Progress in Nuclear Energy 123 (2020) 103321

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: http://www.elsevier.com/locate/pnucene

Analysis of feasibility of a new core catcher for the in-vessel core melt retention strategy

Rosa Lo Frano [*], Riccardo Ciolini, Alessio Pesetti

Department of Civil and Industrial Engineering, University of Pisa, Italy

A R T I C L E I N F O

Keywords:
Passive safety system
In-vessel core melt retention
Ceramic material
FEM
Innovative design
Severe accident

A B S T R A C T

This study deals with the feasibility study of a new in-vessel core melt retention (IVCMR) strategy capable to extend the coping period in the event of adverse situations, involving the melting of the core.

Since Fukushima accident, many studies have been carried out to resolve the severe accident mitigation issues related to the corium stabilization inside and outside the reactor vessel. This is in fact one of the most relevant safety issues to secure LWRs from the point of view of severe accident mitigation and containment integrity. As for the corium stabilization inside the reactor vessel, in this study it is proposed a new IVCMR concept, developed at the University of Pisa, based on the adoption of an original core catcher design made of batches of ceramic material. By profiting of its low thermal conductivity, this core catcher is capable to retard the heat-up of the lower head of the vessel during the phase of relocation of the corium. To support the feasibility of its design analytical and numerical analyses have been performed assuming homogeneous pool condition. Results show that the adoption of the proposed core catcher solution extends the severe accident coping period: after 1 h from the initiating event, the maximum temperature of the vessel wall is below the limit for which localized failure may appear.

1. Introduction

The Fukushima incident highlighted, among other aspects, the need for the implementation of strategies for the severe accident management (SAM), in the form of engineering safeguards aimed at minimizing the risk of release of radioactive substances and likewise to increase the level of protection of the plants. For this reason, the international scientific community focused on the identification of favorable engineering measures capable to cope with the consequences of the interactions that a core melt may have with the pressure vessel, such as the in-vessel corium retention (IVCR).

Corium stabilization in/outside the reactor vessel is extremely important to assure the reactor safety from the point of view of severe accident mitigation and containment integrity (Kim et al., 2018). The failure of the vessel bottom head, recognized as the “Achilles heel” for Gen II or earlier NPP (Lo Frano et al., 2019), which could occur during a postulated severe accident (SA), is the most important issue to deal with. It becomes even more important in consideration of the real (actual) capacity of these plants.

Fig. 1 shows the most important in-vessel melt progression (IVMP) with consequent failure modes. There has been not noticeably change from TMI-2 accident: core melt forms a pool in the original core volume, relocates into the lower plenum and then thermal load begins to affect it.

For the purpose of this study, it is important to estimate and understand as accurately as possible the main issues related to: corium relocation to lower head, lower head debris and molten pool behaviour, thermal and mechanical loadings of structures, and external vessel cooling rate. In doing that, several analytical, numerical and experimental investigations have been performed to identify the most important physical parameter characterizing the heat-up of the vessel lower head.

Core heat-up and degradation (first IVMP stage) start once the core becomes uncovered and the fuel clad temperature rises rapidly due to the decay heat in the fuel: 1) beyond 900 °C the fuel cladding and the steam react producing hydrogen and generating additional heat; 2) when the clad material reaches the melting point, molten material starts to relocate downwards (Fig. 2); 3) a relocation of the melted material (oxides and metals) to the lower head of the RPV is obtained. The solidified debris (oxides) would be submerged, and the thin metal layer above may increase the focusing effect.

---

[*] Corresponding author.
E-mail address: rosa.lofrano@ing.unipi.it (R. Lo Frano).

https://doi.org/10.1016/j.pnucene.2020.103321
Received 30 July 2019; Received in revised form 26 February 2020; Accepted 5 March 2020

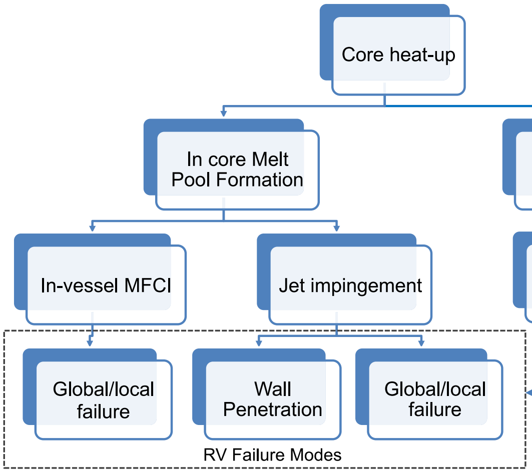


Fig. 1. Main stages of the IVMP from the core-heat-up to the failure modes for the reactor pressure vessel (RPV).

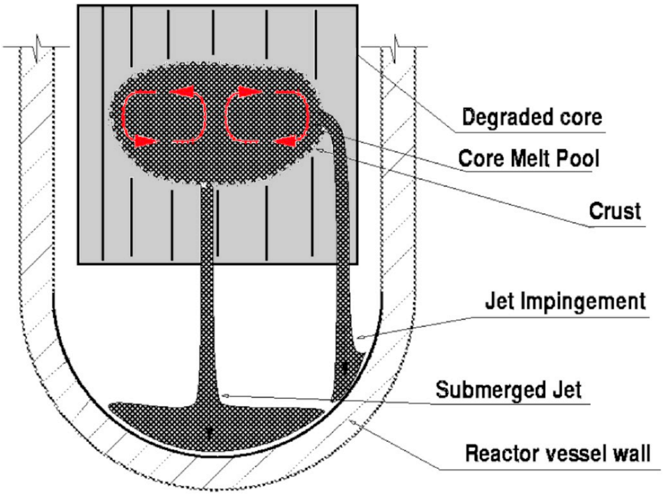


Fig. 2. Schematic representation of the phenomena characterizing the core degradation.

The mechanisms leading to such melts may involve several behaviors (debris does not uniformly spread downwards), from that associated with the initial partial relocation to the (quasi) steady state, where all the core materials are relocated on the lower head. Due to these thermal interactions, mechanical loads can be generated which can compromise the integrity of the lower head.

Different analytical investigations (Globe and Dropkin, 1959; Cheung et al., 1997; Esmaili and Khatib-Rahbar, 2004; Henry and Fauske, 1993; Park et al., 2012, 2016; Wang and Cheng, 2015; NEA, 2017) and experiments have been carried out year by year in order to improve the knowledge of basic phenomena and mechanisms of SA, from those involved in the core degradation to the molten corium-concrete interaction (typical of the core meltdown). Zhang et al. (2010) developed models to simulate the steady-state endpoint of two core melt configurations of AP1000 reactor starting from the benchmark calculations of AP600. The main results they obtained indicate that the decay heat flux remained below the CHF value, even if in the metallic layer the CHF can be exceeded because of its thinning caused by the focusing effect.

In particular, Park et al. (2012) discussed the state of the art and the main physics of the corium behavior in the lower plenum, such as the initial pool formation characteristics, the layer inversion between the oxidic and metallic layers caused by the evolving chemical reactions, the latter aspect also confirmed by Ma et al., (2016), etc. The obtained Nu numbers, with and without crust formation, in the high aspect ratio and for natural convection cooling, resulted lower than literature correlation. This discrepancy was due to the molten metal used in the experiments. Park et al. also highlighted the important role of the water to prevent the lower head failure, as also shown in Rempe et al. (1993) study.

Park et al. (2016) investigated the thermal integrity of a reactor vessel under external reactor vessel cooling conditions. In this study an in-vessel three-layered corium model, a heavy metallic bottom layer, an oxide pool in the middle and a light metal layer on the top, are developed to analyze the focusing effect caused by the metal layer. Less zirconium is oxidized, lighter is the mass that stratifies beneath the oxides; this may affect the gradual temperature increase and wall ablation. The 1D calculation of the remaining thickness agreed with that obtained by Esmaili and Khatib-Rahbar (2004) for an oxide polar region from 40° to 75° along the vessel hemisphere. Larger difference characterized the metallic region due to the differences of heat fluxes. Nevertheless, it emerged that enough thickness (to ensure integrity) remains in the metal region due to heat diffusion to the lower temperature regions: thickness are from 12 to about 13 cm for decay power variation from 25 to 40 MW. Valincius et al. (2018) investigated, by means of RELAP/SCDAPSIM mod. 3.4, the application of in-vessel retention (IVR) strategy in a BWR reactor assuming a scenario with the large break LOCA without injection of cooling water, showing the limitations of the considered code in simulating the debris bed behaviour, particularly the formation of the metal layer on the top of the oxidic layer. More recently, Okawa (2018) studied numerically the BWR in-vessel core degradation phenomena, referring for validation of the assessed model to the data obtained from the CORA-18 experiment, and demonstrated that a molten corium breakup occurred in the vessel lower head (axial- and lateral-directional motion). The results indicate that for progression timing, lowering the decay heat is of meaningful importance in retarding the failure modes associated to the corium accumulation on the lower head.

As far as the numerical analysis is concerned, lumped parameter SA codes, such as MELCOR, MAAP, and SCDAP/RELAP, have been adopted to capture/simulate 3D thermal effects and evaluate the IVR performances; however, it is widely accepted that their results are affected, to a some extend, by uncertainty because the modelling simplification due to the incomplete knowledge about SA phenomena.

Lo Frano et al. (2019) focused on the integrity of the reactor vessel and, in particular, on the thermal effects that could jeopardize the safety margins and even may cause the vessel failure. The heat transfer, mainly due to conduction through the vessel wall, non-linear boiling heat transfer at the external surface of the vessel and corium heat-up, appears to be the dominant mechanism that strongly affects the lower head performance. Moreover, since the key strategy of IVCR is to arrest and confine the corium in the lower head of the RPV by flooding the reactor pit (cavity), thus the adoption of an original and internal core catcher may be a possible solution to retard the wall heating, ablation or thinning.

In what follows, firstly the IVR strategy, considered as the most effective measure to prevent the failure of the reactor vessel, is presented. Subsequently a new original internal core catcher, developed at the University of Pisa and made of low thermal conductivity material, is described and analyzed. Moreover, the performed thermo-mechanical analyses (by using FEM code), to support its feasibility study, are presented along with the obtained results.

2. The IVR strategy

The IVR strategy is considered the most effective measure to prevent the failure of the vessel bottom head, and, later, of the containment and/or basemat melt-through. This accident management type is based on the idea that the lower head, externally cooled, will be able to arrest the

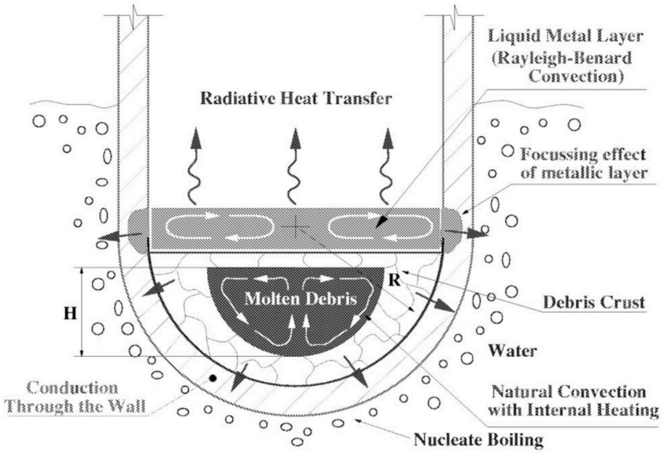


Fig. 3. Phenomena and heat transfer processes evolving during the core melt progression (EU, 1999). Radioactive decay processes within the core debris, according to the driving potential (temperature differences) and corresponding resistances, generate the indicated pathways for the thermal energy flow.

downward relocation of a degraded (melting) core. Therefore, the key issues are whether and for how long the lower head integrity can be maintained under to the thermo-mechanical loads created by such SA scenario. These loads are due to the high temperature of the melt (~3000 K for the oxidic, ~1800 K for the metallic fuel) inside and to the several mechanisms leading it (see Fig. 2). The lower head integrity can be compromised by melt through, or by a combination of reactor vessel wall thinning and thermo-mechanical loading, that can cause structural failure. In Fig. 3 some open issues due to the core melt and relocation scenario still under investigation are represented, such as the melt coolability in the presence of water, the effects of crust, the CHF during external cooling, the creep-rupture process, and the vessel wall ablation caused by the jet impingement. In addition, the mechanical loads due to the thermal interactions in the lower head may be of particular concern because of possible steam explosion, containment (direct) heating, long-term over-pressurization and basemat penetration.

So far, the subject has been approached mainly from the standpoint of the thermal regime in the long term (NEA, 2000; Sehgal, 2012; Theofanous et al., 1996). In this study, the attention is focused on the adoption of an innovative system capable to retard the effects of the core melt heat-up. The idea of the presented device moves from the concept of IVCR proposed for the Loviisa (Finland) nuclear power plant and that relies on the external cooling (flow normally driven by natural circulation) for the removal of the decay heat of the core melt relocated onto the reactor lower head (Theofanous et al., 1997). By keeping the vessel wall cooled, the creep failure is prevented; wider the CHF margin, longer the time to manage plant emergency. On the contrary, RPV melt-through may occur if water-cooling/injection is not enough or unavailable for a prolonged time. The idea of in-vessel retention has been pursued till to define and to develop, at the University of Pisa, an internal core catcher (ICC) solution, made of matrices inside which boxes with pebble ceramic material (i.e., alumina) are inserted. In this framework, it has to remark that several operating or new nuclear reactors (e.g., VVER-440 and AP1000) use IVMR strategy implementing dedicated systems (Zdarek, 2017).

Fig. 4 shows the basic geometry scheme of the proposed device: it is a passive component to be installed inside the lower head of the reactor vessel (“safety-oriented solution”), composed of matrices with boxes of pebble ceramic (‘thermal criterion’), which make the proposed ICC an innovative and helpful engineering system (Aquaro et al., 2016). The boxes contain alumina (Al_2O_3) in forms of pebbles. This material has been chosen because of its high refractoriness, favorable thermal properties and capability to accommodate thermal expansion without high thermal stresses. ICC will affect the strongly coupling between heat production and dissipation. The way it will work is theoretically simple: the alumina layer will not only increase the thickness of the bottom head of the RPV but also will retard the core heat-up by acting as “thermal resistance” (in reason of its thermal conductivity lowering with the increase of temperature, as explained in Lo Frano et al., 2014). Accordingly, the thermo-chemical attack of the lower head caused by the gradual decay-heated core melt (corium) relocation and/or impingement downwards is minimized or prevented.

3. ICC feasibility: modelling and analysis

The adoption of ICC, by spreading ceramic material on the lower head, will require a higher heat exchange area to keep the imposed heat flux below ~1.5 MW/m^2 (value measured in ULPU-2000 facility, see Ma et al., 2016). ICC is based on the successful coolability of the core melt: the instauration of heat transfer processes through the vessel wall will ensure to not establish “heat flux focusing effects” and to maintain unaltered its structural properties. To assess the feasibility of ICC solution the following analyses have been performed:

- Parametric analysis on a simplified mathematical model, based on the standard Fourier’s equation, to study the static solution and the time-constant of the system.
- Computational analysis: transient thermo-mechanical FE analysis (by MSC©Marc code) to simulate the heat exchange involving the core melt (to the aim, a conservative scenario is assumed).

No chemical reactions are considered for the evaluation of the core

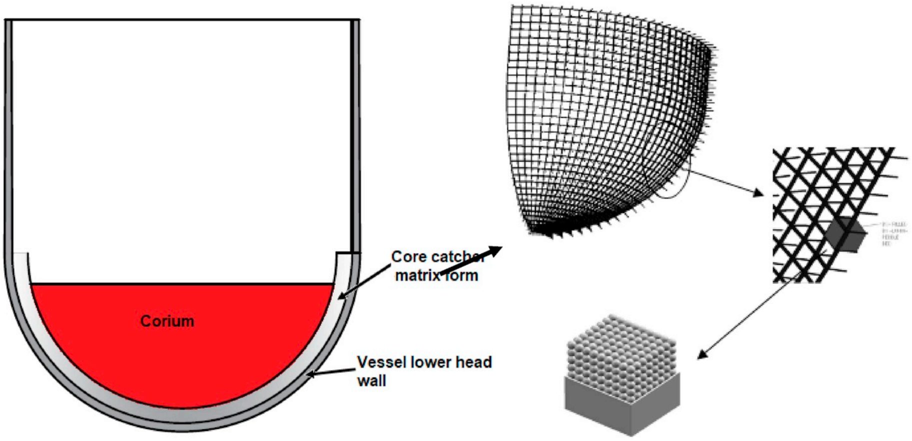


Fig. 4. ICC scheme proposal: the grey surface is the structure with alumina pebble boxes. The internal and external liners of core catcher are made of high alloy steel.

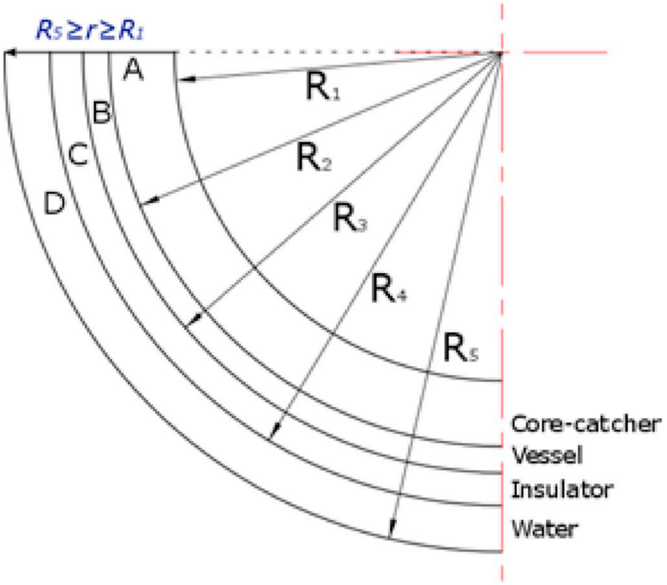


Fig. 5. Axial section of lower head model.

catcher thickness or temperature trend within the pool. Since the stop of lower head heat-up and, eventually of quenching, is the key of the survival of the RPV, in the performed assessment the ICC thickness is firstly determined. In doing that, the mathematical model of the core melt heating (thermal loadings) relocated in the lower head of the reactor vessel is analyzed. For this purpose, the maximum thermal loadings are considered.

Despite the existence of several real physical shapes of relocated corium and melt RPV internals, they may fall in the category of one-dimensional systems because of the clearly identified boundary conditions, and also because the temperature in the "body" is a function only of the radial distance (see Eq. (1)). As for the energy balance across the corium-alumina-steel system, we may hence assume that the heat contribution of the axial, azimuthal and time-dependent terms are negligible. Therefore, equation (1) can be rewritten as equation (2). Moreover, the heat transfer equation (2) in spherical coordinates can represent the radial heat transfer, in the calculation domain of Fig. 5.

$$\rho c_p \frac{\partial T}{\partial t} = -div(q'') + q''' \tag{1}$$

$$0 = -div(q'') + q''' \tag{2}$$

Substituting in the above the equation:

$$q'' = -k\nabla T \tag{3}$$

it becomes:

$$0 = div(k\nabla T) + q''' \tag{4}$$

For constant thermal conductivity (k) and $q''' = 0$, the equation can be rewritten as:

$$0 = k\nabla^2 T \tag{5}$$

In static condition, the problem is described in terms of the classical Laplace equation ($\nabla^2 T = 0$), with a temperature distribution only radius (r) dependent, as:

$$T(r) = C_1 + \frac{C_2}{r} \tag{6}$$

Fig. 5 illustrates the axial section of the lower head model: moving outwards we encounter the alumina or A layer (from $R_1 = R_{int}$ to R_2), the vessel wall or B layer (from R_2 to R_3), the reactor vessel insulator or C layer (from R_3 to R_4), and the water or D layer (from R_4 until the bulk R_5).

Table 1
Values of the geometrical and material properties considered for the analytical calculations performed on the simplified model.

Region	Radius r [m]	Thickness t [m]	Thermal conductivity k [W/m/K]
Core catcher	2.50–3.00	0.50	0.50
Vessel	3.00–3.20	0.20	18.00
Insulator	3.20–3.45/3.50	0.25–0.30	0.15
Water	3.45/3.50–3.80	0.30/0.35	0.60

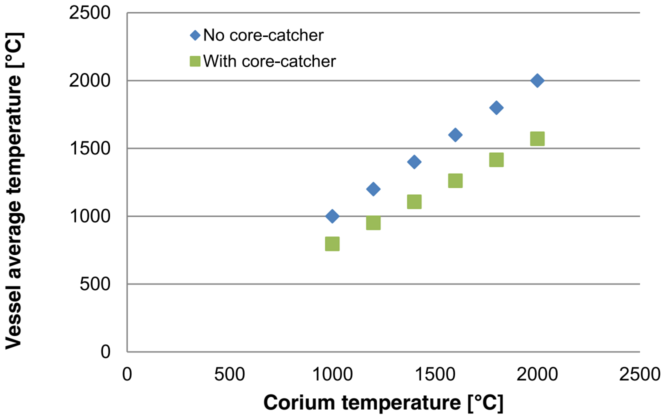


Fig. 6. Temperature trend for IVR with and without ICC solution.

The boundary conditions are $T(R_1) = T_{corium}$ (equivalent to the melting temperature) and $T(R_5) = T_{water}$ (assumed equal to 40 °C, to have a heat transfer completely conductive and to guarantee the capability of the ICC thickness to avoid increase in the reactor cavity temperature, even in the most severe accidental conditions). As concerns the insulator, it was assumed to have low thermal conductivity (0.15 W/m/K) and thickness of 0.25 m. Moreover, at each subdomain interface the continuity of temperature and thermal flux are imposed. Finally, temperature plots are calculated from Eq. (6) considering the geometrical and material properties summarized in Table 1.

The analytical results showed that a core catcher of 0.2 m alumina reduces of about 12% the average vessel wall temperature: thicker ICC lowers this temperature (Fig. 6).

Indeed, the reduction of the heat-up immediately results in an increase of thermal safety margin. Moreover, ranging T_{corium} from 1000 to 2000 °C and assuming the worst heat transfer condition between the insulator and water (no convection); we obtain a representation of the behaviour of the heat loss through the wall.

Fig. 7 shows the radial temperature profile along the vessel wall thickness: the water temperature at the thermal insulator surface is about 100 °C.

A preliminary FE model, as shown in Fig. 9, has been implemented based on the scheme of relocation of the core debris provided in both the previous Figs. 2 and 5. In addition, in such a model the water in the reactor lower plenum is not represented (conservatism) to simulate the worst SA condition without vessel coolability.

The alumina box was implemented using an equivalent mechanical model since the pebbles are characterized by a high packing factor with voiding tending to zero in the SA considered conditions (melting of the core and its relocation in the lower head).

The reactor lower head wall is assumed subjected to thermal and mechanical loadings represented in terms of core melting temperature

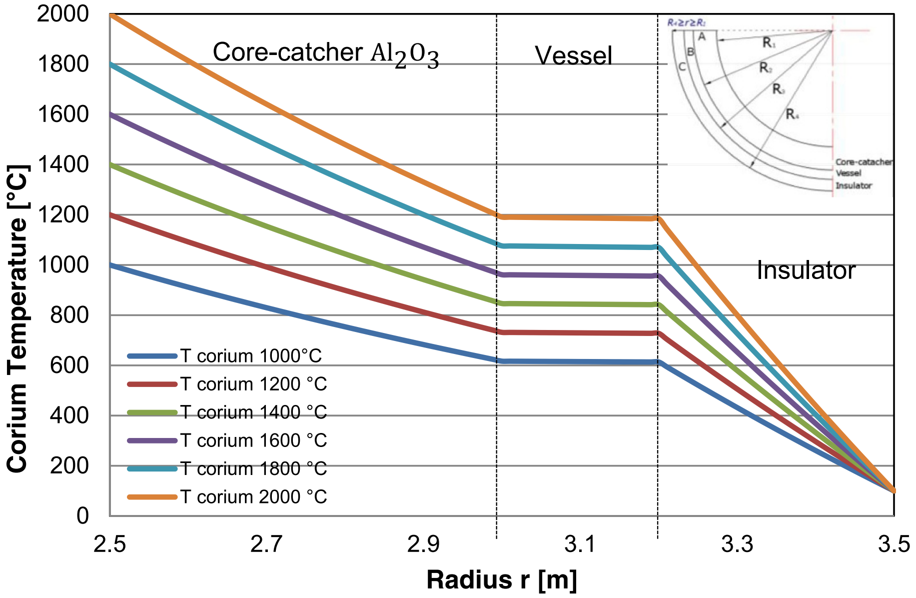


Fig. 7. Radial temperature across the bottom head reactor wall.

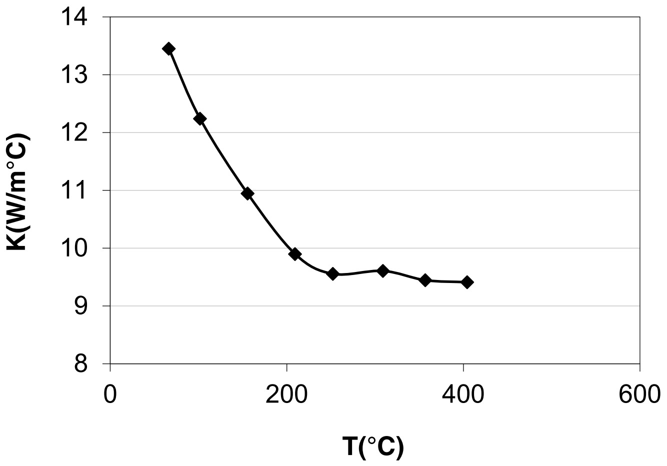


Fig. 8. -Values of alumina thermal conductivity determined experimentally at steady state conditions with hot wire method.

and pressure acting on the top surface.

The trend of the alumina thermal conductivity, obtained experimentally by performing hot rig test, is shown in Fig. 8 (for more details, see Lo Frano et al., 2014). To suitably represent the behavior of all the components of the reactor lower head, in the FE model of Fig. 9 the type 43 element was selected, which is an eight-node, isoparametric, and arbitrary hexahedral element suitable for three-dimensional heat transfer applications. The thermal conductivity is performed using eight-point Gaussian integration. For both the steady state and transient analyses, direct integration method is used.

Sensitivity analyses have been performed, doubling and halving the number of the elements; the obtained results showed that the simulations are grid independent (the discrepancy among the results is about 1.5%). For the thermo-mechanical simulations, the following assumptions have been also made:

- adiabatic condition on the core catcher external surface (no radiation flux surface);
- no top surface cooling of corium by passive emergency cooling systems;
- isothermal boundary condition to represent the external vessel surface cooling;

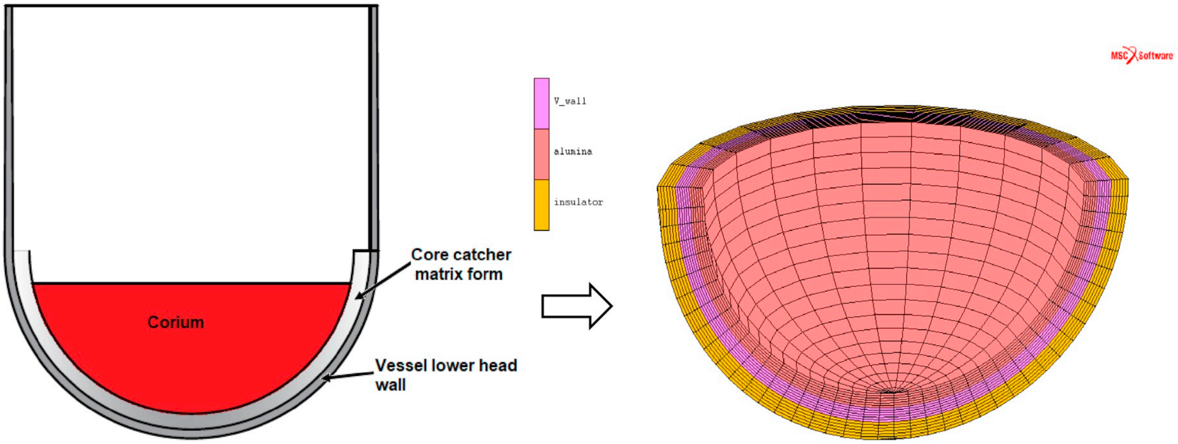


Fig. 9. Model of the reactor lower head with ICC: the core catcher (on the left) is the innermost component represented in light red color.

Table 2
Material properties for components implemented in FE simulations.

Property	Core catcher	Reactor vessel
Density [kg/m^3]	3970	7800
Specific heat [J/kg K]	1560	514
Conductivity [W/m K]	10.5	30
Latent fusion heat [kJ/kg]	3577	–
Young modulus [MPa]	380000	196500

- elastic-plastic behavior for the vessel.

The initial temperature of 2000 K for the oxidic debris and 1550 K for the metallic layer become of minor importance because the thermal load to the vessel lower head is maximized when debris pool reaches a steady thermal state. Furthermore, for a proper description of the heat processes, a thermal contact resistance along the junction (contact interface) formed by the steel vessel and the ICC (mainly made of materials having dissimilar thermal conductivities) has been imposed. This parameter allows weighing the heat transfer efficiency among the steel and alumina interfaces.

In this assessment, we assumed the surfaces are microscopically rough and macroscopically conforming. Table 2 provides the specific material properties assumed as input for the simulation.

In general, the heat transfer from the debris to the vessel wall causes the reactor lower head heat-up, which in the long term may be responsible of the weakening of the vessel strength. This occurs because of the degraded material properties caused by the high temperature.

Fig. 10 and Fig. 11 show the distribution of the temperature as numerically calculated for thermal steady state condition in the case of presence or absence of water external cooling. These contour plots clearly indicate the benefit of the ICC in retarding the heating of the vessel wall also when the external cooling is exhausting. This is due to the alumina layer that acts as “insulator” retarding the heat transfer through its thickness. Moreover, comparing the numerical and analytical results, it is possible to observe a quite good agreement, since the thermal conduction is the dominant heat transfer mode that may determine the heat-up of the vessel wall.

Without interposing the ICC, the heat conduction leads very soon to

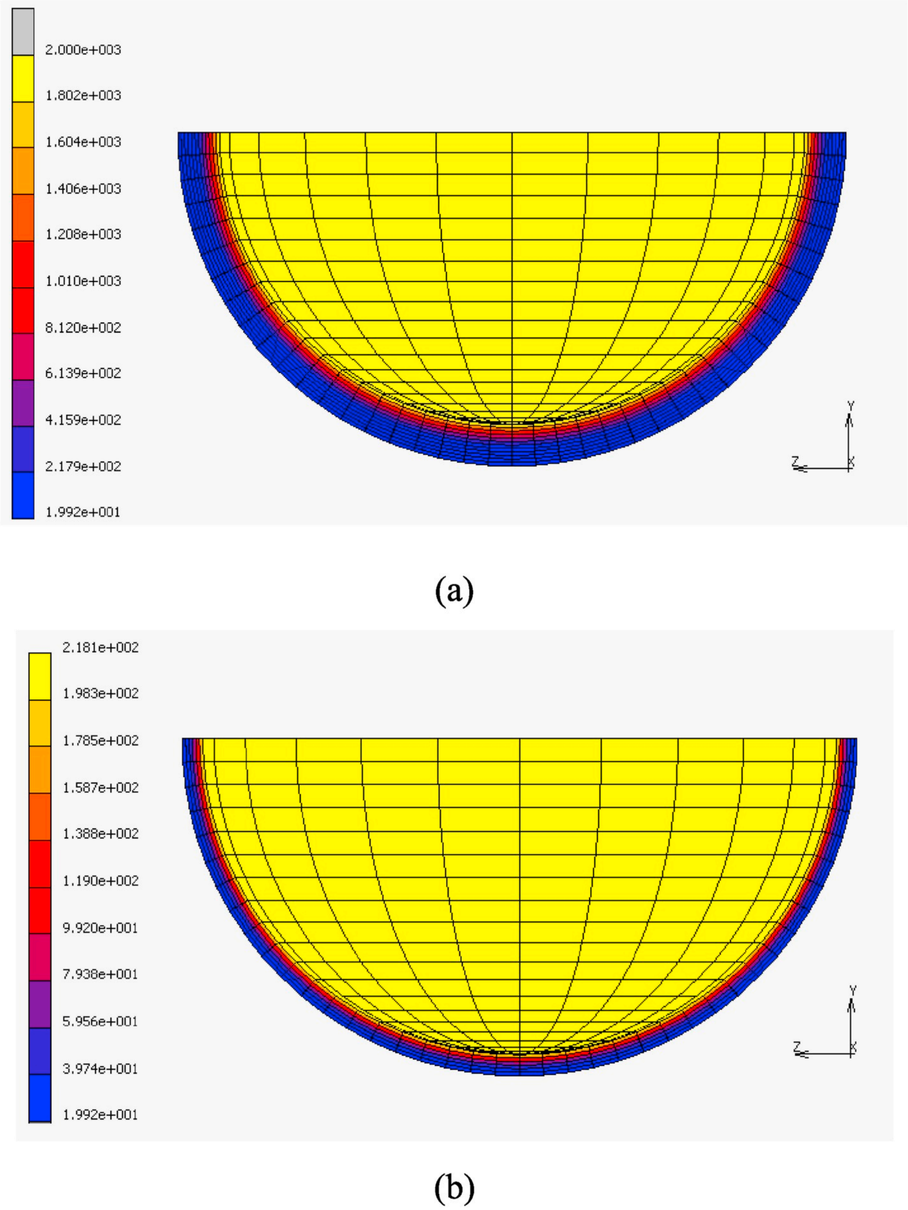


Fig. 10. Contour plot of temperature [°C] in the alumina and steel wall (a) and through the vessel wall (b) in the case of external water-cooling.

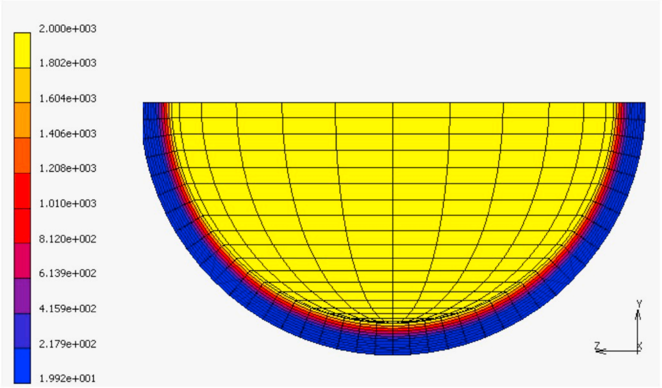
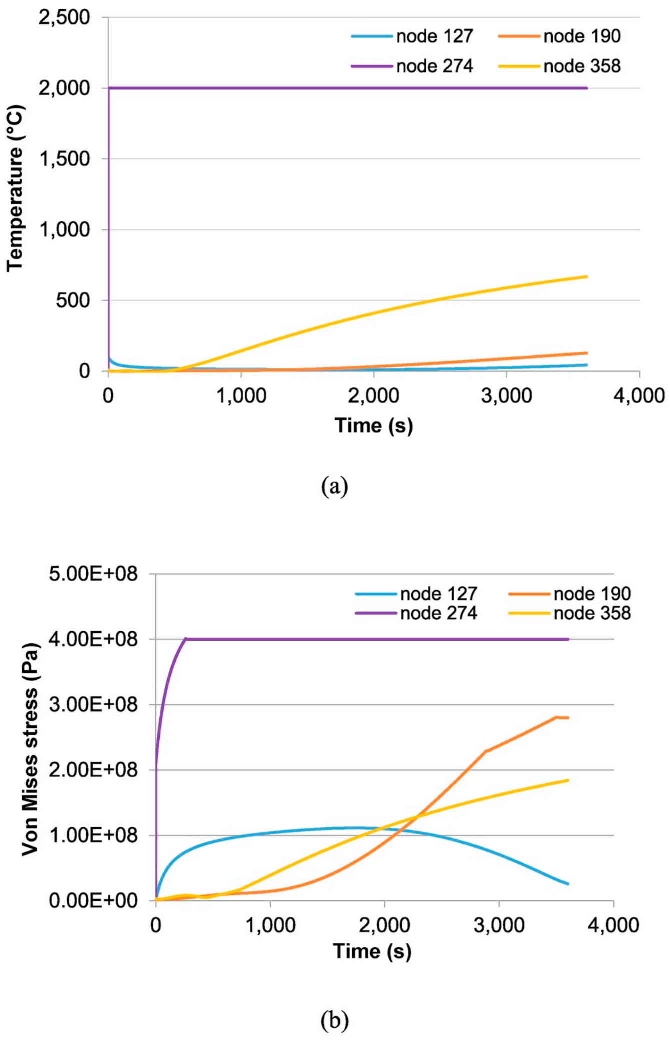


Fig. 11. Contour plot of temperature [°C] in the ICC and lower head wall without external cooling.



(a)

(b)

Fig. 12. Temperature (a) and stress (b) vs. time in the bottom head thickness (outward radially oriented) in the case of external cooling and full core melt relocation. The nodes 127 and 274 are, respectively, the outermost and the innermost points (in contact with the corium) of the bottom head wall. The nodes 190 and 358 are respectively equidistant 0.06 m from the average thickness of the bottom head of the vessel.

pre-heating of the vessel wall (see Fig. 11), due to the high steel conductivity. When the removed heat flux is overwhelmed by the corium heat flux, the vessel ablation starts. In absence of an external cooling, it is expected to increase slightly.

Simulations have been performed varying the thickness of ICC layer. The results obtained showed that reducing the alumina layer below 10 cm the temperature in the lower head increases at unacceptable level, posing thus a serious risk for the reactor integrity.

Indeed, after 1 h from SA, it is possible to observe in Fig. 12 that the maximum value of the temperature is below the limit for which localized failure may appear. Moreover, the temperature distribution along the bottom head wall (alumina plus steel) and the Von Mises stress highlighted that the inner part of alumina (facing the corium) reaches quite soon the allowable stress limit. Consequently, local thinning may appear even mostly part of the lower head remains intact.

4. Conclusions

A new IVCR strategy to cope with the issues due to corium relocation in the pressure vessel lower head is presented. It is based on the adoption of an innovative ICC, developed at the University of Pisa, made of batches of ceramic multi-layered pebble with low thermal conductivity.

The proposed ICC has been investigated by mean of analytical and numerical simulations. The obtained results mainly showed:

- heat transferred from debris to the vessel wall causes the lower head heat-up;
- long heat-up is responsible of the weakening of the vessel strength;
- alumina core catcher retards the heat transfer to the vessel wall also when the external cooling is going to exhaust;
- without ICC, the heating of reactor lower head may lead to localized damages because of local thinning or creep.

When the removed heat flux is overwhelmed by the corium heat flux, the vessel ablation starts and in absence of external cooling increases slightly.

Finally, it is worthy to remark that, further investigation is necessary to account for focusing effects and ablation, which may play an important role in jeopardizing the reactor integrity and in turn for proper SAM and strategy.

CRediT authorship contribution statement

Rosa Lo Frano: Conceptualization, Methodology, Writing - original draft, Funding acquisition. **Riccardo Ciolini:** Writing - review & editing. **Alessio Pesetti:** Writing - review & editing, Software.

Acknowledgement

The funder is Ministero dello Sviluppo Economico (MiSE) throug Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (ENEA). The project is Piano Annuale di Realizzazione (PAR) 2017; project unique code number (CUP: I12F17000070001).

NOMENCLATURE

AP600/1000	Advanced Passive 600/1000 reactor
CHF	Critical Heat Flux
C_p	specific heat
FE	Finite Element
ICC	Internal Core Catcher
IVCR	In-Vessel Corium Retention
IVMR	In-Vessel Melt Retention
IVMP	In-Vessel Melt Progression
IVR	In-Vessel Retention
k	Thermal conductivity
LOCA	Loss of Coolant Accidents
LWR	Light Water Reactor
MFCI	Molten Fuel-Coolant Interaction
NPP	Nuclear Power Plant
q	Internal heat source
q_w	Decay heat
r	Radial distance
RPV	Reactor Pressure Vessel
SA	Severe Accident
SAM	Severe Accident Management
t	Time
T	Temperature

Greek letter

ρ	Density

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pnucene.2020.103321.

References

Aquaro, D., et al., 2016. Original Core Catcher Design in Order to Manage the Core Meltdown Severe Accident with the In-Vessel Retention Strategy. IAEA technical meeting, Shanghai, 17-21 October 2016.

Cheung, F.B., et al., 1997. Critical Heat Flux (CHF) Phenomenon on a Downward Facing Curved Surface. NUREG/CR-6507, PSU/ME-97-7321.

Esmaili, H., Khatib-Rahbar, M., 2004. Analysis of In-Vessel Retention and Ex-Vessel Fuel Coolant Interaction for AP1000. Energy Research Inc, Rockville, USA. NUREG/CR-6849, ERI/NRC-04-201.

Globe, S., Dropkin, D., 1959. Natural-convection heat transfer in liquids confined by two horizontal plates and heated from below. J. Heat Tran. 81 (24).

Henry, R.L., Fauske, H., 1993. External cooling of a reactor vessel under severe accident conditions. Nucl. Eng. Des. 139, 31–43.

Kim, H.Y., Bechta, S., Foit, J., Hong, S.W., 2018. In-Vessel and Ex-Vessel Corium Stabilization in Light Water Reactor, Science and Technology of Nuclear Installations, vol. 2018. https://doi.org/10.1155/2018/3918150. Article ID 3918150.

Lo Frano, R., et al., 2014. Thermo-mechanical test rig for experimental evaluation of thermal conductivity of ceramic pebble beds. Fusion Eng. Des. 89, 1309–1313.

Lo Frano, R., et al., 2019. Innovative engineering safeguards to cope with corium relocation: identification of loads and failure modes. Proceedings of ICONE 27. May 19-24, 2019 Tsukuba, Japan.

Ma, W., et al., 2016. In-vessel melt retention of pressurized water reactors: historical review and future research needs. Engineering 2, 103–111.

NEA/OECD Nuclear Safety, 2000. In-vessel Core Degradation Code Validation Matrix. NEA/CSNI/R, p. 21, 2000.

NEA/OECD Nuclear Safety, 2017. State-of-the-Art Report on Molten Corium Concrete Interaction and Ex-Vessel Molten Core Coolability. NEA/CSNI/R (2016)15, NEA No. 7392.

Okawa, T., 2018. Validation progress and exploratory analyses of three-dimensional simulation code for BWR in-vessel core degradation. Ann. Nucl. Energy 117, 73–83.

Park, R., et al., 2012. Corium behavior in the lower plenum of the reactor vessel under IVR ERVC condition: technical issues. Nuclear Eng. Technol. 44 (5), 237–248.

Park, J.W., et al., 2016. Conjugate heat transfer analysis for in-vessel retention with external reactor vessel cooling. Ann. Nucl. Energy 88, 57–67.

Rempe, J.L., et al., 1993. Light Water Reactor Lower Head Failure Analysis. NUREG/CR-5642 EGG-2618.

Sehgal, B.R., 2012. Nuclear Safety in Light Water Reactors: Severe Accident Phenomenology. Academic Press.

Theofanous, T.G., et al., 1996. In-vessel Cool-Ability and Retention of a Core Melt. DOE/ID-10460, Revised October.

Theofanous, T.G., et al., 1997. In-vessel coolability and retention of a core melt. Nucl. Eng. Des. 169, 1–48.

European Union, 1999. 4th EU FP, Final Report for the Melt-Vessel Interactions.

Valincius, M., et al., 2018. Modelling of severe accident and in-vessel melt retention possibilities in BWR type reactor. Sci. Technol. Nuclear Installations 2018, 1–14. Article ID 7162387.

Wang, X., Cheng, X., 2015. Analysis of focusing effect of light metallic layer in stratified molten pool under IVR-ERVC Condition. J. Nucl. Eng. Radiat. Sci. 1 (2) article 021007.

Zdarek, J., 2017. In vessel melt retention strategy - status of work for VVER 1000 Units applications. In: 10th ISTC "Safety Assurance of NPP with VVER", Podolsk, Russia. May 16–19, 2017.

Zhang, Y.P., et al., 2010. Analysis of safety margin of in-vessel retention for AP1000. Nucl. Eng. Des. 240, 2023–2033.