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Synthesis report about the updated methodology for demonstration of In-Vessel melt retention

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In-Vessel Melt Retention Severe Accident Management Strategy for Existing and Future NPPs

IVMR – Grant Agreement 662157

Synthesis report about the updated methodology for demonstration of In-Vessel melt retention

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In-Vessel Melt Retention Severe Accident Management Strategy for Existing and Future NPPs

IVMR

EC project officer: **Dr. Roberto Passalacqua**

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Summary: The report describes the updated methodology to be used for safety demonstration of In-Vessel Retention Strategy in "high power" reactors. Starting from the methodology used for VVER-440 plants, it is explained how some assumptions must be abandoned and replaced by a more detailed evaluation. One of the most important points is the consideration of transient states of the corium pool which might cause higher thermal load on the vessel than in steady-state. Another important point is the consideration of detailed mechanical calculations in the cases of very thin remaining vessel thickness. Finally, the methodology introduces a new safety criterion, based on the residual vessel thickness, which is more general than the previously used criterion (based on a comparison of heat fluxes).

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Executive Summary

Molten corium stabilization following a severe accident is of crucial importance in order to ensure containment integrity on a long-term basis and minimizing radioactive elements releases outside the plant. Among the possible options, In-Vessel Retention (IVR) of molten corium in the lower plenum of the reactor pressure vessel by external cooling appears as an attractive solution that would reduce the risk of containment failure. The Horizon-2020 project “IVMR for LWR” was set up to investigate how IVR can be demonstrated for NPP around 1000 MWe electric power and above, knowing that the “bounding case” (or steady-state) methodology developed for plants below 600 MWe in the 1990’s reaches its limits for higher reactor powers.

As a first step of the evaluation, it is important to distinguish between two cases: the first case which corresponds to the use of IVR as a means to prevent vessel failure (probability of failure is negligible) and the second case which corresponds to the use of IVR as a means to delay vessel failure and reduce its probability of failure (which remains not negligible however). The accuracy needed in the evaluation of the probability of vessel failure is not same for the two cases: the first case requires a high accuracy whereas the second one can be evaluated with some approximation.

The results obtained during the IVMR project indicate that the existing “steady-state” approach in which the maximum heat flux from the corium pool is compared to the local critical heat flux achieved by ex-vessel cooling is not sufficient. Limitations of this approach are pointed out by means of state-of the-art transient analyses of the corium pool evolution in the lower plenum during a severe accident: local transient heat fluxes exceed the final steady state HF significantly (by a factor of 1.5 – 1.9 in some cases). In addition, it appears that assumptions of statistical independence of parameters employed in the steady-state approach can be doubtful because some of the parameters are actually related by time. As a consequence, the steady-state approach is not absolutely conservative.

Large localised heat fluxes from the corium pool govern the thermal attack and ablation of the RPV wall. These are strongly impacted by four main issues described in the report: (i) corium arrival in the lower plenum; (ii) heat flux along the top metal layer of the stratified pool; (iii) kinetics of inversion of stratification; and, (iv) metal properties. These issues can be quantified by deterministic severe accident codes, under the condition that suitable transient models for the complex phenomena are implemented.

The residual thickness of the ablated vessel appears as a “natural” parameter for the evaluation because it integrates the vessel ablation by the evolving corium pool and is directly linked to the resistance of the RPV with respect to static (and potential dynamic) loads. Based on this, a minimum thickness criterion is proposed and compared to the heat flux criterion that is at the centre of the steady-state approach.

An updated methodology for demonstrating IVR is proposed: it is based on the minimum thickness criterion. During a transient analysis of an accident scenario, vessel ablation is monitored and the smallest wall thickness compared to a minimum thickness value that is sufficient to withstand mechanical loads. The analysis is carried out for the scenarios causing the most severe conditions for

the IVR strategy, and can be further extended to an uncertainty analysis that covers uncertainties in scenarios and models.

The impact of design parameters, scenario parameters and phenomenological models, as it has been evaluated in the applications work package, highlights important points. In particular, it shows the importance of delaying the time of corium arrival in the lower plenum (with sufficient water capacities) to significantly reduce the probability of vessel failure. It also shows the importance of having a low ratio of the mass of fuel to the mass of molten steel in the lower plenum to reduce the intensity of the focusing effect. Those results, achieved by different codes, reflect the progress made on the relevant phenomenological models, and indicate that code predictions agree to some extent.

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Acronyms

BWR	Boling Water Reactor
CHF	Critical Heat Flux
ECCS	Emergency Core Cooling System
ERVC	External Reactor Vessel Cooling
FP	Fission Products
HF	Heat Flux
HTC	Heat Transfer Coefficient
IVR	In-Vessel Retention
IVMR	In-Vessel Melt Retention
LBLOCA	Large Break LOCA
LOCA	Loss of Coolant Accident
NPP	Nuclear Power Plant
PDF	Probability Distribution Function
PWR	Pressurized Water Reactor
ROAAM	Risk-Oriented Accident Analysis Methodology
RPV	Reactor Pressure Vessel
SA	Severe Accident
SAM	Severe Accident Management
SBLOCA	Small Break LOCA
SBO	Station Black Out
VVER	Russian Pressurized Water Reactors
WP	Work Package

Nomenclature

Notation	Description	Unit
$\delta(t)$	Local vessel wall thickness	[m]
δ_{min}	Minimum vessel wall thickness	[m]
δ_{CHF}	Vessel wall thickness when $\varphi = \varphi_{CHF}$	[m]
δ_{rup}	Vessel wall thickness for which mechanical rupture occurs	[m]
σ_{cr}	Ultimate strength	[MPa]
σ_{e}	Effective stress	[MPa]
$\Delta P(t)$	Pressure difference between inside and outside the vessel	[MPa]
$Q(t)$	Residual power per unit mass of UO_2	[W]
R	Average radius of the vessel	[m]
T_{fus}	Melting temperature of steel	[K]
T_{sat}	Water saturation temperature (outside the vessel)	[K]
T_{cold}	Maximum temperature of the "cold shell" of the vessel	[K]
X_{cold}	Relative thickness of the cold shell (w.r.t. total thickness)	[-]
ΔT_{cold}	Temperature difference across the cold shell	[K]
$\varphi(t)$	Local heat flux along the vessel wall	[MW/m^2]
φ_{max}	Maximum heat flux along the vessel wall	[MW/m^2]
φ_{CHF}	Maximum heat flux that may be extracted by external cooling	[MW/m^2]
φ_{rup}	Heat flux value when $\delta = \delta_{rup}$	[MW/m^2]
M_i	Total mass of element "i"	[kg]
H	Height of top metal layer	[m]
k	Vessel steel heat conductivity	[W/m/K]

1 Introduction

Molten corium stabilization following a severe accident is of crucial importance in order to ensure containment integrity on a long-term basis and minimizing radioactive elements releases outside the plant. Among the possible options, In-Vessel Retention (IVR) through external cooling appears as an attractive solution that would minimize the risks of containment failure (no corium-concrete interaction, less Hydrogen produced, less contamination in the containment), nevertheless it has to be proved to be feasible.

The IVR strategy is already adopted in Europe for some VVER 440 type 213 reactors thanks to thorough research work started in the '90s for the Finnish Loviisa power plant, and subsequently extended to Bohunice and Mochovce (Slovakia), Dukovany (Czech Republic) and Paks (Hungary) power plants. The strategy is also included in the design of some high power new Gen.III reactors such as AP1000, APR 1400 and Chinese HPR1000 and CAP1400. It has also been studied in the past for other reactor concepts like KERENA (BWR), AP600 or VVER-640.

Current approaches for reactors with relatively small power, such as VVER 440 or AP600, use conservative assumptions for the safety demonstration. However, for higher power reactors (around 1000 MWe), the safety margin is reduced and it is necessary to evaluate the IVR strategy with best-estimate methods in order to reduce the uncertainties associated with the involved phenomena. Additional R&D as well as a revision of the methodology are needed to ensure and demonstrate adequate safety margins, including, in particular, best-estimate evaluations of thermal load applied on the vessel and mechanical resistance of the ablated vessel.

The IVMR project (In-Vessel Melt Retention) was created with the goal of providing new knowledge (experimental, theoretical and technical) and a new methodology able to provide a best-estimate evaluation of IVR strategy for large power reactors. The main objective of Task 2.1 within WP2 is to define a common methodology to analyse IVR Severe Accident Management (SAM) strategy for the different types of EU NPPs). Task 2.1 started by reviewing the status of existing methodology and aimed at elaborating a more general, updated and less conservative one applicable to several types of reactors.

This document describes the proposed new methodology. It starts with the identification of the deficiencies of the standard methodology when it is applied to a high power reactor. It introduces the minimum vessel thickness as a parameter representing the cumulated balance between internal heat load and external cooling. Then it explains how to use that parameter in the evaluation of the safety margin. Finally, the impact of design and scenario parameters is discussed. Some examples are given as illustrations but it must be kept in mind that **this document proposes a generic methodology but there cannot be any generic conclusion: any reactor design must be evaluated independently**.

2 The possible roles of IVR and ERVC: mitigation or termination of the accident progression

The terminology "In-Vessel Retention" or IVR was initially proposed to describe a strategy that would lead to the termination of corium progression by using the lower part of the vessel as a heat exchanger through which it would be possible to extract the residual power and progressively stabilize the corium. For the investigated cases (Loviisa plant, for instance (Kymäläinen et al., 1997)), it was proved that the vessel would not fail, because the remaining vessel thickness was estimated to be most likely around 10 cm and, in any case, always larger than 6 cm. With this statement established, the remaining elements of the safety demonstration are essentially related to the design (reliability and performance of the implemented hardware): depressurization system, efficient external cooling system, efficient containment condensation system, etc.

When investigating the possible IVR application to higher power reactors (such as AP1000 (Esmaili and Khatib-Rahbar, 2005) or APR1400 (Rempe et al., 2004)), a new point had to be considered in the safety analysis: the probability of vessel failure was not zero and not even negligible. This led to shifting the safety assessment to the evaluation of the risk of containment failure due to the energetic interaction of corium with water after vessel failure. In that case, the main issue was not "Can the corium be retained within the vessel?" but "Can the containment withstand a possible steam explosion in case of vessel failure?" If the answer to this question is positive, then it is acceptable to flood the external part of the vessel in order to either stop the corium progression in the vessel or delay the vessel failure. Another consequence, in that case, is that additional measures must be implemented to ensure the stabilization of corium outside the vessel (core catcher or corium spreading and/or sacrificial concrete for example).

Therefore, we see that there are two different uses of External Reactor Vessel Cooling (ERVC):

1. ERVC to **prevent** vessel failure: in that case, it is right to talk about in-vessel retention of corium and the objective of safety evaluation is to evaluate the risk of vessel failure and show that it is practically eliminated (i.e. extremely unlikely with a high degree of confidence).
2. ERVC to **prevent or delay** vessel failure: in that case, the objective is not in-vessel retention but it is a defence-in-depth approach where the possibility to stop the corium progression inside the vessel is considered with an appropriate system but it is not the only possibility and ex-vessel systems are also implemented. The objective of safety evaluation is to identify the cases leading to vessel failure, to evaluate the associated risk of containment failure, and show that it is negligible. If the probability of vessel failure is too high, it may even lead to the conclusion that implementation of ERVC does not provide a significant improvement of the safety of the reactor and is not necessary.

In the worst cases, depending on the reactor design, the implementation of ERVC may even increase the risk of containment damage or failure (Fichot et al., 2014).

So, it must be kept in mind that ERVC implementation is not equivalent to IVR and that it may be only a safety measure in a chain of other measures, following the principle of defence-in-depth. The association of the two terminologies (ERVC and IVR), which is frequently done, may be confusing or misleading.

Therefore, one of the key issues in the safety analysis of a reactor where ERVC is implemented is to determine if the probability of vessel failure is extremely unlikely with a high degree of confidence, or if it is not negligible. **The two cases correspond to two different approaches**. In the first case, the probability of vessel failure must be evaluated with the highest possible accuracy. In the second case, the evaluation does not need to be very accurate. In-between those two cases an arbitrary threshold of residual risk can be chosen to accept the IVR strategy or to require additional measures for ex-vessel stabilization of corium. This threshold should be examined on a case-by-case basis, depending on the reactor design.
The following table summarizes the possible situations:

Probability of vessel failure	Safety assessment conclusion	Accuracy needed
Negligible	IVR can be assumed, with a residual risk	High
Not negligible	IVR is not guaranteed. Ex-vessel stabilization must be implemented too.	Medium

3 Background

The methodology introduced initially for the AP600 (Rempe et al., 1997; Theofanous et al., 1997a) and the Loviisa plant (Kymäläinen et al., 1997; Kymäläinen and Tuomisto, 2000) included a probabilistic evaluation of the maximum heat flux and minimum thickness of the vessel. The analysis was made with a single configuration of corium and metal in the lower plenum: the entire core was assumed to be molten, forming the oxide pool and all the internal steel structures and ablated vessel were assumed to be included in the top metal layer, above the oxide pool. This configuration was initially called “bounding situation” by (Theofanous et al. 1997). In their paper, they explain that “this configuration is of fundamental significance in assessing the problem at hand, not only because it bounds all intermediate states, but also because it represents the final state that would actually be realized in any in-vessel retention scenario”. But this statement is proven wrong by today’s phenomenological modelling. Most of the reactor calculations performed by IVMR partners during the project have shown that:

- **The bounding case does not bound all intermediate states**: there are transient situations where the peak heat flux is higher than the heat flux at final state.
- **The bounding case does not represent the final state**: the metal and oxide layers masses may vary, depending on assumptions about densities and thermochemical equilibrium compositions. Moreover, the shape of the ablated vessel obtained after a transient may significantly differ from the shape deduced from the final state.

These statements are illustrated in Figure 1 obtained from the results of IVR benchmark calculations performed in the IVMR project and presented in (Carénini et al., 2019). Six different codes were used to simulate the same reactor configuration, starting from the steady-state case and then calculating the transient evolution with progressive molten steel incorporation. The heat flux profile at the outer surface of the vessel wall obtained when the maximum heat flux is reached is compared to the heat flux profile obtained in steady-state configuration. All codes show an increase of the heat flux in the transient case. This maximum is located between elevations 1.5 and 2 m in the metal, and corresponds to the initial height of the layer, at a time when the mass of molten steel is still small. The heat flux is multiplied by a factor 1.5-1.9 compared to the simplified steady-state case.

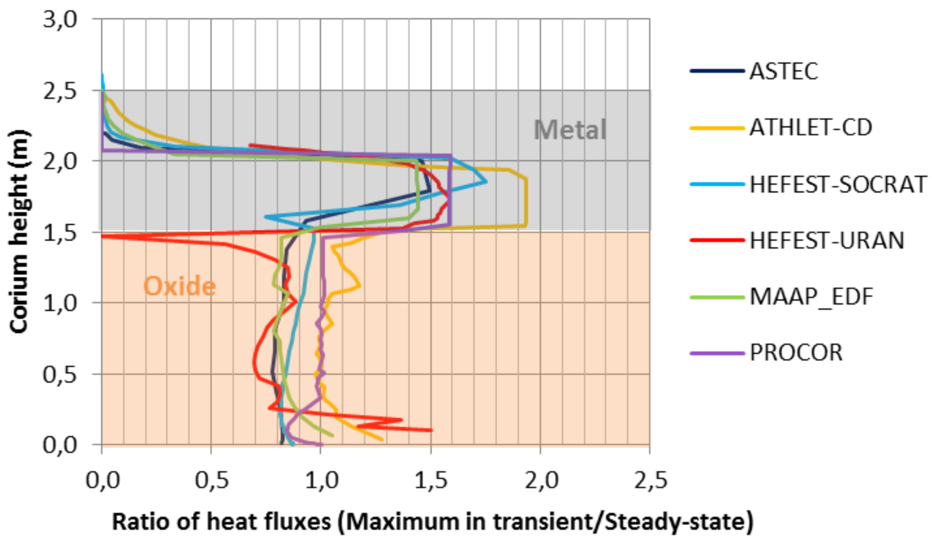

Figure 1 – Multiplying factor obtained between heat fluxes at the outer surface of the vessel calculated based on a steady-state configuration, and the maximum value reached when the transient evolution for the molten steel incorporation in the pool is considered

Other corium configurations were introduced as in (Rempe et al., 1997) or (Seiler et al., 2007). But the introduction of more configurations, and therefore more parameters in the probabilistic study, made the mathematical analysis more complex and several authors have proposed simpler methods to evaluate the maximum heat flux along the vessel wall. They replaced the complete probabilistic analysis by a selection of conservative assumptions which would provide directly the maximum heat flux as in (Seiler et al., 2007). However, it is not possible to make a conservative assumption for the mass of molten steel, since standard models predict that the maximum heat flux along the metallic layer increases when the height of the metallic layer decreases (so-called focusing effect). Therefore, the conservative or "bounding case" approach has a limited interest. It is useful to make a quick estimate of the maximum heat flux along the vessel wall, with "reasonably conservative" assumption concerning the minimum thickness of the top metal layer, but it omits deliberately (i.e. assuming a negligible probability for) a whole range of transient situations which could result in higher heat flux, at least temporarily.

Nevertheless, the probabilistic approach introduced initially is still the most widely used approach (Ma et al., 2016). Different approaches may be chosen to evaluate the probabilities of the input parameters and the significance of the probability of the maximum heat flux and minimum wall thickness. In the ROAAM method, the probabilities represent a level of acceptability of an event or physical process with respect to expert judgement or physical sense. Other methods follow an approach similar to PSA and the probabilities are assigned to a frequency of occurrence. It has the advantage of allowing taking into account the frequency of occurrence of some accident scenarios. In such a case, the range of frequency covered is continuous and the acceptability criteria are more difficult to define. To illustrate this, in ROAAM approach, an event with a probability lower than 0.01 is considered as “outside the spectrum of reason” (this is a “cut-off” frequency) whereas in a PSA, it would be considered as “possible”. Therefore, one has to be very careful when interpreting the results of a probabilistic study of IVR: probabilities may have different meanings.

3.1 Important drawbacks of the probabilistic approach

Among the uncertain variables, **the mass of metal plays a key role but** it is also one of the most difficult to define in terms of distribution. **It includes too many sources of uncertainties**: it is related to the accident scenario, to the modelling of corium relocation and to the time when steady-state is reached. Moreover, it is not independent of the residual power, which is another uncertain variable. This clearly shows one of the weaknesses of the probabilistic approach: it does not allow taking into account time-dependent variables in a consistent way. Moreover, it assumes that some uncertain variables are independent when they are actually both related to time. As an illustration, it can be seen in Figure 2 that there is clearly a linear correlation between the mass of molten steel from vessel melting and the residual power. Therefore, those variables cannot be considered as independent.

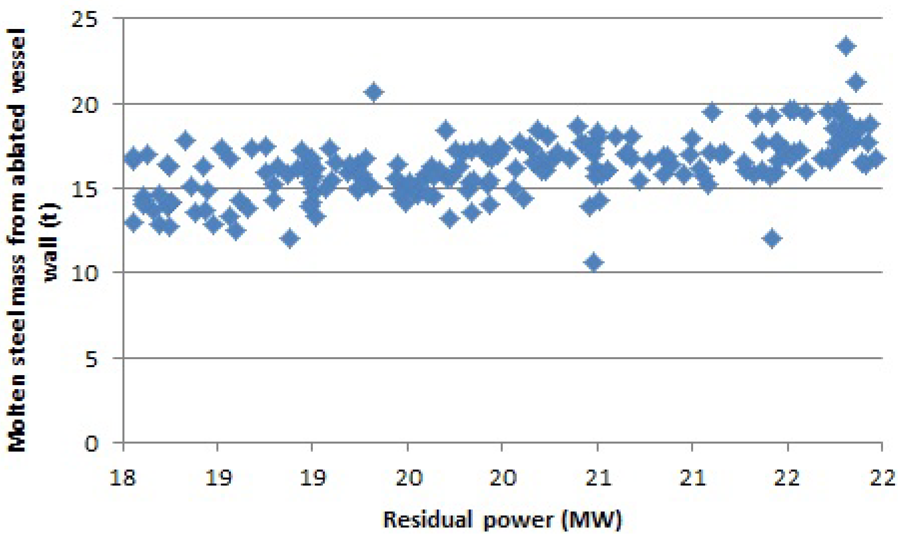

Figure 2: Variation of the mass of molten steel from the vessel as a function of residual power taking into account transient melting and stratification in the probabilistic evaluation (from ASTEC sensitivity simulations described in D2.2.1 (Carénini et al., 2019))

There is also a possible inconsistency of the probabilistic approach coupled with the “bounding case”: the bounding case is “assumed” to be conservative (although it is not) but, if the probability distributions of the uncertain parameters are not defined carefully, it may end up with too much probability for combinations of more favourable parameters (i.e. large mass of steel, low residual power or high emissivity of the metal layer, for instance). In the end, **it may lead to overestimate the probability of non-conservative situations**.

Finally, another drawback of the probabilistic approach as it is usually presented is that it mixes uncertainties coming from the scenario and phenomenological uncertainties. This induces confusion in the meaning of the probability of vessel failure. For example, if the result of the probabilistic analysis has a 10% probability of vessel failure: it is a completely different interpretation, if it is found that the vessel would always fail in case of large break which has a probability of 10% or if it is found that the vessel does not fail for any scenario, except with the worse combination of model parameters, which has a probability of 10%.

3.2 The issue of mechanical resistance

In the steady-state approach, two criteria for vessel failure were postulated: thermal failure and structural failure. The thermal failure mechanism of the lower head is due to boiling crisis (BC) which occurs when the heat flux through the vessel exceeds the critical heat flux (CHF) at the same location, and it results in a sudden transition of the flow regime from nucleate to film boiling. It has been suggested for an AP600-like reactor (Theofanous 1997) that boiling crisis is a sufficient condition for lower head failure, but also a necessary condition meaning that, unless BC occurs, there can be no failure. This was demonstrated with a detailed mechanical calculation on the most vulnerable point of the vessel, around 90° which means vertical vessel wall, supposing the boundary conditions of Figure 3.

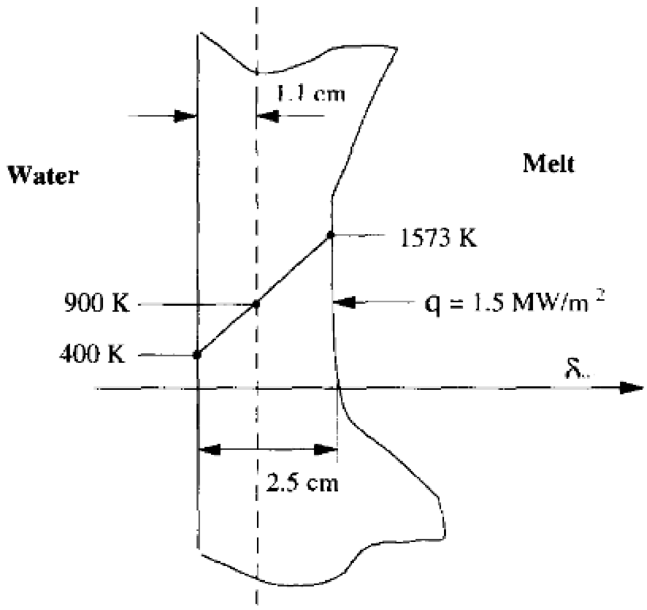

Figure 3. Illustration of conduction-limited wall thickness, and of the full-strength "cold external shell" region (T < 900 K), under an imposed heat flux of 1.5 MW m^{-2} (from (Theofanous 1997))

For the studied cases (Loviisa, AP600), the cold shell was almost 100 times larger than the minimum thickness required to withstand internal overpressure, and the risk of structural failure soundly rejected.

Analyses, in the IVMR project, of reactors around 1000 MWe power have shown that the thickness of the cold shell may reach values around 1 cm, which is just about 10 times more than the minimum thickness required to withstand static loads of the lower plenum. Conditions like accidental pressurization of the primary loop or an unfavourable vessel ablation profile reduce this margin further. Thus, for high-power reactors it becomes important to evaluate the margin and check if it is sufficient to deal with the uncertainties on mechanical properties and on the mechanical loading.

3.3 Conclusions about existing methodology

The existing methodology appears suitable to demonstrate the efficiency of IVR with ERVC when the safety margin is large (i.e. the residual vessel thickness is almost two orders of magnitude larger than the minimum thickness required to withstand the internal pressure load). Although it is quite comprehensive, this methodology misses an important point: there are transient situations that may cause more damage to the vessel than the supposedly "bounding" case. Moreover, when too many details and parameters are involved, there is also a source of confusion or underestimation in the evaluation of the risk when combining the use of bounding cases and probabilistic assessment. Those drawbacks do not lead to significant errors as long as the safety margin is very large. Reactor calculations performed in the IVMR project support that conclusion. Figure 4 and Figure 5 show the residual thickness of the lower head once the corium is stabilized for a VVER440 and a VVER1000 respectively. In the former case the smallest and most critical residual thickness is about 10 cm, while in the latter is about 2.5 cm.

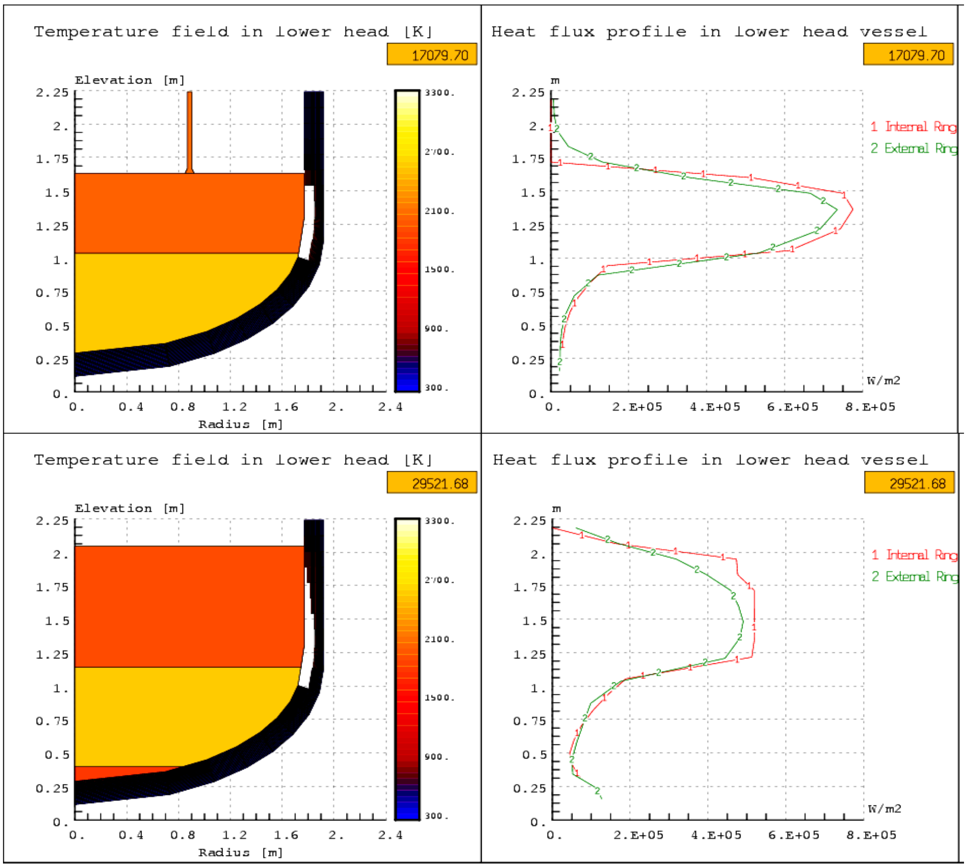

Figure 4. VV440, LBLOCA, Temperature and HF profile at the time of HF culmination (top) and stabilised state (bottom). Minimum wall thickness is seen to be about 50% of the original RPV thickness (ASTEC simulation by IVS).

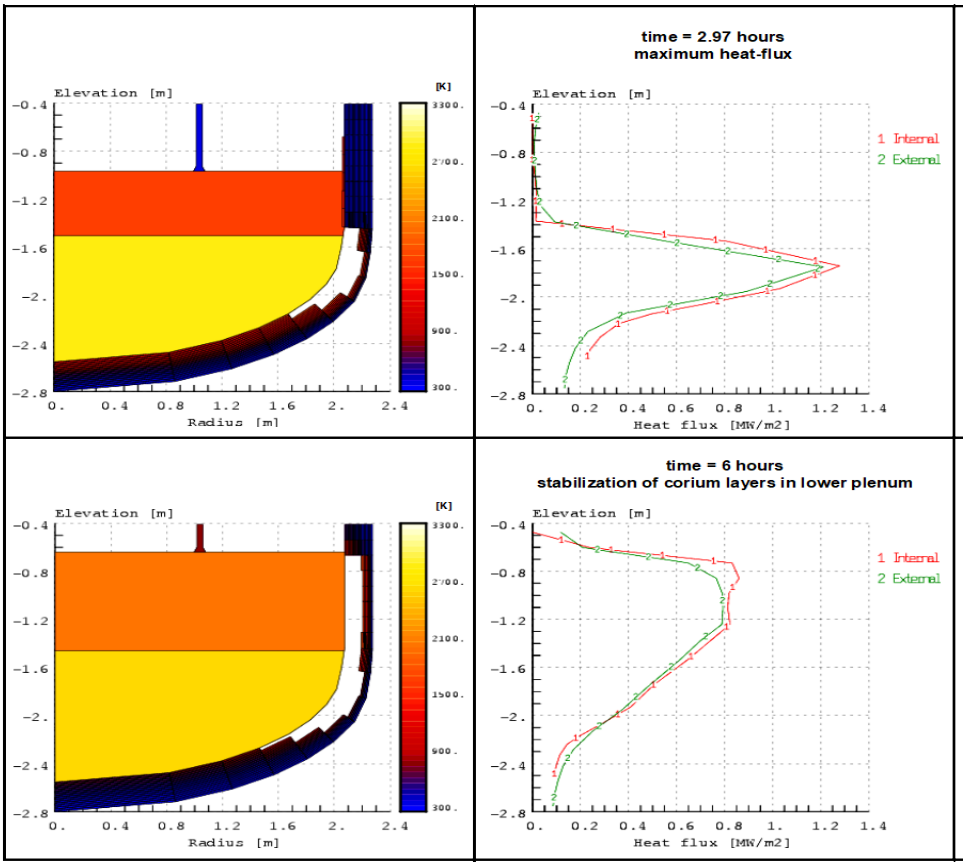

Figure 5. VVER1000, LBLOCA, temperature and HF profile at the time of HF culmination (top) and stabilised state (bottom). For this latter state - quasi the steady state of the process - the smallest wall thickness caused by the transient process is in a different place than 90˚(ASTEC simulations by IVS).

When the safety margin is reduced, more accuracy is necessary to estimate the margin and all the "details" of the methodology are important. **One way of improving both identified drawbacks is to introduce time as a parameter in the evaluation**. This can be done in two different ways: either using deterministic (and time-dependent) calculations instead of steady-state cases or, keeping the probabilistic approach on steady-state cases but refining the PDF of uncertain parameters, in order to take into account the fact that most of them are time-dependent and, therefore, they do not have uniform distributions and all combinations of parameters cannot have the same probability. The deterministic way appears more straightforward and more comprehensive and was followed in the IVMR project.

4 Identification of the main phenomena to be considered in the evaluation of the risk of excessive heat flux

In order to make a deterministic evaluation of IVR, it is necessary to use a code that includes all the important phenomena. It is not obvious to identify them because of the variety and the complexity of the phenomena. This is why, to identify the phenomena generating the highest uncertainties, a PIRT was elaborated during the IVMR project. In that PIRT, several "parameters" (phenomena, physical properties, etc.) were ranked according to their level of uncertainty and their impact on the risks of vessel failure or the risk of excessive heat flux. The detailed ranking of the parameters, which impact the risks of excessive heat flux in stabilized or in transient situations is presented in (Fichot et al., 2019). The parameters are listed only when their overall impact is above 10%. Other phenomena with a high impact were identified but they were considered to involve low or medium uncertainties and, therefore, they were not kept in the table.

Table 1: Ranking of the phenomena inducing the highest uncertainties in the evaluation of excessive heat flux

	Overall impact (%)
Molten pool formation	52
Transient establishment of heat transfers	52
Kinetics of stratification	43
Correlations of heat transfer in upper metal layer	38
Chemical interactions between metal and oxide crusts	34
Crust mechanical resistance	32
Metal properties	28
Corium pool / vessel structures failure	26
Emissivity of metal layer	20

From these results, the following 4 main issues can be identified:

1. The first one deals with the molten pool formation. This item is linked with the core degradation and the necessity to better evaluate the melt progression in the core and the oxidation of Zircaloy. This issue was highlighted by the recent crosswalk activities performed between MELCOR, MAAP and ASTEC (Wachoviak et al., 2014 and Belon et al., 2017). In the “previous” approach for IVR studies, the conservative case corresponds to the steady state configuration where the whole core has relocated and corium pool is already molten and stratified. In such approach, those phenomena do not appear as significant but it should be kept in mind that uncertainties related to core degradation must be taken into account in the safety evaluation by introducing uncertain parameters such as the degree of oxidation of Zircaloy or the mass of steel. Currently, it is acknowledged that the maximum heat flux to the vessel wall and the risk of vessel failure may be higher in transient situations when stratification of the corium pool is still evolving and when the steel mass is lower than its final value. Based on this consideration, it becomes necessary to better evaluate the way the core degrades and the kinetics of molten steel formation.
   To summarize, the important parameters characterizing corium arrival in the lower plenum are: timing, oxidation degree, mass of fuel, mass of steel.

2. The second issue appears to be the heat transfers in the top metal layer, in particular, under transient conditions. Ongoing work with CFD codes performed in the scope of the IVMR project (Le Guennic et al., 2017) is expected to provide significant insights and possibly new correlations adapted for thin layers. In a complementary way, new experimental data for convective heat transfers in prototypical metal layer heated from below and with a progressive incorporation of molten steel or superheated metal would also be necessary to better simulate such transient effects and evaluate their impact on the heat flux along the vessel wall.

To summarize, the important parameters governing the heat flux along the top metal layer are: heat transfer correlations, peaking factor, superheat.

3. The issue of thermochemical effects, with the kinetics of stratification in the lower head and the chemical interactions between metal and oxide crusts, is also highlighted. The impact of the crust on the kinetics of stratification was investigated in the CORDEB program conducted by the Alexandrov Research Institute of Technology (NITI) in Russia (Almjashev et al., 2018). This issue was further studied in ongoing CORDEB2 tests performed in the scope of the IVMR project and models dedicated to the evaluation of this kinetics have been proposed (Le Tellier et al., 2015, Fichot and Carénini, 2015).
   To summarize, the main parameters governing the kinetics of inversion of stratification are: species diffusion coefficients, crust thickness and composition.

4. The final issue deals with the properties of the metal layer, which includes at equilibrium metallic Uranium in addition to molten steel and Zirconium. The emissivity was identified as significant but the metal density and heat conductivity appear to be the properties with the highest impact. However, the evaluations calculated for the other properties are also close behind and it does not allow a clear identification of the properties for which the overall impact on the risk of excessive heat flux is the highest. The predominant effect of metal properties compared to those of the oxide is clear. In a separate sensitivity analysis, the viscosity appeared as the most significant property, followed by the thermal expansion coefficient and the thermal conductivity. This illustrates the need for more sensitivity studies to go further in the identification of the main parameters and consolidate the results obtained in this PIRT.
   To summarize, the metal properties with the highest impact are: heat conductivity, viscosity, emissivity and density.

5 A key safety parameter: the minimum vessel thickness

As it was shown, the peak heat flux may occur during transient situations, for short time intervals. Nevertheless, this may cause significant ablation of the vessel wall at the location of maximum heat flux. Moreover, the position of maximum heat flux in steady-state may be different from the position of peak transient heat flux. As a result, at any time of the transient, the profile of vessel thickness cannot be deduced only from the knowledge of the heat flux profile in steady-state.

It is clear that **the local vessel thickness is a more relevant parameter than the local steady-state heat flux** to be used as a criterion of vessel failure **because the vessel thickness includes all transient effects since the beginning** of the transient, in particular the occurrence of short but very high heat fluxes. It is also a parameter that can be used directly for mechanical calculations over the entire ablated vessel profile.

The residual thickness is a parameter for which it is rather straightforward to estimate a safety margin, as it is usual for other mechanical failure criteria based on thickness/load relationships (such as for the fuel cladding or for the containment). Classically, the safety margin for a structure is defined by a relation such as:

$$\sigma \leq \sigma_{max} = \frac{\sigma_{\mathrm{fail}}}{m} \qquad \text{Eq. 1}$$

Where σ is the stress and m is a safety factor larger than 1. Typically, for standard applications, it can be around 5 when the evaluation of the load is uncertain or if the material properties are not well known. If we have a linear relation between the minimum thickness δ and the stress at failure, then the previous safety margin can be reformulated as:

$$\delta \geq m\,\delta_{\text{fail}} \qquad \text{Eq. 2}$$

Because of uncertainties on the scenario (possible re-flooding, reliability of the pressure release valves) and on the models (vessel ablation), there are uncertainties in both terms of the thickness/load criterion. Therefore, it is appropriate to choose a factor *m* that is sufficient to cover all possible extreme cases where the residual thickness is reduced by high transient heat fluxes or if the mechanical properties are not well known. In the following parts, evaluations are performed to give orders of magnitude and illustrate the impact of different parameters. The reference values used for calculations are given in the table below.

Table 2: Example of realistic parameters in an IVR analysis

Notation	Description	Reference value	Unit
σ_{cr}	Ultimate strength	600	[MPa]
R	Average radius of the vessel	2.5	[m]
T_{fus}	Melting temperature of steel	1700	[K]
T_{sat}	Water saturation temperature (outside the vessel)	400	[K]
T_{cold}	Maximum temperature of the "cold shell" of the vessel	700	[K]
X_{cold}	Relative thickness of the cold shell (w.r.t. total thickness)	0.23	[-]
ΔT_{cold}	Temperature difference across the cold shell	300	[K]
ΔT_{fus}	Temperature difference across the vessel wall	1300	[K]
k	Vessel steel heat conductivity	30	[W/m/K]

5.1 Introducing of a new generic safety criterion

To assess the structural integrity in a simple way, we can consider the following 'classical approach'. For the elastic-plastic behaviour, we adopt the failure criterion from (Theofanous et al., 1997) with the assumptions that creep and thermal stresses are neglected:

$$\Delta P_{\text{max}} = \frac{2\sigma_{\text{cr}}\delta_{min}}{R} \qquad \text{Eq. 3}$$

where ΔP_{max} [MPa] is the maximum admissible pressure difference, σ_{cr} [MPa] is the ultimate strength, δ_{min} [m] is the calculated minimum vessel wall thickness, and R [m] is the average radius of the wall.

As it was done before, we may consider that only the "cold part" of the vessel contributes to the mechanical resistance. This can be justified by observing the strong decrease of mechanical properties (Young modules, ultimate strength) when the temperature is above 800K (Willschuetz et al., 2003). In the range 300-800K, the ultimate stress is almost constant and has a minimum value around 600 MPa.

If we consider that the maximum overpressure is $\Delta P_{\text{max}} = 1\ bar$ (i.e. approximately the weight of corium and steel minus buoyancy), we obtain the minimum "cold" thickness:

$$\delta_{cold} = 0.2mm$$

Assuming a linear temperature gradient through the vessel, we can estimate that the calculated vessel thickness leading to rupture is:

$$\delta_{rup}^{min} = \frac{\Delta T_{fus}}{\Delta T_{cold}} \delta_{cold} = 0.87mm$$

Actually, detailed finite element calculations seem to indicate that the criterion based on the plastic rupture of the cold shell is too conservative. The reason is that the "hot part" plays a positive role on the mechanical resistance. This is illustrated in Figure 6 where the limit between safe domain and failure domain evaluated with finite element calculations and estimated with the simple equations introduced above are compared.

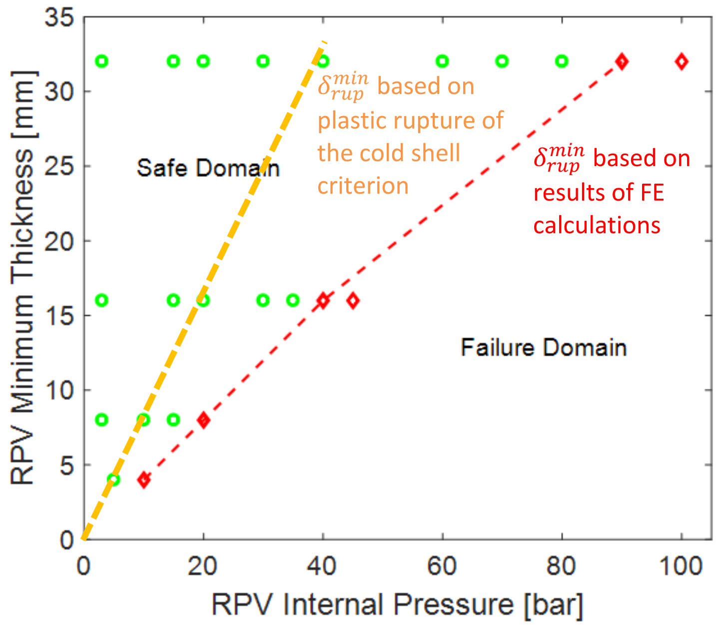

Figure 6: Comparison of results of finite element calculations (performed by KTH, one point is one calculation) and evaluation performed using the simple mechanical criterion defined in the present report (cf. Eq. 3)

While a significant decrease of δ_{rup} values is identified, it is not possible to conclude on a reasonable quantitative value in this report. In addition, uncertainties on mechanical properties (non-homogeneity in the wall, impact of aging in the reactor…) and impact on the value of δ_{rup} would have to be assessed.

Nevertheless, if we keep the conservative criterion based on the plastic rupture of the cold shell and introduce an additional safety margin $m = 10$, we can re-evalute δ_{rup} as:

$$\delta_{rup} = 8.7mm$$

Then, a simple safety criterion can be defined as:

$$K_\delta = \delta_{rup}/\delta_{min}.$$

In the example of the VVER440 (Loviisa) where the minimum vessel thickness is always larger than 6 cm we have $K_\delta < 0.145$; this shows that, for an overpressure of 1 bar, there are almost two orders of magnitude for the mechanical safety margin.

5.2 Links of steady-state heat flux criterion and thickness criterion

Before comparing the significance of the heat flux criterion and the thickness criterion, it is useful to introduce a new reference value for the heat flux. We define it as the heat flux for which the mechanical failure of the vessel would occur (i.e. when $\delta = \delta_{rup}$):

$$\varphi_{rup} = \frac{k\Delta T_{fus}}{\delta_{rup}}$$

and, for the example of section 5.1

$$\varphi_{rup}(\Delta P_{\max} = 1bar) \approx 4.5\ MW/m^2$$

This means that in case of an internal overpressure of, for instance $\Delta P_{\max} = 5\ bar$, φ_{rup} would be reduced to 0.9 MW/m^2. Any higher heat flux would reduce the mechanical safety margin.

At the same time, the maximum heat flux is limited by the capacity of EVRC. In the standard approach, the main “safety” variable is

$$K_\varphi = \varphi_{max}/\varphi_{CHF}$$

What is exactly the meaning of K_φ ? If it is above 1, it means vessel failure, without ambiguity. If it is below 1, it represents a “distance” with respect to φ_{CHF}. But it is not really a safety margin because **there is no classical or standard criterion to determine an acceptable margin for a heat flux**. Therefore, in order to replace that unknown margin factor, the statistical evaluation of this parameter must be done. Then, if $p(K_\varphi > 1) = 0$, it means that there is no risk of vessel failure.

An easy link between both safety criteria can be done by using the ratio $B = \frac{\varphi_{rup}}{\varphi_{CHF}} = \frac{\delta_{CHF}}{\delta_{rup}}$:

1. If $B > 1$, rupture occurs because of excessive heat flux (melt through), irrespective of the internal load
2. If $B < 1$, rupture can occur by mechanical failure before reaching an excessive heat flux

The first case is more realistic, in general, because we assume that the design and accident management measures will allow an effective depressurization. But the second case corresponds, for example, to a scenario where the internal overpressure could reach 30 bar ($\varphi_{rup} \approx 1.5\,MW/m^2$ (calculated without margin, i.e. $m = 1$), whereas the CHF would be quite efficient, with a value of 2 MW/m^2or above.

6 A revised methodology

In the previous sections, we have seen that, **in order to be general and take into account both risks of mechanical failure and thermal melt-through, it is necessary to consider two safety criteria K_φ**

and $\boldsymbol{K_\delta}$, based on the two parameters $\boldsymbol{\varphi_{max}}$and $\boldsymbol{\delta_{min}}$. There are two ways of taking them into account: the “steady-state configuration” approach, which is a fast way to obtain approximate results, and the transient one, which is the most accurate and the best suited way to take into account time-dependent phenomena, in particular in the evaluation of δ_{min}. With both approaches, it is necessary to provide probabilistic results, i.e. distributions of the safety criteria, in order to include uncertainties in the evaluation of the cumulated probability of vessel failure.

6.1 Characterization of the transient approach

Considering the points discussed above, it seems obvious that the best way to take into account the uncertainties related to transient processes is to directly calculate vessel ablation in a deterministic way. The vessel thickness is the only variable that is able to keep track of the temporary peaks of heat flux. Another advantage of the deterministic approach is to implicitly take into account the correlations (or dependencies) between several uncertain variables. Among these variables, the most important ones are the mass of steel (which can be calculated as a function of time), the residual power and the internal pressure. This way, the approach is less conservative but more physically grounded as it avoids taking into account non-realistic combinations of variables. The main idea is to use as safety criterion the coupled parameters (minimum vessel thickness / maximum internal load). Of course, this modified methodology is not necessary if the standard criterion on heat fluxes comparison leads to predict failure of the vessel. **The modified methodology is made for a more accurate and rigorous demonstration of the non-occurrence of vessel failure**.

As a first step, the relationship between those two parameters, for which the integrity of the vessel is kept, needs to be tabulated from the results of detailed mechanical calculations, for different types of vessel steel. If such tabulation is not available for the considered steel, a simpler criterion based on the “cold shell” approach can be used (but it is inaccurate). Actually, this task could not be completed in the IVMR project but it should be achieved in the future (for French steel). Then, as a second step, various integral scenarios are calculated, providing curves for the evolution of local vessel thickness as a function of internal load for each angular position along the vessel wall. Finally, this curve is compared to the relationship giving the minimum thickness, checking that it is always reasonably above the minimum thickness, as it is illustrated in Figure 7 for two different „virtual” scenarios. The different steps of the evaluation are summarized below:

1. Tabulation of minimum vessel thickness δ_{min}
    a. Function of vessel material
    b. Function of internal load: $\delta_{min} = f(P_{int})$
2. Evaluation of internal loads as a function of time
    a. Primary pressure
    b. Corium weight
3. Evaluation of “cumulated” wall ablation as a function of time: $\delta(\theta, t)$ for each angular position θ
    a. Taking into account short peak transient heat flux
    b. Taking into account variation of the angular position of maximum heat flux
4. Checking that $\delta(\theta, t) \gg \delta_{min}$
    a. At any location θ along the vessel
    b. At any time t.

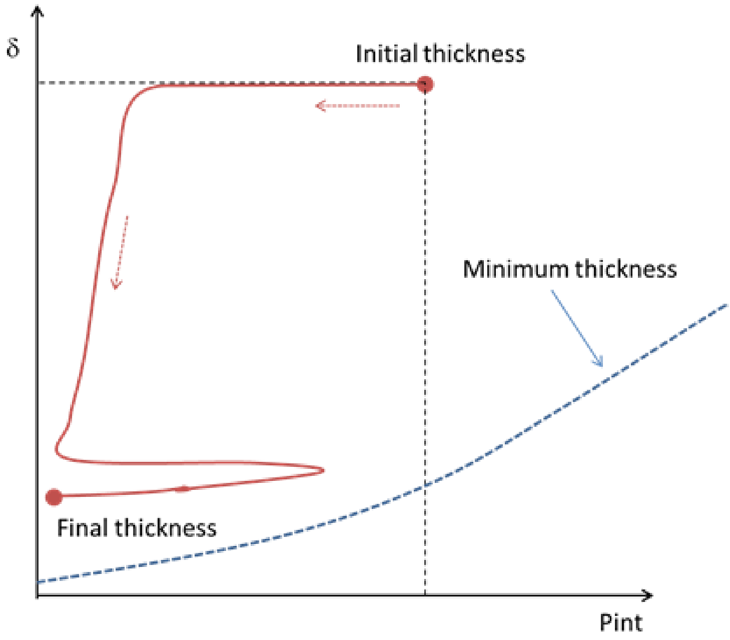

Figure 7: Example of transient evolutions of local thickness as a function of internal load, compared to the criterion of minimum thickness (fast depressurization followed by a late pressure peak when significant ablation is reached)

7 Application of the methodology to various reactor designs and scenarios

In this section, we illustrate how the success of IVR strategy in the different reactor designs strongly depends on key design parameters. Furthermore, we provide results selected from the reactor applications of work packages WP2.2 and WP2.5, where severe accident modelling improvements achieved during the IVMR project (core degradation, corium pool evolution including inversion of stratification) were applied by project participants to the different types of reactor designs.

7.1 Impact of design parameters

It was shown in all calculations that the maximum local heat flux comes from the top metal layer and the "focusing effect". Hence, the most relevant parameter to characterize the focusing effect and compare various reactor designs is the ratio $\frac{M_{UO_2}}{M_{steel}}$ (Fichot et al., 2018). It appears in both safety criteria, as seen in the equations below. The radius of the vessel is also an important parameter. It plays a role on the maximum heat flux but it does not play any role on the mechanical criterion (the benefit of increasing the minimum vessel thickness is cancelled by the increase of the stress).

$$K_\varphi \approx \frac{M_{UO_2}}{M_{steel}} \frac{k\Delta T_{\text{fus}}}{R\varphi_{CHF}}$$

$$K_\delta \approx \frac{M_{UO_2}}{M_{steel}} \frac{\sigma_{cr}}{\Delta P_{\max}}$$

From those two parameters, it is possible to show that different reactor designs may be approximately equivalent from the point of view of IVR (i.e. they have comparable safety margins). In the following table, we provide examples of reactors of different powers which are equivalent (in this very simple analysis), assuming that it is possible, in the design, to adjust the efficiency of ERVC (φ_{CHF}), the mass of molten steel in the lower plenum (M_{steel}), the radius of the vessel (R) and the capacity to reduce overpressure in the vessel ($\Delta P_{\max}$). Of course, in reality, it is not obvious to adjust each parameter and reach the proposed values, especially for high power reactors. In addition, this is a very simple demonstration which does not take into account the possibly significant variations around the mean values of φ_{max} and δ_{min}.

Table 3: Examples of "equivalent" designs from the point of view of IVR

Power	M_{UO_2}	M_{steel}	φ_{CHF}	$\Delta P_{\max}$	R	K_φ	K_δ
500MWe	50t	50t	1 MW/m²	10 bar	2.5 m	0.7	0.14
1000MWe	100t	50t	2 MW/m²	5 bar	2.5 m	0.7	0.14
1000MWe	100t	40t	2 MW/m²	4 bar	3 m	0.7	0.14
1500MWe	150t	40t	3 MW/m²	2.7 bar	3 m	0.7	0.14

We see that, for a high power reactor, the goal is to reach high values of the critical heat flux, which implies that depressurization should be absolutely reliable. The other important conclusion is that **the safety margin does not depend only on the reactor power**. The success of IVR can be achieved for reactors of power larger than 600 MWe (this value was considered as a threshold up to now) but it implies to pay attention to parameters like the mass of molten steel, the external cooling efficiency (φ_{CHF}) and the maximum pressure in the vessel.

Within the reactor applications work package of IVMR (WP2.5), project partners have analyzed IVR strategy for different reactor types, using different SA codes. Results obtained confirm the importance of the design parameter $\frac{M_{UO_2}}{M_{steel}}$ on the evaluation of the maximum heat flux from the corium pool φ_{max} and associated minimum thickness of the vessel δ_{min}, as illustrated in Figure 8. A clear increase of the maximum heat flux with the $\frac{M_{UO_2}}{M_{steel}}$ ratio is observed.

One important output from the results of reactor calculations which consider the transient evolution of the molten pool in the lower head is that attention should be paid to the definition of the mass of steel used in the mass ratio defined above. Indeed, the relevant mass to consider is the one which is molten at the time when the maximum heat flux is reached and not the one at steady-state (which may be larger). This can make a significant difference depending mainly on the location of the metallic structures in the reactor. This impact is shown in Figure 9, where the $\frac{M_{UO_2}}{M_{steel}}$ ratio is compared for each design at steady-state and at the time of maximum heat flux. It is shown that this ratio may be significantly higher during the transient than at steady state. The impact of model assumptions, depending on the code used, is also visible but the order of magnitude is comparable.

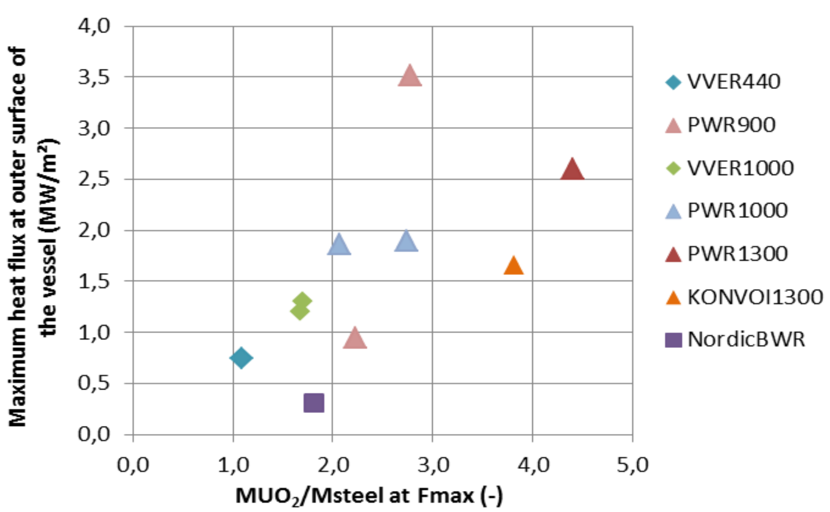

Figure 8: Maximum heat flux evaluated at the outer surface of the vessel for different reactor designs (from WP2.5 results of 2nd set of reactor calculations, LBLOCA scenario) and relation with the design ratio MUO_2/Msteel

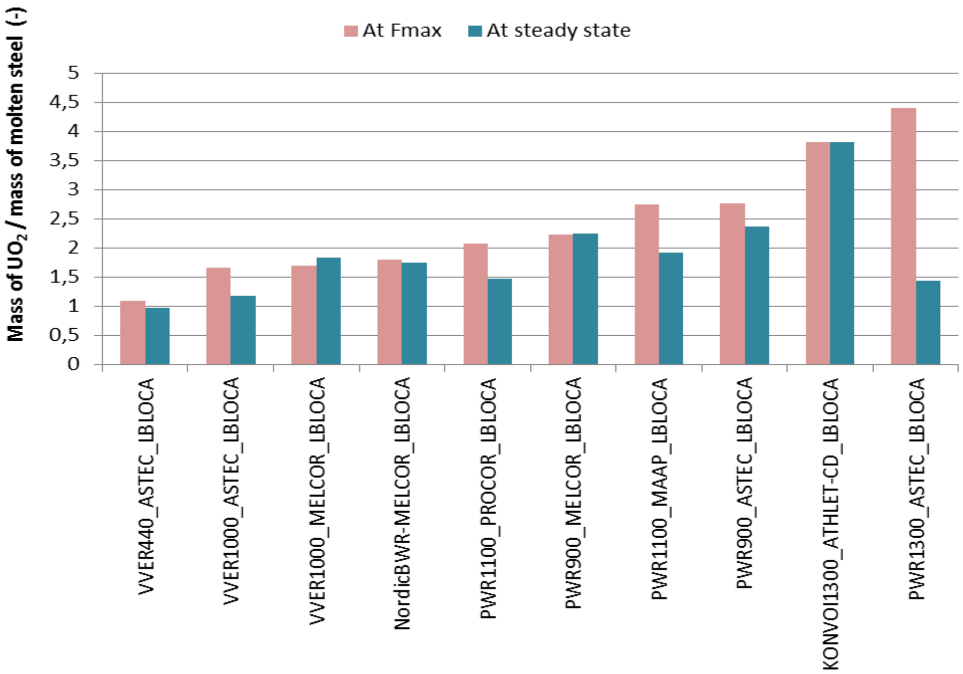

Figure 9: Ratio MUO_2/Msteel evaluated for each LBLOCA calculation at the time of maximum heat flux (Fmax) and at steady state

7.2 Impact of scenario parameters

The transient deterministic approach opens the path to addressing the role of different scenario parameters, in particular (i) the initiating event; and assumptions on the evolution of the accident regarding (ii) the availability of mitigating systems and (iii) the application of SAM actions. As initial and boundary conditions of the transient analysis, the parameters determine not just extreme thermal and mechanic loads, but also the transient phenomena that – altogether – define the IVR scenario that requires evaluation.

Some transients are selected again from the reactor applications performed in work package WP2.5 of IVMR project. Typically, different kinds of LBLOCA and SBLOCA were analysed as well as SBO scenarios. In all of them the unavailability of the Emergency Core Cooling Systems (ECCS) leads to core melting and relocation of corium into the lower plenum. In Figure 10, the main impact of scenario parameters is illustrated looking at the delay of corium relocation to the lower head which may be gained compared to the worst case of LBLOCA scenario. This delay may have a preponderant impact on the success of the IVR strategy since the residual power decreases significantly during the first 3h after the shutdown of the reactor: it is typically divided by a factor 2 between 30min (500W/kg of UO_2) and 3h (250W/kg of UO_2) as reported in IVMR report D5.9, where a summarising analysis of reactor calculation results is provided.

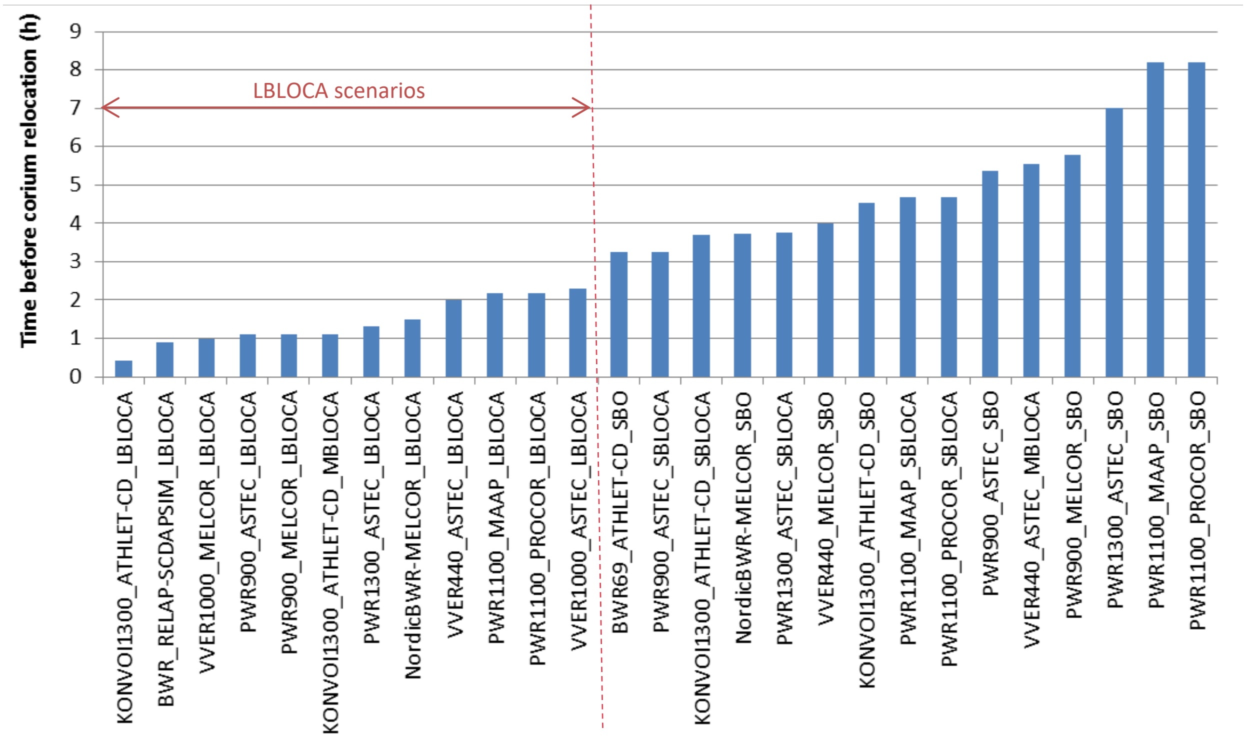

Figure 10: Time before corium relocation in the lower head, for all reactor calculations performed in WP2.5

Integral reactor calculations also allow the evaluation of the wall thickness evolution with time and corresponding internal RPV pressure. The resistance curve $\delta_{min} = f(P_{int})$ of the material proposed in Section 5.1 is used as a generic reference.

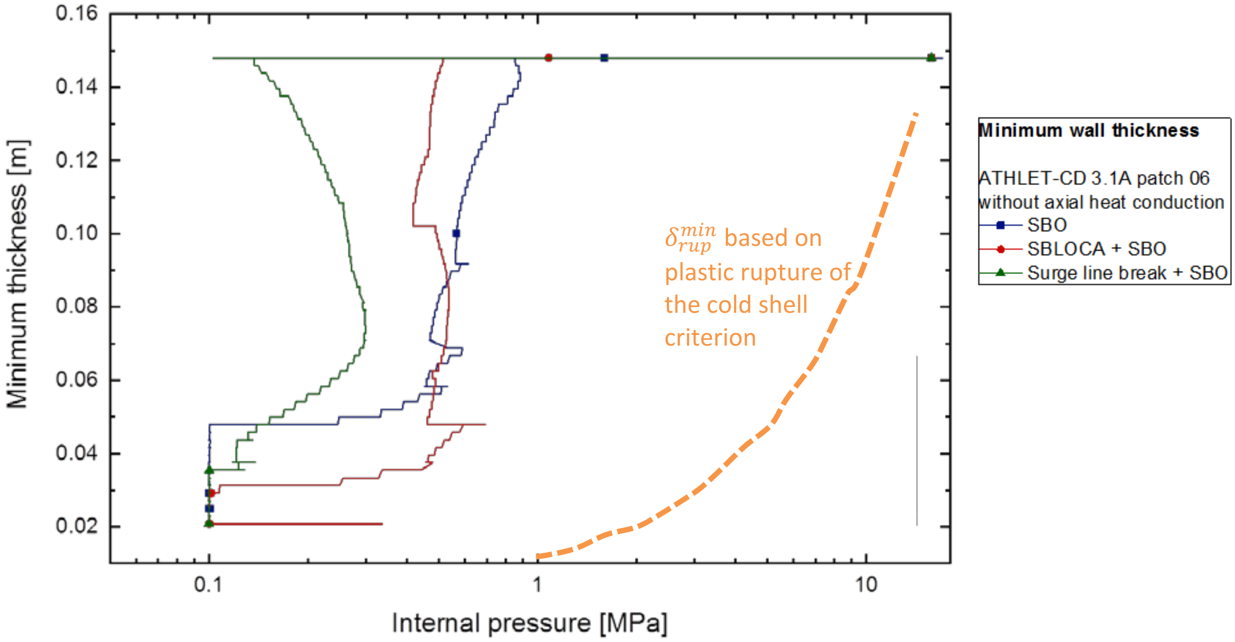

Figure 11: Illustration of IVR thickness criterion as proposed in chapter 6 (from HZDR results, Sangiorgi et al., 2019)

Another important aspect of the scenario which was investigated through reactor calculations by some partners in the IVMR project is related to the consequences of in-vessel water injection. In the example presented in Figure 12 it is shown that the injection of water leads to an increase in the minimum residual vessel thickness without increasing the internal pressure.

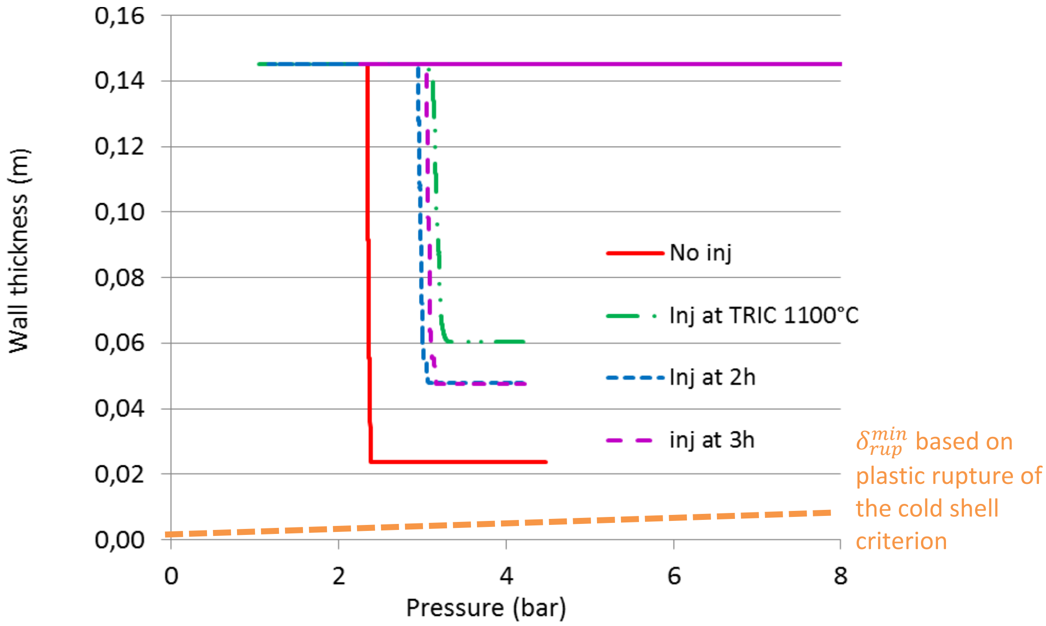

Figure 12: IVR thickness criterion as proposed in chapter 6 – Impact of in-vessel water injection (from Framatome results, Sangiorgi et al., 2019)

It is interesting to mention that there have been attempts to also couple calculations of core degradation and mechanical behaviour of the vessel: by exporting thermal information from the severe accident code (heat fluxes or temperatures) to a FE code, it is possible to analyse stresses, deformations and creep in the RPV, in a separate step, which is more accurate. This is a promising way of improving the proposed methodology of transient analysis.

In this report, the description of the impact of scenario parameters is separate from phenomenological models for didactical purposes. It needs to be stressed that the two are not independent: as an example, the reduced oxidation degree of Zr in the fast LBLOCA scenario has been seen to cause the formation of a heavy metal layer and then inversion of stratification when applying new models described in the section below. As a result, the accident evolution is very different from a SBO scenario with late corium slump and higher oxidation degree in the pool, without formation of heavy metal.

7.3 Impact of phenomenological models

It is obvious that the transient deterministic approach proposed here relies strongly on the capacity of phenomenological models to capture the processes governing the heat flux distribution and its evolutions. This requires describing the relevant physics and implementing them in the codes used, but the models require validation by relevant experiments. The most important phenomena as well as remaining uncertainties were analysed during the IVMR project thanks to the elaboration of a PIRT on IVR modelling (Fichot et al. ,2019) and a code benchmark on IVR involving different corium pool configurations (Carénini et al., 2019). The following important phenomena can be mentioned:

(i) Fission products, and to a lesser extent activation products, are the sources of residual heat; modelling their distribution in the system and in particular in the layers of the corium pool is an important aspect of tracking the transient heat distribution.

(ii) Heat losses at the surface of the pool have a large impact on transient heat fluxes; the focusing effect expected for a top light metal layer could be less severe when taking relevant heat losses into account in the modelling. Typically, radiative heat losses can reach up to 20% of the heat flux transmitted by the top metal layer to the wall. This value may be even higher in case of very thin metal layer

(iii) Heat resistance due to crust at the interfaces (i) of different pool layers and (ii) between pool and the RPV has a significant impact on heat flux distribution (Carénini et al. 2019) and thus on the temperature distribution, RPV ablation, etc.

(iv) The melting of materials and its addition to the corium pool has important consequences for the material evolution of the pool, for processes like layer inversion, and for the thickness of the different layers, including the top metal layer and the consequences on the focusing. Models have been proposed for taking into account the collapse and slump of structures in the core and upper area of the RPV, and the inclusion of steel ablated from the RPV wall.

(v) The phenomena of a pool experiencing layer inversion are expected to be potentially severe when light metal in a bottom metal pool is separating from heavy metal, and is superheated on its way to the top through the very hot oxide layer. Models can seek to catch the effect that this metal will have when disposing its heat to the RPV wall.

The points (i) to (v) were discussed during the code benchmark on IVR performed during the project (Carénini et al. 2019). It was shown for the given configurations studied that:

- Considering radiative heat transfer at the top of the pool, the heat flux is divided by 1.2.

- Considering the progressive melting of the metallic structures, the maximum heat flux is multiplied by a factor 1.4-1.7 compared to steady state configuration.
- Considering material interactions between corium pool and molten steel increases the maximum transient heat flux by factor 1.2-1.3, when the metal layer remains lighter than the oxide.
- Considering formation of a heavy metal layer and later stratification inversion (when relevant), the maximum (transient) heat flux may be multiplied by a factor up to 2-3 compared to a configuration with a single metal layer on top.

These results clearly identify the importance of including all relevant transient models in the codes and of evaluating the risk associated to configurations with stratification inversion.

Of course, these transient models also bring forward new uncertainties which are important to consider in the evaluations. But the first uncertainty analyses performed (Carénini et al., 2019) have shown that phenomenological uncertainties do not lead to too large dispersion of the results (+/-20% for the minimum vessel thickness) and may be comparable to uncertainties on the scenario and corium characteristics.

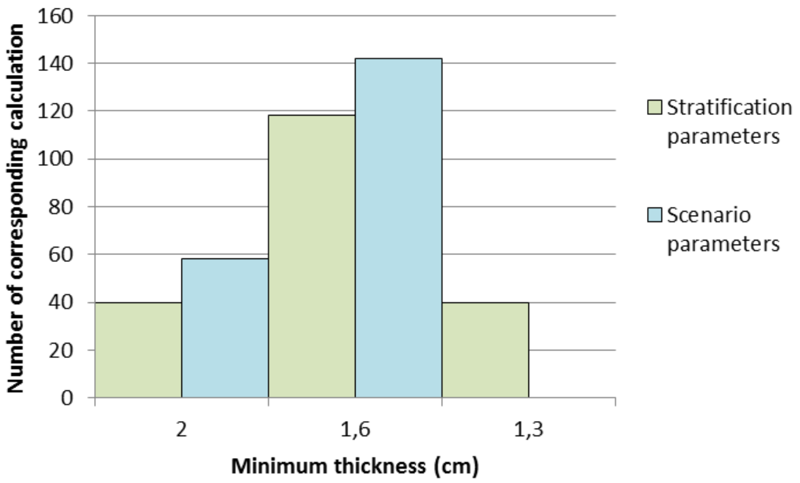

Figure 13: Uncertainty analysis based on 400 simulations – Impact of uncertainties on stratification parameters compared to the ones on scenario parameters (from IRSN results, Carénini et al., 2019)

8 Conclusions

In the safety evaluation of a reactor design where ERVC is implemented, the first point is to identify if IVR can be achieved with a very high probability of success (i.e. the probability of vessel failure is below 1%) or if there is a non-negligible probability of vessel failure and ERVC is just one mitigation measure among a set of measures, in order to stop the accident progression. In the first case, safety margins must be evaluated very accurately, paying careful attention to the methodology of calculation and to the assumptions made to simplify the problem. In the second case, the result of the evaluation is just an indication about the efficiency of the ERVC to stop the corium within the vessel and the evaluation does not have to be very accurate because the global safety of the reactor depends also on the evaluation of risks induced by ex-vessel phenomena.

For the case where IVR is supposed to be successful in any case, there are two risks to consider: excessive heat flux (i.e. failure by melting) and vessel rupture (mechanical failure). Those two risks can be addressed by comparing the maximum heat flux and the minimum vessel thickness to their respective “reference” values. The higher the reactor power, the more important it becomes to pay a careful attention to the evaluation of the minimum vessel thickness. It is recommended to perform the safety evaluation following a transient approach, because it will provide a better accuracy in the safety margin and it will give a better idea of the most critical situations. The classical “steady-state” configuration approach has many drawbacks, especially when defining a range of variation of coupled and time dependent uncertain parameters in probabilistic evaluation, and may lead to confusing results. It is recommended to use it only as an approximate evaluation when a quick assessment must be done. But it should be completed by transient “best estimate” analyses at least for the most probable scenarios, allowing justification of the assumptions made for the “steady-state” configurations studied.

Now that models are available to describe the transient kinetics of stratification in the oxide/metal pool, and that computation time is not an issue, there is no justification to avoid the transient approach and to keep using “steady-state” configuration approach with confusing or unrealistic assumptions. Moreover, there are more and more indications that SA codes have reached a level of maturity and confidence which allows using them for probabilistic evaluations (Chevalier-Jabet et al. 2013, Mattie et al. 2015, Moiseenko et al. 2013, Wachowiak et al. 2014), and IVR assessment should follow that direction, too.

When analysing the design parameters that are favourable for IVR, the mass of molten steel appears clearly as key parameter to increase the safety margin. But it seems also possible to investigate technical options to increase the CHF, as long as the internal pressure is kept low (less than 3 bar overpressure).

At the moment, there are still large uncertainties (or missing correlations) for two main phenomena: the heat flux along the top metal layer at the outer surface of the vessel (which is dependent on heat transfers in the thin metal layer but also on the kinetics of metal layer thickness growth) and the minimum vessel thickness before rupture (which might be lower than the value given by the standard “cold shell” model). Improvements are expected soon for the mechanical resistance and the heat transfers in the thin metal layer. It should allow making a more accurate analysis, which is necessary to evaluate high power reactors’ safety margins with respect to IVR. For remaining uncertainties, it is recommended to evaluate their impact on IVR evaluation based on the results of sensitivity analysis made with transient calculations. In addition, reactor calculations show that fast sequences (such as LBLOCA) are the ones providing the highest heat flux and vessel ablation but also the highest uncertainties because stratification processes play a more important role. Therefore, it can be concluded that any measure leading to the practical elimination of fast core melt transient would lead to a very large reduction of the probability of vessel failure in case of IVR implementation, by increasing, at the same time, the safety margin and the level of confidence of the evaluation.

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