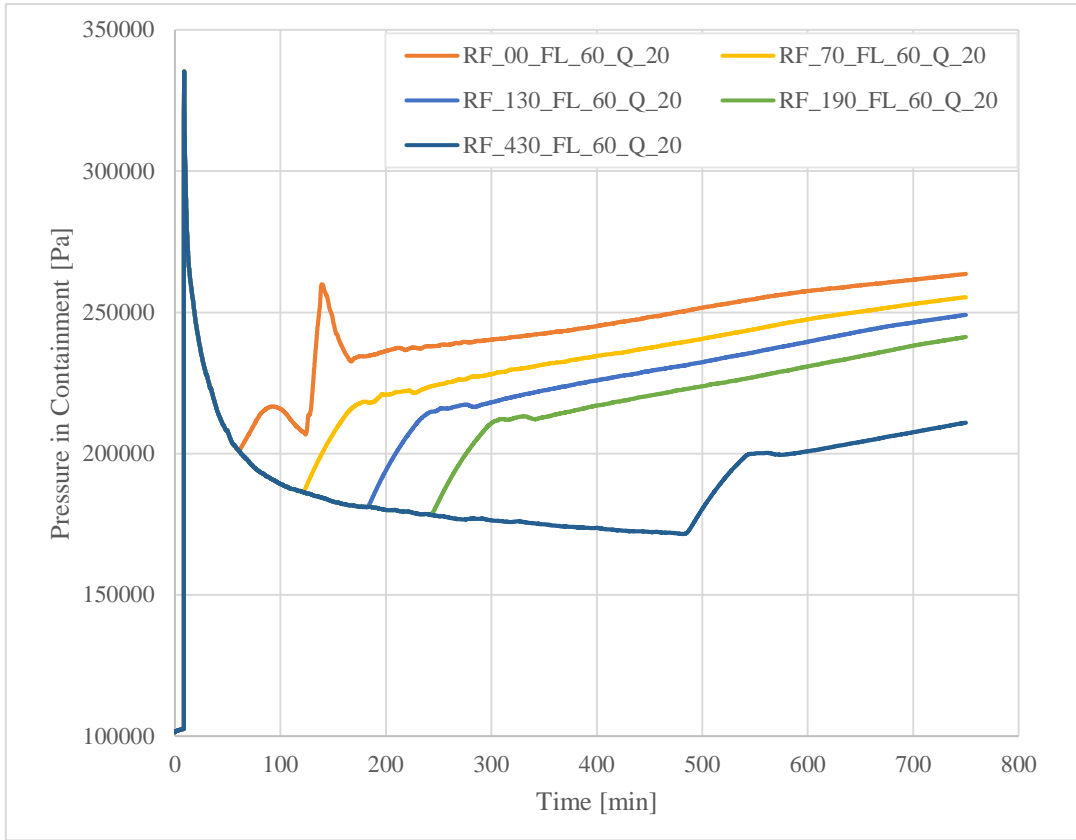


Figure 14. Pressure in containment varying delay in recirculation failure.

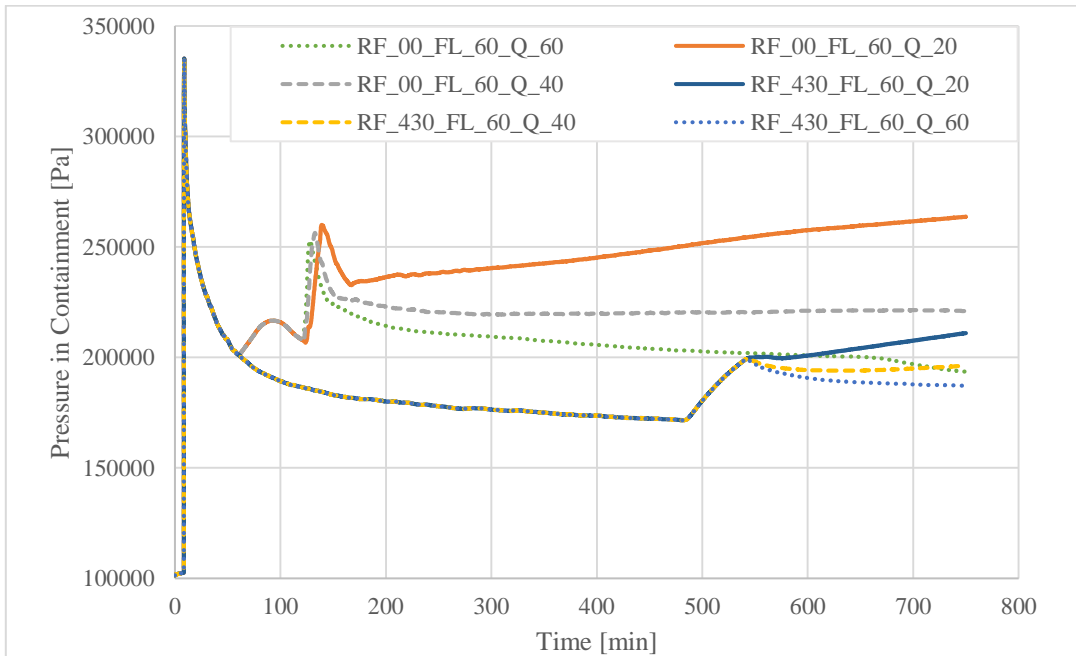


Figure 15. Pressure in containment varying the delay in recirculation Failure and FLEX mass flow rate

5. Conclusions

The FLEX strategies are being implemented in the EOPs and SAMGs of most of the LWR worldwide. Within these strategies, the use of portable equipment is proposed as an adequate accident management measure to prevent or mitigate the consequences of a SA following a loss of core cooling capability scenario.

In the present research, a study of the different timings of water injection into the RCS, together with the failure of the safety injection systems during the recirculation phase of a LBLOCA in a PWR-W are analyzed using the MELCOR 2.2 code.

The study shows that the core end-damage state may be precluded and/or stopped when the appropriate combination of water injection starting time and recirculation failure time are considered. Additionally, it was found out that to inject water into the RCS as soon as possible, is a much better option than to delay the onset of the recirculation phase failure.

A number of variables such as hydrogen generation or containment pressure does show significant differences for different portable water injection rates. It is seen that low or medium head pumps have some benefits relative to high head pumps that could be relevant in the long term.

The present research acts as another step in the necessary study of both FLEX strategies and core quenching of a degraded core. This work is intended to be extended to more equipment capabilities and scenarios, to help in the shaping of the final form of FLEX strategies.

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