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Elaboration of a Phenomena Identification Ranking Table (PIRT) for the modelling of In-Vessel Retention

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Abstract

The strategy for In-Vessel Retention (IVR) of corium is currently considered for several new reactor designs in various countries. One of the issues for the demonstration of the success of this strategy is that there are significant uncertainties in physical modelling of corium in the lower plenum and its transient chemical and thermal interactions with the vessel leading to its significant ablation. Since the initial approaches developed in the nineties for the AP600 and Loviisa VVER-440 plant, knowledge about corium pools (thermochemistry and heat transfer characteristics) and mechanical behaviour of the vessel has improved and it is now possible to model more accurately this phenomenon. The H2020 European project IVMR (In-Vessel Melt Retention) addresses the issue of selecting and improving IVR models for safety evaluation. As a first step, a Phenomena Identification Ranking Table (PIRT) involving the relevant physical processes was developed.

The methodology followed to build this PIRT results from the consideration of a few principles:

- Identifying and separating the risks with respect to which the importance of a physical process is evaluated
- Defining physical processes or parameters which can be considered as independent of the other ones
- Avoiding expert judgement, as much as possible, and using, instead, the results of previous sensitivity studies to estimate the impact of each physical process or parameter.

In order to obtain results representing the currently “shared” state of knowledge, code developers of the most widely used codes were consulted. It includes ASTEC, MELCOR, MAAP (EDF version), SOCRAT, ATHLET-CD integral codes and PROCOR, SIMPLE, HEFEST_URAN, and IVRSYS dedicated codes (specific to IVR calculations).

One of the positive outcomes of this PIRT is that the results show significant tendencies, with distinct groups of phenomena or parameters. This allows the identification of the uncertainties and of the phenomena/variables with the highest (or lowest) importance. Some dispersion in the results could also be noticed but it can be understood either because of the variability due to reactor design or the impact of models chosen by experts in the codes they have developed. When the dispersion cannot be explained, it indicates that the phenomenon is poorly understood and may deserve further research. Among the

phenomena with highest importance, the heat transfers in the top metal layer and the chemical/thermal interaction with the oxide crust have been identified, as well as the transient formation and stratification of metal and oxide layers, including thermochemical peculiarities of the (U,Zr,Fe,O) system. Another phenomenon of highest importance is the mechanical behaviour of the thin ablated vessel wall, where elasticity, plasticity and creep all play a role. It is concluded that codes should include improved models for those phenomena in order to be able to provide a reasonable assessment of potential for IVR.

Keywords: IVR strategy, PIRT, molten pool, reactor pressure vessel, stratification

1. Introduction

A PIRT on in-vessel retention phenomenology was developed as part of the European IVMR project within the H2020 framework. Its first objective was to identify the main relevant physical phenomena, in order to give a priority ranking of development needs for codes within the work-package WP2.2 dedicated to modelling. Soon after the start of this action, it was decided to extend the scope of this PIRT to experts outside of the IVMR project in order to gather more technical opinions and obtain a consolidated evaluation in the end. The Korean institute KAERI was involved (as new partner of the project), as well as Russian organizations (IBRAE and Kurtchatov Institute) and the U.S. NRC and the Sandia National Laboratory (MELCOR code developers) due to their expertise in IVR phenomena. It should be noted that it is the first international effort dedicated to the identification of the most important models and parameters for IVR assessment. A more general PIRT was made previously during the EURSAFE project (Magallon et al., 2005) but it was not specific to IVR and not really intended as a list of model requirements, contrary to the present PIRT. We may also mention the work performed in the ASAMPSA2 project (Raimond et al., 2013), where the IVR issue was treated with identification of phenomena needing to be addressed (but without ranking).

At first, a specific methodology was proposed for this PIRT, with the main objective of being able to identify, as simply as possible, the main processes and variables, used in the safety demonstration, which have the greatest impact on the evaluation of risks and for which the uncertainties are significant, considering a severe accident (SA) scenario for a given design. The further identification of more detailed physical phenomena or properties with high uncertainties and impact is proposed in a second step.

In addition to the first goal of code development focused on integration and implementation of models having the most significant impact on risk evaluation and the identification of those with limited impact, other benefits are also expected from this PIRT. The identification of phenomena for which complementary tests are needed will be very important in the design of the experiments. For safety analysts, this PIRT can provide a synthesis of the main phenomena and uncertainties to be considered in the IVR evaluation.

It is important to keep in mind that the evaluated “knowledge” corresponds to what is implemented in the models of widely used codes, therefore it is what we may call the “common knowledge”: in this sense, the paper is also a critical review of this “common knowledge”. The idea is not to identify what should be included for the most detailed modelling of in-vessel retention but what the essential and necessary models are for a severe accident code, considering the degree of accuracy commonly associated with such codes. Of course, some simplifications or assumptions are made when using severe accident codes but it is important to realize that such codes have been the basis and are still the basis for evaluations of severe accidents consequences and mitigation strategies. Therefore, the identification of important models for IVR, using severe accident codes remains crucial.

This paper intends to present the main results and outcomes of this work. First, the methodology used to develop this PIRT on IVR phenomena is described. Then, the main results are presented and discussed.

2. Methodology

The methodology for the development of the IVR PIRT results from the consideration of a few principles:

- Identifying and separating the risks with respect to which the importance of a physical process is evaluated;
- Defining physical processes or parameters which can be considered as independent of the other ones;
- Avoiding expert judgement, as much as possible, and using, instead, the results of previous analytical and experimental analyses including sensitivity studies to estimate the impact of each physical process or parameter.

Beyond these principles, the details of the methodology followed to elaborate this PIRT are described hereafter. Indeed, it appears that to better understand the results of the evaluations, it is important to keep in mind how they have been obtained.

The ranking of the phenomena is proposed with respect to the 4 safety issues, which have to be considered in the safety demonstration of the IVR strategy:

1. Risk of mechanical failure of the vessel (including all possible mechanisms, i.e. plastic deformation, creep, chemical damage, etc.).
2. Risk of excessive heat flux compared to local Critical Heat Flux (CHF) under steady state (stabilized) conditions.¹
3. Risk of excessive vessel ablation under transient situations.
4. Risk of energetic ex-vessel steam explosion in case of vessel failure (this risk is outside the scope of IVR in the strict sense but it is nevertheless considered here because of the impact of IVR models on the boundary conditions of ex-vessel corium-water interaction).

In order to simplify the evaluation and to have a more direct link with the issues associated to the models implemented in the codes, two steps have been defined in the methodology: first, the impact of “main variables (or equivalently “macro-phenomena” defined further in the paper) on the risks and, second, the effect of “elementary phenomena or variables” on the “main-variables”. Both steps are identified in Figure 1. The reason for such approach is to provide a clearer “evaluation grid”. Indeed, for some phenomena, it is difficult to evaluate their direct impact because they are always coupled with other phenomena. For example, mass transfers between oxide and metal phases play a role on the stratification of layers and therefore on the heat transfer from the layers. For this reason, the evaluation of the impact of a mass transfer coefficient is too complex and model-dependent (at the current stage of modelling in most codes) and it is more convenient to define “macro-variables” such as the thickness of the metal layer or its composition, which are independent of modelling assumptions. Then, the impact of individual parameters/phenomena on those macro-variables is easier to estimate. Other parameters/phenomena can be directly related to a simpler macro-variable commonly used for safety evaluation, such as the CHF or the residual power in the corium. Therefore, the evaluation of risks is proposed to be performed regarding a limited number of “macro-variables” used in safety evaluation, which may be directly related to one parameter/phenomenon or to several coupled parameters/phenomena. Macro-variables actually may encompass several variables or may even represent different occurrences (such as “crust” or “no-crust” assumptions). A careful choice of the macro-variables was made by considering two necessary conditions:

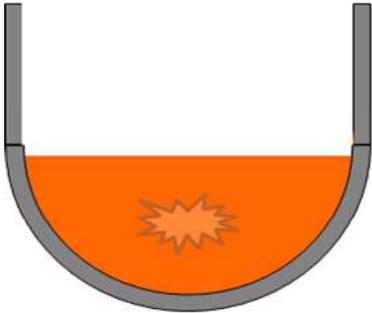
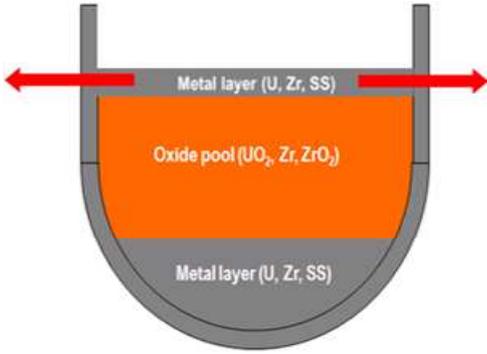
- All macro-variables are independent (or the dependencies are of second order)

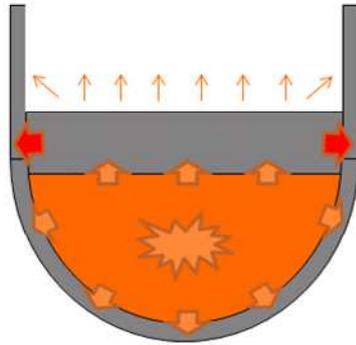
¹ It should be noted that for this risk, the relative impact of a variable was evaluated based on its impact on the heat flux or on the CHF and not on the margin between both. Generally, for this PIRT, it was recommended to keep in mind that the evaluation of direct impacts of physical phenomena are performed with the goal of identifying those which are the most significant and not for evaluating the margin associated with the IVR strategy.

- The problem can be entirely described by the set of macro-variables

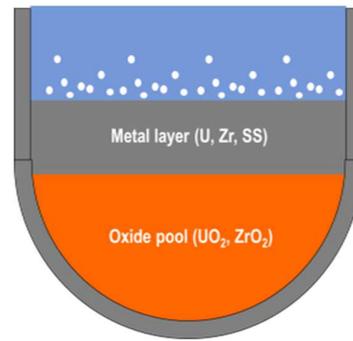
Fifteen main macro-variables were defined and are described in Table 1.

Table 1 – Description of the main variables considered in the first step of the PIRT elaboration

<p><u>The residual power</u></p> <p>This variable should be evaluated for a given reactor and SA scenario. Thus, it corresponds to the uncertainty related to the radioactive decay heat and the volatile Fission Products (FP) release. The FP partitioning in stratified melt is excluded here and should be considered through the variables dedicated to the stratified pool itself (characteristics of the layers).</p>	
<p><u>Characteristics of the top metal, the oxide and the bottom metal layers</u></p> <p>This includes 3 variables intended to describe the corium pool configuration. Those are the mass, composition and, as a consequence, thermo-physical properties of the layers. These 3 layers are considered separately to deal with all possible corium stratification either in transient or stabilized configurations. The thermal and chemical behaviour is evaluated in transient situation through the risk of having an excessive ablation of the vessel (Risk 3) and in stabilized configurations (i.e. the layers heights and compositions are constant) through the risk of having a heat flux above the local CHF (Risk 2).</p>	
<p><u>Top conditions and heat flux</u></p> <p>This includes 2 heat fluxes estimated with two different boundary conditions at the top of the molten pool. It should be considered for a given SA scenario with or without overlying water. The uncertainties associated with the corium-water interaction or to the radiative heat transfers from the top of the corium are then evaluated, as well as the impact on the risks.</p>	



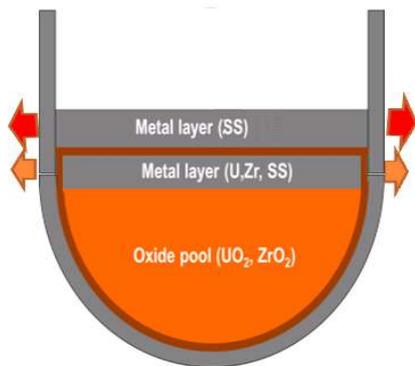
Radiative heat transfer



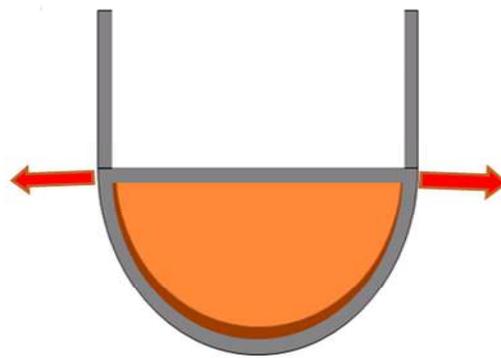
Top cooling

Presence of oxide crusts

It is proposed to evaluate, through this macro-variable, the uncertainties associated to the boundary conditions between the corium layers and the vessel, as well as the role of the crust in heat and species transfers, which may be significant. It includes the effect of thermochemical interactions between oxidic crust and molten metal and the thermo-mechanical resistance of the crust.



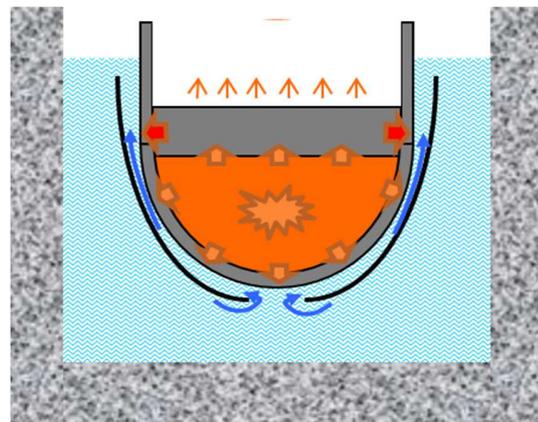
Presence of oxide crust in front of the metal layer after stratification inversion



Absence of oxide crust at the top of the oxide pool due to melting when the top metal layer becomes thin

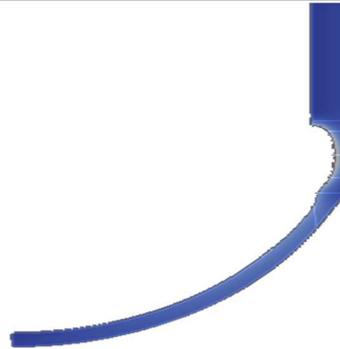
CHF profile

It considers the uncertainties on the CHF along the vessel wall for specific design including water boiling phenomena, convective flow, 3D effects, etc.



Ablated profile

It is the result from transient and stabilized thermal ablation and corium/vessel wall material interactions (e.g. corrosion...). With this variable, the impact of the overall shape of the ablated vessel is considered in addition to the value of the minimum vessel thickness.



Creep and elastic-plastic behaviour

This includes 2 main variables dealing with the mechanical behaviour of the vessel wall and including uncertainties on material properties and deformation laws considering a strong temperature gradient across the vessel wall. Since we do not deal with the problem at the microstructure level, those two behaviours can be distinguished macroscopically by the deformations (or strains):

- For the creep behaviour, it is a time-dependent deformation under a certain load (typically below yield stress limit for a prolonged period of time) that generally occurs at elevated temperatures.
- For the plastic behaviour, it is an irreversible deformation after yield point and is not time-dependent.

Comparison against classical approaches can be done, such as: the failure pressure approach (as in Kymäläinen et al., NED, 1997) for the elastic-plastic behaviour and the Larson-Miller Parameter (LMP) approach (or something similar) for the creep behaviour.

Breach size and location

Potential for vessel failure, even if with a very low probability should be considered in the safety evaluation. The breach size and location are important input variables for the risk of ex-vessel steam explosion. With this macro-variable, the uncertainty on the shape of the vessel breach for a given ablated vessel wall and thermal and mechanical load is also considered.

Characteristics of ejected corium

With this macro-variable, composition, mass and temperature of the corium interacting with the water are considered.

Ex-vessel conditions (water characteristics, pit geometry)

This macro-variable includes water characteristics in the reactor pit (e.g., height and temperature) but also the pit geometry (size, vessel height, presence of insulator or deflector...) which influence the mechanical efficiency of the energy release in case of steam explosion.

Steam explosion configuration

This macro-variable includes different configurations which may happen, with very different consequences: stratified in-vessel steam explosion or ex-vessel steam explosion of a corium jet falling in the water or of a corium jet projected towards the lateral wall.

For each of these macro-variables, its importance is evaluated from the number of risks it may impact and from its relative impact for each of the identified risks. The relative impact $I_{i,j}$ of the macro-variable “ j ” on the risk “ i ” may be evaluated based on the formula:

$$I_{i,j} = E_j \cdot S_{i,j} \quad (\text{Eq. 1})$$

Where E_j is the estimated variability of the macro-variable j , and $S_{i,j}$ the quantitative effect of this variable j in the evaluation of the risk i . The variability (or relative uncertainty) of a macro-variable is not obvious to evaluate: it was chosen to estimate it as the maximum variability of the set of variables included in the macro-variable.

There are two different ways to evaluate this relative impact. The first way is using existing deterministic and sensitivity analyses. In this case, considering the variability of the input macro-variables (E_j), the consequences on the evaluated risks are directly estimated ($I_{i,j}$). This way of evaluation is favoured when it is possible and when dedicated codes are available to simulate the corresponding phenomena. The second way is using expert judgement and justifications from existing modelling to estimate the direct impact $S_{i,j}$ of a macro-variable on a specific risk.

In order to have results directly comparable between participants of the PIRT, rules have been proposed to estimate the level of uncertainty E_j of a macro-variable j and the effect $S_{i,j}$ of a macro-variable j on the risk i (cf. Table 2). When data are available, values considered for uncertainty and direct impact have to be justified. In order to limit the dispersion, an upper bound value of 100% of uncertainty is set for an unknown phenomenon and an upper bound value of 2 is set for the direct impact in the case of a highly non-linear impact. Those upper values are particularly useful in case of expert judgement.

In order to better illustrate the use of this direct impact $S_{i,j}$, an example for each kind of impact is described below:

- $S_{i,j} < 1$: It is the case of the heat transfer in the oxide pool (as shown in the sensitivity study presented in Carénini *et al.*, 2018, for example). The uncertainty for the Nusselt number at the boundaries of the pool may be estimated up to 30% but when considering the impact on the maximum heat flux obtained for the top metal layer, the impact is less than 15%. This evaluation allows estimating the direct impact $S_{i,j}$ as 0.5;
- $S_{i,j} \sim 1$: It is the case for the impact of the residual power on the maximum heat flux, which is directly proportional to the power produced inside the oxide pool;
- $S_{i,j} > 1$: An example of this case is the thickness of the metal layer when it becomes thin, as observed in BALI-metal experiments: A small decrease in the thickness leads to a high increase of the heat flux.

Table 2 – Rules to evaluate uncertainties and direct effect

Uncertainties associated to a specific macro-variable j			Direct effect of a specific macro-variable on a risk i		
Well known	Significant uncertainties remain	Unknown phenomenon or high uncertainties	Very low impact	Medium impact	High impact
$E_j \leq 10\%$	$10\% < E_j \leq 50\%$	$E_j > 50\%$	$S_i < 1$ The uncertainty is reduced by other phenomena (compensating effect)	$S_i \approx 1$ The impact is proportional to the uncertainty (linear effect)	$S_i > 1$ The uncertainty is amplified (non linear effect)

In principle, it is possible that the direct effect of one parameter may be different, depending on the value of another parameter, when complex phenomena occur (for example, the sensitivity to the metal emissivity may vary according to the value of the metal thickness). We believe that such cases are rare and we have not refined the methodology into such “sub-cases”.

In the second step, we consider more detailed phenomena or model parameters (associated with physical phenomena) and physical properties. In the rest of this paper, those phenomena, parameters or physical properties will be named “parameters”. 68 parameters were defined. At this stage, only the level of dependence of any macro-variable v_j to any parameter k denoted $p_{k,j}$ (no dependence, low or high dependence) is evaluated in order to identify parameters linked with the macro-variables used in the safety evaluation. If necessary, and particularly for material properties, it is proposed to allow 4 levels of ranking in order to be able to better rank those parameters :

- 0 - no (or almost no) dependence,
- 0.5 - low dependence,
- 1 - medium dependence,
- 2 - high dependence.

When ranking phenomena, the objective is to deal with independent variables and thus the participants paid attention not to account several times for the same physical process.

It is important to mention here that the evaluations made for $p_{k,j}$ are independent of the methodology used to make the ranking but mostly related to the physical modelling. The same is almost true for the evaluation of $I_{i,j}$ although it is partly related to the number of variables included in each macro-variable.

The final ranking of all parameters is obtained combining the results of these two steps of evaluations. From the first step, the overall impact combining all the risks is evaluated for each macro-variable v_j :

$$o_{v_j} = \sum_{i=1}^{nb \text{ of risks}} I_{i,j} \quad (\text{Eq. 2})$$

Then, the overall impact for each parameter (o_{p_k}) is evaluated from the results obtained in the 2nd step for each $p_{k,j}$, normalized for each macro-variable (v_j) and multiplied by the overall impact (o_{v_j}) obtained in the 1st step:

$$o_{p_k} = \sum_{j=1}^{nb \text{ of macro-variables}} \left(\frac{p_{k,j}}{\sum_{k=1}^{nb \text{ of parameters}} p_{k,j}} \times o_{v_j} \right) \quad (\text{Eq. 3})$$

In the end, based on the identification of the most important parameters, the evaluation of the associated uncertainties and of their impact could be re-evaluated afterwards to identify more precisely the needs in terms of new knowledge (cf. §4).

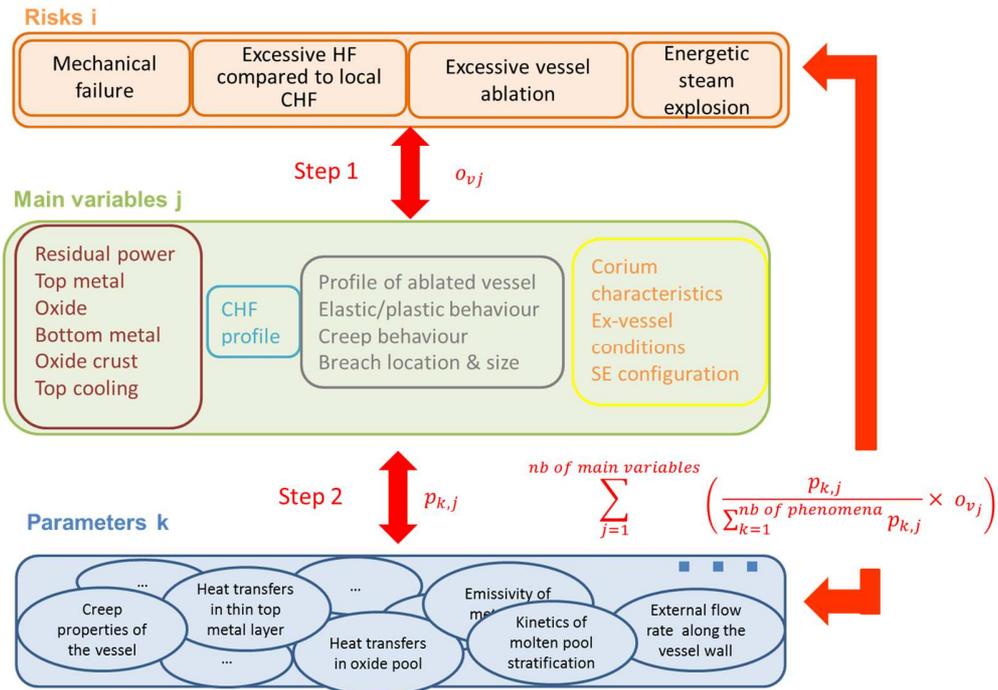


Figure 1 Synthesis of the methodology used to rank the phenomena or parameters

If we take, as an example, the macro-variable “Oxide crust” and we consider that it depends only on 3 parameters x_1 , x_2 and x_3 , which have respective levels of uncertainty of 1.7, 0.9 and 0.2. From the table given in Appendix 1, we see that the impact of “Oxide crust” on risk 2 is 0.9 and the impact on risk 3, is 1.2, which gives an overall impact of 2.1. Then, the ranking of parameter x_1 is calculated as $2.1 \cdot 1.7 / (1.7 + 0.9 + 0.2) = 1.25$ and similar calculations provide the ranking of x_2 as 0.68 and the ranking of x_3 as 0.15. Of course, if a parameter plays a role in other macro-variables, its rankings must be cumulated, as expressed in Eq. 3.

3. Evaluations of uncertainties and impacts for the macro-variables

The uncertainties have been evaluated by each participant for each macro-variable. The results presented in Figure 2 are the average values obtained. The macro-variables are grouped depending on what they are related to, i.e., the corium pool, the External Reactor Vessel Cooling (ERVC), the vessel wall or the Steam Explosion (SE) in case of vessel failure. The level of 50% is arbitrarily marked with the red line at the top of Figure 2 and macro-variables above that level are identified as having high uncertainties (as defined in Table 2). For the corium pool, those macro-variables are the characteristics of the top metal layer and the presence of crust. In addition, the characteristics of the bottom metal layer and to a lesser extent the radiative top condition above the pool are also identified as uncertain. Then, high uncertainties are associated to the vessel failure with the location and size of the vessel breach and to the configuration of steam explosion expected in this case. It should be noticed that the macro-variable “profile of ablated vessel thickness” is defined as an intermediate variable for the risk of mechanical failure of the vessel and includes uncertainties on the heat load applied from the corium pool, for which uncertain macro-variables have already been identified.

Including the direct impact of each macro-variable on the different risks and making the sum on all risks, the overall impacts obtained using Eq. 2 are presented at the bottom of Figure 2. This operation decreases the impact of some of the previously identified variables. The main macro-variable appears clearly to be

the characteristics of the top metal layer. This result is related to the issue of the focusing effect, which corresponds to the concentration of the heat flux applied to the vessel wall at the location of the top metal layer due to its reduced thickness compared to the oxide. It is worth noting that the characteristics of the oxide pool appear notably below the ones of the metal layers. The impact of the CHF profile appears limited. This output should be interpreted by keeping in mind that the objective of the present PIRT is to rank phenomena for code modelling. Indeed, for a given reactor design, the results of dedicated experiments allow the reduction of the uncertainties associated with the efficiency of the ERVC and therefore the CHF modelling becomes reliable.

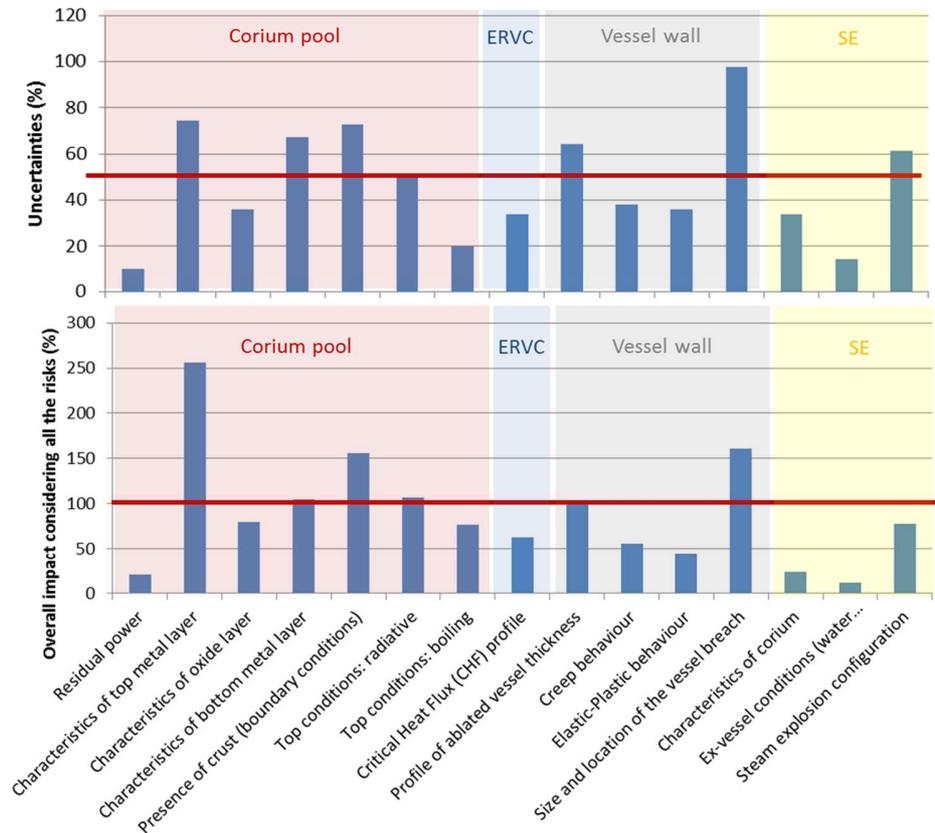


Figure 2 Uncertainties (top) and overall impact considering all the risks (bottom) evaluated for each macro-variables

In Figure 3, the cumulative impacts of each risk which have to be considered in the safety evaluation of the IVR strategy are presented. The risks 2 and 3, dealing with the risk of excessive heat flux from the corium pool to the vessel wall, either in stabilized or in transient situations, are notably the ones with the main impact. Parameters involved in the evaluations of those two risks are presented in details in Section 4.

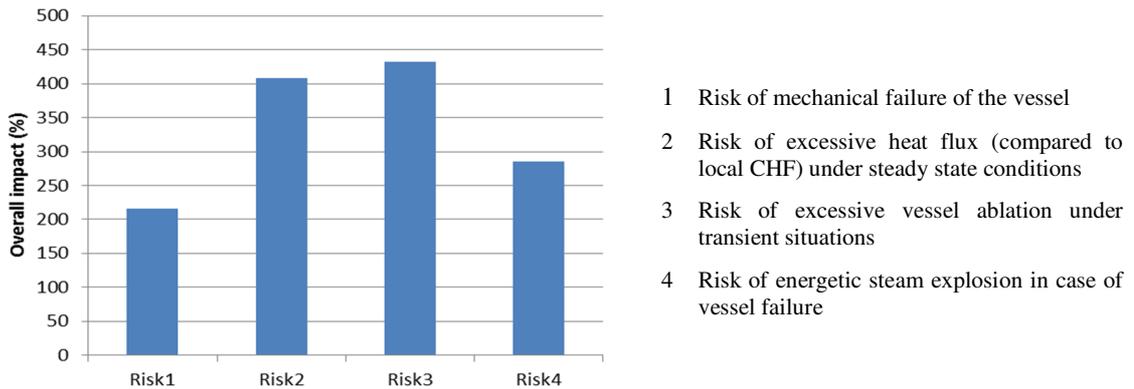


Figure 3 Cumulated impact on each risk considering all the main macro-variables

4. Ranking of parameters impacting the risks of excessive heat flux and ablation under transient situations

The detailed ranking of the parameters, which impact the risks of excessive heat flux in stabilized or in transient situations (risks 2 and 3) is presented in Table 3. The parameters are listed only when their overall impact calculated using Eq. 3 is above 10%.

Since uncertainties have been evaluated first for the macro-variables only, it is useful at this stage to distinguish in the list of significant phenomena:

- The ones associated with high uncertainties, which correspond to the main issues impacting the safety;
- The others with high ranking but low or medium uncertainties, which represent phenomena for which models exist and which must be taken into account in codes.

Table 3 – Ranking of parameters impacting risks 2 and 3

	Overall impact (%)	Uncertainties
Molten pool formation	52	High
Transient establishment of heat transfers	52	High
Oxide and metal phases composition	48	Low
Kinetics of stratification	43	High
Correlations of heat transfer in upper metal layer	38	High
Chemical interactions between metal and oxide crusts	34	High
Progressive ablation of vessel wall	32	Low
Crust mechanical resistance	32	High
Debris bed heat-up and melting	31	Medium
Oxidation during degradation in the core	29	Medium
Ratio UO ₂ /Steel (mass)	29	Low
Progressive ablation of lower core plate	28	Medium
Metal properties	28	High
Progressive ablation of lower plenum internals	28	Low
Corium pool / vessel structures failure	26	High

Radiative heat transfer modelling	25	Medium
Partition of FP between metal and oxide	24	Low
Correlations of heat transfers in oxide pool	24	Low
Heat transfer with top water	22	Medium
Crust thermal conductivity	22	Medium
Emissivity of metal layer	20	High
Oxidation during relocation of corium and interaction with water in the lower head	19	Medium
Formation of debris bed	19	Medium
Correlation of heat transfer in heavy metal layer	15	Medium
Oxidation after corium relocation due to steam above the corium	14	Medium
Oxide properties	14	Medium
Residual power evolution after scram	11	Low
Release of FP	10	Low

Those evaluations have been justified by the participants based on the following references:

- H. Esmaili and M. Khatib-Rahbar (2004) and Theofanous et al. (1996) for general IVR analysis,
- Carénini and Fichot (2018), Filippov et al. (2014) and Le Tellier et al. (2015), as references of sensitivity studies;
- Bonnet and Seiler (1999, 2000), Cho et al. (2004), Lopukh et al. (2000), Park et al. (1999), Zhang et al. (2015) for the evaluation of the parameters dealing with heat transfers;
- Bechta et al. (2009), Seiler et al. (2007), Strizhov and Filippov (2016), Ozrin et al. (2013), Fischer et al. (2011) for thermochemical phenomena.

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

1. The first one deals with the molten pool formation. This item is related to the core degradation and the necessity to better assess 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 (Wachowiak et al., 2014 and Belon et al., 2017). It includes the way the core materials relocate to the lower head: as molten jet following the failure of the oxide crust around the molten pool formed in the core region and/or as a collapse of partially solid elements (fuel, grids) due to mechanical failure of the structures supporting it. Those two different relocation paths lead to different corium oxidation degrees.
In the “standard” 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 (Le Tellier, et al. 2015; Fichot & Carénini, 2015; Carénini & Fichot, 2016; Loktionov & Mukhtarov, 2016). Based on this consideration, it becomes necessary to better evaluate the way the core degrades and the kinetics of molten steel formation;
2. The second issue appears to be the heat transfer in the top metal layer, in particular, under transient conditions. Calculations with CFD codes performed in the scope of the IVMR project

(Le Guennic et al., 2017) have provided significant insights and new correlations adapted for thin layers have been proposed. 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;

3. Then, the issue of thermochemical effects, with the kinetics of stratification in the lower head and the chemical interactions between metal and oxide crusts, is highlighted. The impact of the crust on the kinetics of stratification was investigated in CORDEB program conducted by the Alexandrov Research Institute of Technology (NITI) in Russia (Almjashev et al., 2018). This issue is 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). It is worth noting that, for now, some of the SA codes still do not include models for the evaluation of the thermochemistry in the molten pool even for the equilibrium (without consideration of the transient effects mentioned above). Such requirement is also clearly identified in this PIRT (“Oxide and metal phase composition” being the third parameter with the highest overall impact);
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. For practical reasons, the emissivity of the layer was considered separately from the variable “metal properties” but it was also identified as significant (cf. Table 3). For the other properties, the ranking obtained from the PIRT is presented in Figure 4 (a). The metal density and heat conductivity appear to be the main properties. 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. This identification would require performing more sensitivity studies with the codes and a more precise evaluation of the existing uncertainties in material properties. Such work was initiated in the scope of the benchmark exercise on IVR performed between ASTEC, ATHLET-CD, HEFEST-SOCRAT, HEFEST-URAN, MAAP EDF proprietary version and PROCOR (Carénini et al. 2019). The predominant effect of metal properties compared to those of the oxide was confirmed. In addition, a sensitivity analysis allowed establishing a clearer ranking between the properties (Figure 4 (b)). Contrary to the results of this PIRT, the viscosity appears as the most significant property, followed by the thermal expansion coefficient and the thermal conductivity. This apparent contradiction 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.

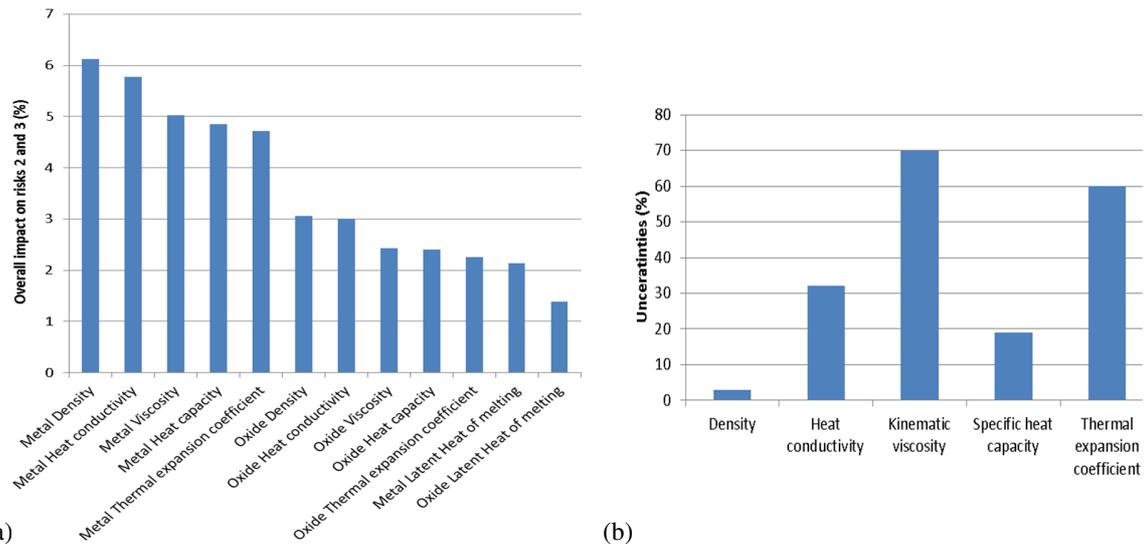


Figure 4 Ranking of material properties for metal and oxide layers (from PIRT results) (a) and uncertainties associated with metal properties (from Carénini et al., 2019) (b)

5. Risk of vessel failure

The risk of vessel failure for a given ablated profile of the vessel wall was also investigated. Results are presented in Figure 5 and based on the following references mentioned by the participants Chu et al. (1999), Fichot et al. (2018), Filippov et al. (2016), Lichachev et al. (1994), Mao et al. (2015, 2016), and Rempe et al. (1993). Regarding this risk, all the parameters appear with non-negligible impact and remain within 10-20%. This indicates that it was not enough investigated and that there is a need to better assess this issue with relevant models and codes and perform sensitivity studies to identify the main parameters in the configuration of interest for IVR, i.e. when a small thickness of steel is submitted to a large temperature gradient.

In the initial methodology developed for the AP600 (and further extended to the AP1000), the criterion for mechanical resistance of the ablated vessel wall is based mainly on the idea that even a very thin external “cold layer” of the vessel would be able to withstand the internal overpressure (assumed to be rather small, as it is a requirement for successful IVR). In this case, only the elastic/plastic modelling has an impact but the variability of the material properties may depend on the temperature considered for this cold part, which make the uncertainty evaluation more complex. In addition, such vision is obviously simplified because the “hot part” of the vessel also plays a (possibly negative or positive) role on the overall resistance, due to thermal and creep deformations. Therefore, the conditions for which creep may be neglected in the evaluation should be assessed rigorously. In addition, for “long term” retention of corium in the vessel, other issues have to be considered and in particular the chemical interactions between corium and the vessel wall.

In the scope of the IVMR project, the capabilities of mechanical models to predict the potential for vessel failure near the location where the vessel wall is significantly thinner are being assessed. A benchmark was initiated, with the objective to reach a consensus on the methodology of calculation for the IVR situations. This explains why there is not yet a clear distinction between mechanical parameters in this PIRT. Clearly this ranking should be re-evaluated after further studies. This also underlines the necessity of a relevant experiment to validate codes and models for the particular case of IVR, which is characterized by a very high temperature gradient across the wall.

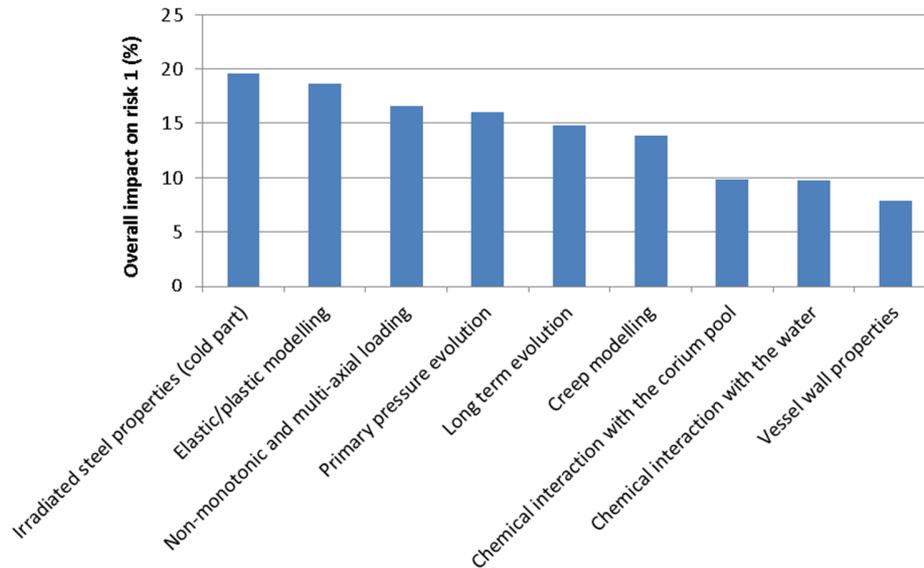


Figure 5 Ranking of parameters impacting the risk of mechanical failure (for a given ablated profile)

Finally, the risk of energetic ex-vessel steam explosion in case of vessel failure was also introduced in this PIRT. The idea was not to evaluate this risk in terms of general phenomenology (see the OECD Status Report (Piluso et al., 2018)) but to identify the specificities of this IVR configuration. The main outcome was that in addition to the characteristics of the corium which flows out of the vessel (composition, temperature, mass, etc.), the design of the external cooling is of primary importance to evaluate the mass of water available for interaction, the space for the corium flow out of the vessel and /or water flow into the vessel. For designs with a deflector forming a narrow gap along the lower head and the vessel wall, the small amount of water available for a direct interaction with the corium appears likely to reduce the risk of having an energetic steam explosion.

6. Conclusions

A PIRT on IVR phenomena was developed, based on the evaluations performed by the developers of the main SA codes and selected experts of IVR. It is the first time that such work is performed and the outcomes allow the identification of the main uncertainties and of the important phenomena or parameters and physical properties for the modelling of IVR. The phenomena or parameters with negligible impact were also identified.

The most important identified needs are:

- New models should be included in codes: transient effects (stratification, heat transfer in the metal layer), heat/mass transfers through crusts;
- Comprehensive sensitivity studies (physical properties, mechanical behaviour laws) should be done to consolidate this PIRT;
- New experimental data are necessary for some phenomena identified with high ranking and high uncertainties (formation of a stratified pool, mechanical behaviour);
- More detailed simulation tools (CFD, mechanical behavior) might help making progress in the absence of experimental data.

However, it is important to also keep in mind the intrinsic limitations of such PIRT exercise. Indeed, the results reflect the current level of understanding and modeling. New or more detailed models might lead to modifications of the ranking of parameters. In addition, the reactor design may affect the order of importance of some phenomena (e.g. heat fluxes at the bottom part of elliptical vessels as in VVER types)

that have not been considered in this PIRT. It was also noticed that a larger number of sensitivity studies would be necessary to quantify the direct impact of phenomena on the four different risks. Finally, it appears that the uncertainty range remains too large for some of the parameters, mostly due to a lack of experimental data or an insufficient understanding or, sometimes, a lack of details in the models which leads to the use of model parameters encompassing too many uncertainties.

Nevertheless, this PIRT should be helpful for a harmonization of codes including models having the most significant impact on risks evaluation and for the definition of new experiments that would help to reduce the main uncertainties.

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9. Appendix 1: Evaluation of risks for IVR strategy induced by the main phenomena or variables (Results of first step)

Phenomenon or variable j		Level of uncertainties E_j (%)	Direct impact S_i on risk “i” *				Overall Impact $I_{i,j}$ (%) (= $E_j \cdot S_i$) *			
			1	2	3	4	1	2	3	4
Molten pool	Residual power	10,3	N/A	1,2	0,8	N/A	N/A	12,9	8,2	N/A
	Characteristics of top metal layer	74,4		1,7	1,7			128,2	128,2	
	Characteristics of oxide layer	36,0		1,2	1,0			43,2	36,4	
	Characteristics of bottom metal layer	67,2		0,6	1,0			41,1	64,2	
	Presence of crust (boundary conditions)	72,8		0,9	1,2			67,5	88,1	
	Top conditions: radiative	50,0		1,1	1,1			53,1	53,3	
	Top conditions: boiling	20,0		0,7	1,1			1,5	0,5	
External cooling	Critical Heat Flux (CHF) profile	33,9	N/A	1,2	0,7	N/A	N/A	40,3	22,6	N/A
Vessel wall	Profile of ablated vessel thickness	64,3	1,6	N/A	N/A	102,2	N/A	N/A	N/A	
	Creep behaviour	38,0	1,5			56,1				
	Elastic-Plastic behaviour	36,1	1,2			44,7				
	Size and location of the vessel breach	97,8	N/A			1,7				161,3
Water inlet	Characteristics of corium	33,9	N/A		0,7	N/A			24,1	

Phenomenon or variable j	Level of uncertainties E_j (%)	Direct impact S_i on risk "i" *				Overall Impact $I_{i,j}$ (%) (= $E_j \cdot S_i$) *			
		1	2	3	4	1	2	3	4
Ex-vessel conditions (water characteristics, pit geometry)	14,4				0,8				11,7
Steam explosion configuration	61,1				1,3				77,9

* 1 Risk of mechanical failure of the vessel (including all possible mechanisms, i.e. plastic deformation, creep and chemical damage)

2 Risk of excessive heat flux (compared to local CHF) under steady state (long term) conditions (i.e. the mass of the different layers is stabilized)

3 Risk of excessive vessel ablation under transient situations

4 Risk of energetic steam explosion in case of vessel failure