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ET DE SÛRETÉ NUCLÉAIRE

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Considerations concerning the strategy of corium retention in the reactor vessel

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Foreword

Third-generation nuclear reactors are characterised by consideration during design of core meltdown accidents. More specifically, dedicated measures or devices must be implemented to avoid basemat melt-through in the reactor building. These devices must have a high level of confidence. The strategy of corium retention in the reactor vessel, if supported by appropriate research and development, makes it possible to achieve this objective.

IRSN (the French Institute for Radiological Protection and Nuclear Safety) works alone or in partnerships to address all the issues associated with in-vessel corium retention.

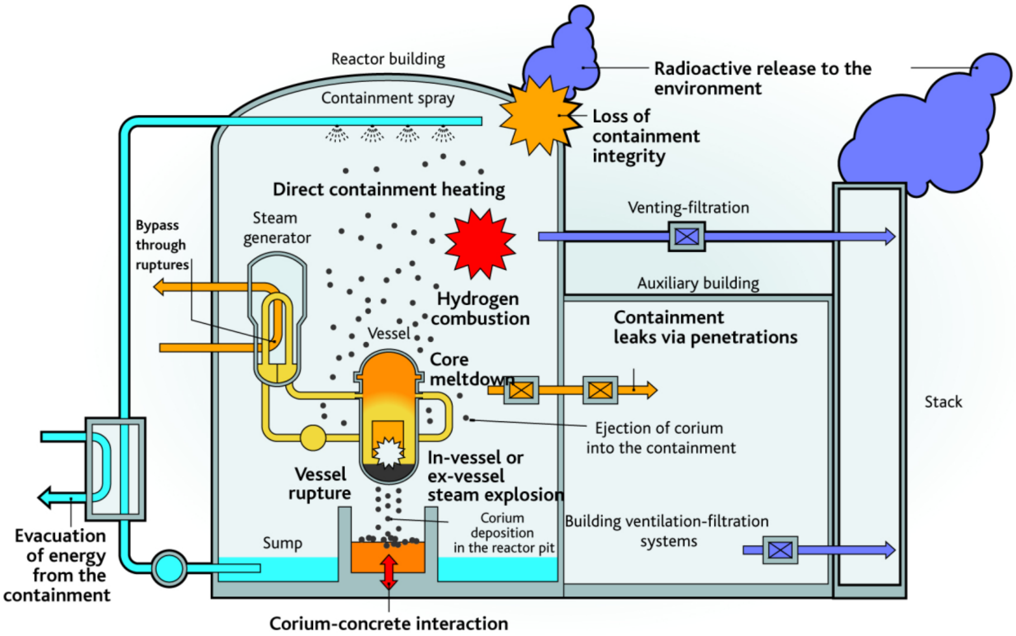
This document describes the in-vessel corium retention strategy and its limitations, along with the research programmes conducted by IRSN in this area.

I. Introduction

In case of a severe accident affecting a nuclear reactor, one of the specific questions concerns the management of the mixture of fuel and core structural materials (corium) resulting from the loss of fuel cooling. The design strategies for third-generation water reactors are mainly based on two different approaches, the first with corium retention and stabilisation outside the vessel (case of EPR via spreading and cooling of corium by flooding), the second with corium retention in the vessel (case of AP1000 reactor).

II. Controlled management of a severe accident

In a core meltdown accident, **the main objective is to minimise releases to the environment, exposure of the public to radiation, and long-term contamination. To this end, integrity and leaktightness of the reactor containment must be maintained.**



Severe accident phenomenology and identification of leakage paths to the environment

The risk of vessel failure can be minimised with early and sufficiently high-flow injection of water into the vessel to remove the decay heat released by the fuel. The availability of early injection is, however, unlikely since it depends on the operator's capacity, shortly after the beginning of fuel degradation, to find a means of water injection that was not previously available and to maintain it over time.

In addition to water injection into the vessel, which may occur at a later phase, reactor pit flooding increases the possibilities of maintaining the corium in the vessel. The in-vessel corium retention strategy is thus based on sufficiently early water injection into the vessel so that an already degraded core can be cooled at least in part, and on the performance of an external cooling of the vessel.

The decay heat must be evacuated out of the reactor containment to avoid a slow pressure increase. Increased pressure would lead to containment failure, unless there is a venting-filtration system, whose opening time and efficiency in trapping aerosols and gaseous species determine the intensity of environmental releases.

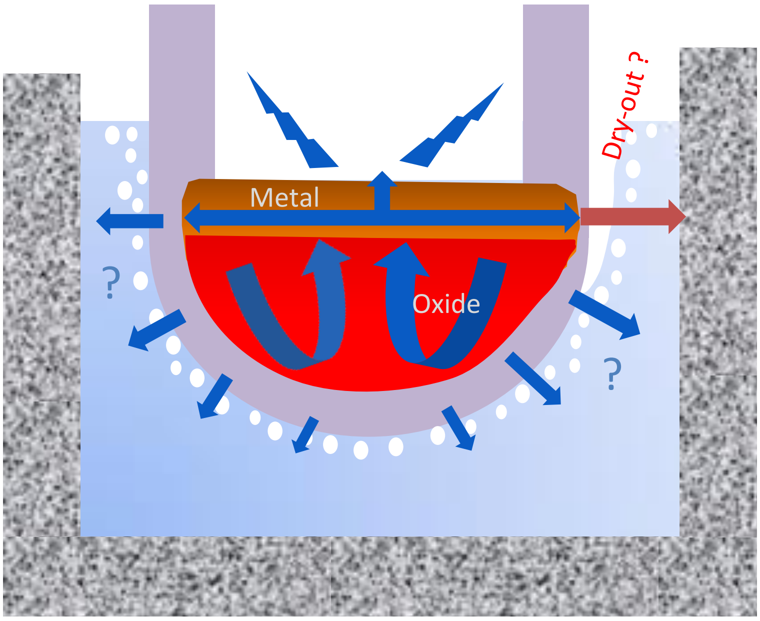
If the corium cannot be maintained in the vessel, dedicated measures or devices protect the basemat. For the EPR, this entails spreading the corium on a large enough surface area to decrease heat flux and promote cooling.

Whatever the approach taken (corium in or outside the vessel), water injection and ongoing decay heat evacuation out of the containment are necessary, and the associated risks in terms of containment failure, through pressurisation or dynamic loads, must be examined.

III. Key points for the feasibility of an in-vessel retention strategy

Demonstrating the robustness of an in-vessel retention strategy requires checking that the heat can be evacuated by the water of the vessel's external cooling system at all points of the vessel's external surface without risk of wall dry-out, particularly in the areas where the heat flux is very high. This depends on the distribution of heat flux on the vessel wall's inside surface and on the variation of critical heat flux (see below) at each point of the vessel's external surface.

The distribution of heat flux on the vessel wall's internal surface depends on natural convection mechanisms within the various pools or layers of corium accumulated at the vessel lower head. A cooling system outside the vessel slows its potential failure. The physical-chemical equilibria in the materials that compose the corium change over time and the situation progressively moves toward a stratified pool where a non-miscible metal layer floats at the surface of a pool of oxides, which may itself be composed of two phases with different densities.



Heat flux distribution and dry-out risk

Without water injection into the vessel, there is a significant imbalance in the temperatures at the boundaries of the metal layer: heat transfer by natural convection occurs to the vessel wall (at the melting point of steel) and to the surface of the corium pool, which is at a higher temperature; at that point, the heat exchanges with the remaining structures occur only by radiation. This results in a phenomenon of flux concentration, known as the "focusing effect", which is more marked when the metal thickness is low and the mass of oxides under the metal layer and to which the decay heat is released, is significant.

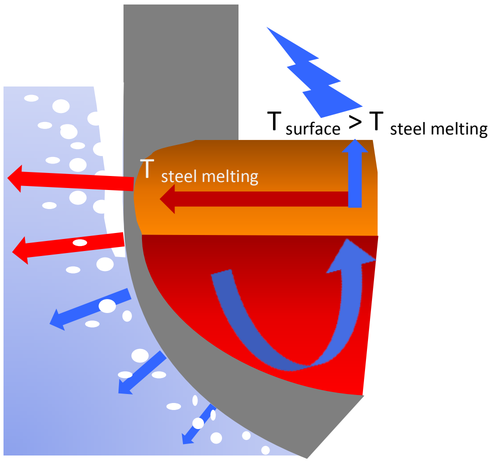


Illustration of '' focusing effect'' phenomenon

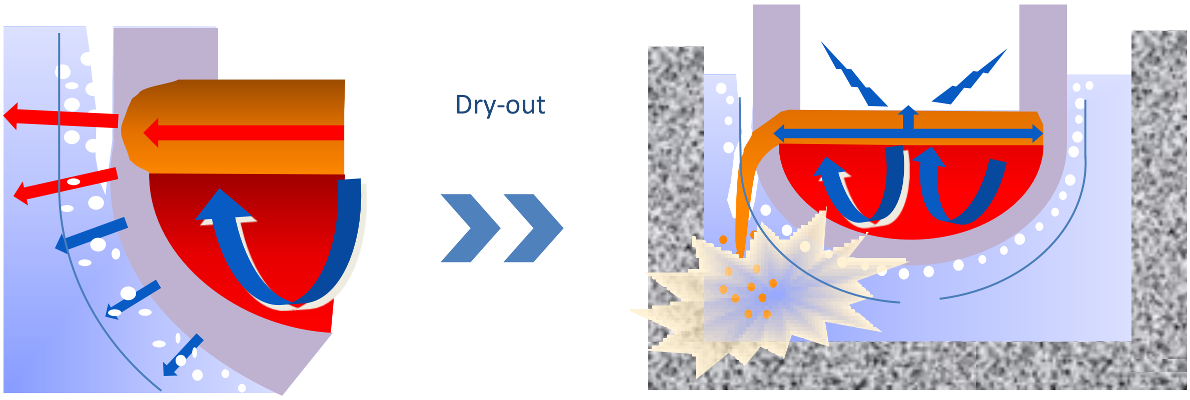
Water injection into the vessel affects the heat flux distribution to the extent that it cools all or part of the degraded core before the corium reaches the lower head, and to the extent that it eliminates the focusing effect. The degree of core degradation when water is injected significantly affects cooling efficiency and thus the fraction of corium at the lower head. Conservatively, heat flux spikes of more than 1.5 MW/m^2 should be considered in the absence of water injection into the vessel for 1000 MWe reactors.

The critical heat flux at the external surface of the vessel is determined by evaluating, at all points of the lower head, the dry-out limit based on the local flow characteristics. This limit is higher when the vessel wall is vertical (resulting in easier steam evacuation) or when the water is subsaturated at the inlet of the external vessel cooling system.

Cooling can be done by flooding the reactor pit, but it is more efficient to create a space that channels water (liquid and steam) around the vessel and increases the cooling flow rate when circulation is by natural convection. Depending on its characteristics, insulation around the vessel may create a space for channelling flow, or act as an obstacle preventing correct steam evacuation.

It should be noted that an absolute critical heat flux value cannot be used, since critical heat flux depends on local conditions and a flow rate that is determined by the characteristics of the cooling system. With natural convection, the cooling flow rate adapts to the available head and two-phase pressure drops, particularly in the space created around the vessel. For AP1000, during the ULPU tests conducted in the USA, values of 2 MW/m^2 were obtained in the most vertical areas of the vessel.

For high heat flux values, wall dry-out leads to vessel failure by meltdown; in this case the postulated event is the interaction of corium with the water in the reactor pit, leading to a steam explosion sufficiently powerful to compromise the leak-tightness of the containment or of the circuits that pass through it.



Consequence of vessel wall dry-out

IV. Impact of reactor power on the robustness of an in-vessel retention approach

Given the current state of knowledge, and using certain assumptions which have yet to be demonstrated as conservative, it is possible to:

- evaluate the hydrogen production during core degradation, then during the reflood phase;
- evaluate the progression of corium from the core to the lower head and the conservative heat loads for the vessel;
- evaluate the performance of a cooling system outside the vessel;
- evaluate the mechanical strength of the vessel;
- estimate the dynamic loading resulting from an interaction between the corium and water or from a hydrogen explosion.

Based on this knowledge, simulations have been performed to validate, for reactors with power less than or approximately 600 MWe, the robustness of an in-vessel corium retention strategy, provided that the external cooling system was designed with regard to this objective and that the lower head does not have a specific geometric feature such as difference in thickness between the lower sidewall and the lower head, or a geometry limiting the cross flow for cooling water.

The in-vessel retention strategy was adopted at the end of the 1990s in Finland in order to increase the power of their VVER-440/213 reactors. To reach this objective, a system of mobile insulation was implemented to create a cooling space around the vessel, and the reactor pit ventilation system was modified to create a cooling loop. Experimental programmes (COPO in Finland and ULPU in the USA) and simulations made it possible to check that the performance of the cooling system was sufficient, taking into account conservative heat flux distributions at the lower head.

Concerning new reactors, AP600 was designed with an in-vessel retention strategy. Given its power level, the margins were sufficient, including in the absence of water injection into the vessel, to validate the demonstration, which led to NRC certification of the reactor in 1999. **The approach taken for AP600 was then extended to AP1000.**

The low-power reactors include the RES test reactor, whose cooling system performance was checked during the CNU tests at the CEA, and SMRs, for which there is a high level of confidence regarding the possibilities of in-vessel corium cooling.

It is more difficult to demonstrate the robustness of an in-vessel retention strategy for the 900 to 1000 MWe reactors because the heat to be evacuated from the corium is greater and, using some assumptions, the dry-out limits are exceeded. It is both necessary to flood the reactor pit and inject water into the vessel to reduce the mass of corium at the lower head and eliminate the focusing effect. For scenarios of rapid degradation leading to corium at the lower head in only a few hours, the time window for finding another possibility for in-vessel injection, which was previously not found, is too short to be able to exclude the risk of vessel failure. The robustness of the demonstration of severe accident containment then requires evaluation of the consequences of an interaction between corium and the water in the flooded reactor pit. Given the current state of knowledge, this evaluation does not offer enough guarantees to be able to exclude the risk of short-term degradation of the containment and early releases to the environment.

In this power range (900 to 1000 MWe), the simulations performed for 900 MWe PWRs in the French fleet, as well as for the AP1000 reactor, do not allow excluding the possibility of vessel failure and early environmental releases, since a steam explosion could take place in the reactor pit. As for the AP1000, its certification by the NRC in 2005 was based both on deterministic arguments and probabilistic arguments.

According to US regulations, deterministic studies must exclude any and all risks of massive releases for 24 hours after core degradation begins. In its demonstration, the designer assumed that in case of vessel failure, a steam explosion in a flooded reactor pit would damage the structures inside the reactor building, but would not compromise the integrity of the metal containment. The designer also showed that basemat melt-through would only occur after 48 hours.

According to US regulations, probabilistic studies must show that the frequency of massive releases is less than 10^{-6}/year.reactor. Given the uncertainties surrounding the models of corium progression to the lower head, the designer assumed a conditional probability of vessel failure of between 4% and 30%, and postulated a systematic failure of the containment with massive environmental release. Since the calculated frequency of containment failure is 1.9×10^{-8}/year.reactor, with 38% of failures leading to early releases, the designer concluded that his design was well below the limit.

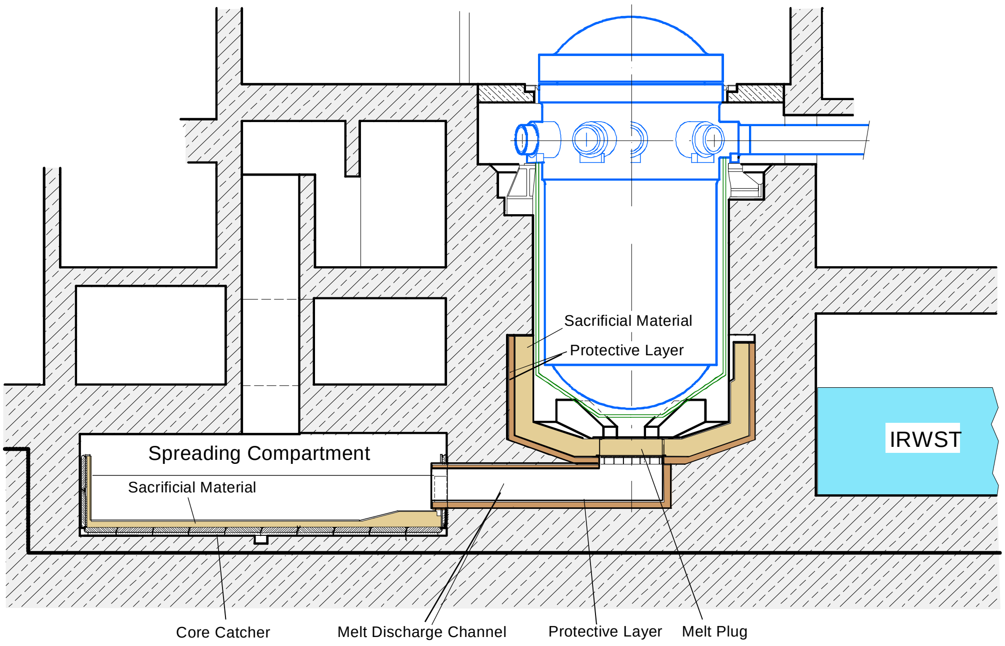
For IRSN, the uncertainties involved in determining the mechanical loads resulting from a steam explosion in a flooded reactor pit make it impossible to rule out massive early releases, and transient heat loads more severe than those considered could further increase the probabilities of vessel failure.

For higher-power reactors (1300 to 1600 MWe), the efficiency of an in-vessel retention strategy is even less robust since the power density to be removed from the vessel is higher. The heat flux is higher and the scenarios in which the dry-out limits are exceeded are more probable.

During the Reactor Standing Committee meeting on 28 March 2013 concerning the VD3 1300 safety review, EDF showed that it was possible for a flooded reactor pit to cool the corium despite the presence of insulation. However, during the technical evaluation with IRSN, EDF acknowledged that the specific geometric features of the vessel, together with the possible lack of internal vessel cooling and the concentration of the entire core inventory at the lower head, could lead to exceeding the critical heat flux, in which case the integrity of the lower head could not be guaranteed. The differences between IRSN and EDF assessments mainly concern the consequences of a steam explosion in the reactor pit. IRSN continued to recommend maintaining the reactor pit as dry as possible before vessel melt-through, so as to avoid a steam explosion, but also to facilitate spreading the corium over the entire basemat surface before corium cooling, as a second step, by flooding the reactor pit; this would require modifying the design of the facility.

The severe accident management strategy for the Korean APR 1400 is not definitively set and may undergo changes. The standard version uses an in-vessel retention approach, whereas a modified version for the European market would have a cooled corium spreader as in the EPR, but placed directly under the vessel, which has disadvantages because it is then not protected from hazards due to collapse or projection of materials from the vessel.

Concerning the EPR, the designers, based on the BALI and SULTAN programmes conducted at the CEA in the 1990s, concluded that an in-vessel retention solution was not sufficiently robust. They opted for a corium spreader outside the vessel, with a first corium collection phase in the reactor pit, then a second spreading phase in a cooling device with water circulation under the corium, followed by water overflow to cover its surface.



Ex-vessel retention strategy after corium spreading adopted on EPR

V. Making an in-vessel retention strategy robust for extension to reactors over 600 MWe

V.1 Technological improvements

Since reactor core meltdown results from the incapacity to ensure core cooling at a given point, it would be paradoxical to assume that a subsequent water injection into the vessel could be systematically guaranteed, particularly for situations leading to corium at the lower head in the space of only a few hours.

An approach that does not require water injection into the vessel would thus be more robust. Such an approach would necessarily entail evacuating higher heat flux areas or decreasing heat flux on the internal surface of the vessel.

Different solutions could be explored to improve the capacities of an external cooling system:

- working on the external cooling system to improve the circulation of water and steam flow around the vessel;
- using forced circulation together with natural circulation, particularly in cases of rapid kinetics;
- implementing a nanoparticule-based coating for the vessel that slows the phenomenon of dry-out.

Some reactor designs use high metal masses to reduce the focusing effect. However, this approach ignores transient thermal loads. A variant would use materials miscible with corium, to increase the surface area of the vessel in contact with the corium and reduce heat flux. In the absence of dilution materials, the increased surface of contact between corium and the vessel would require adapting the design of the lower head.

If, in the absence of water injection into the vessel, the risk of vessel failure could not be ruled out, efforts should focus on measures or devices to practically eliminate the risk of interaction between corium and water. A design where coolant circulation would take place only in a system set up around the vessel could be developed to minimise the quantity of water entering in contact with the corium, in case of vessel failure. Corium management would then take place outside the vessel.

From the analysis of current in-vessel retention designs, it is clear that knowledge is insufficient in two main areas:

- transient loads resulting from corium progression from the core to the lower head, with or without water injection into the vessel;
- uncertainties concerning the evaluation of dynamic loads potentially resulting from a steam explosion.

As for increasing cooling capacities outside the vessel, this is more a question of changes, technological developments or full-scale qualification work on the cooling systems.

V.2 Expected research outcomes: IRSN's scientific strategy

IRSN's aim is to build the scientific foundation it needs it to evaluate the management strategies of a core meltdown accident and in particular, water make-up management. To meet this objective, IRSN must develop and qualify models that reduce current uncertainties, and must also work to make simulations more realistic.

IRSN has thus initiated a research programme with three main areas:

- reflooding of a degraded core and the possibility of cooling a fuel debris bed in the vessel;
- corium spreading configurations in the lower head;
- mechanisms of the corium-water interaction.

Concerning the first research area, the work will focus on:

- modelling the geometric characteristics of the different possible debris bed configurations (porosity, exchange surfaces, permeability, etc.);
- modelling thermohydraulic phenomena likely to occur during reflooding for these different configurations;
- modelling oxidation phenomena of the metal-oxide mixtures in corium and production of incondensable gases;
- impact studies of how all these phenomena interact.

The development of models and their qualification is based on tests conducted in the small-scale facility PRELUDE and now on followed tests conducted in the PEARL facility within an IRSN analytical experimental programme on debris bed reflooding (PROGRES).

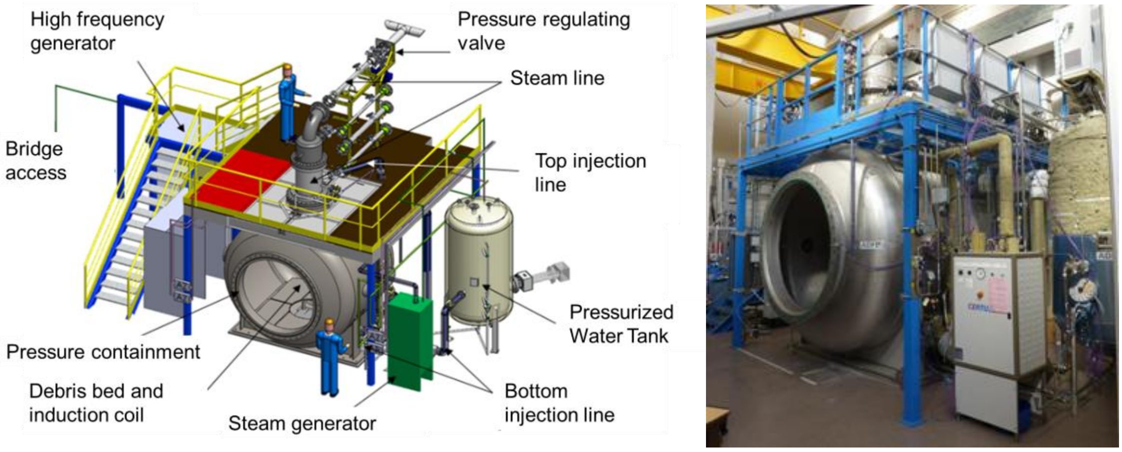


Illustration of PEARL facility designed to study debris bed reflooding

Concerning the second research area, IRSN is particularly interested in the transition kinetics between the oxide layers of the fuel and the metal materials; this involves the appearance of crusts at the interfaces. The relevant experiments are conducted as part of the CORDEB programme (CORium-DEBris) run by the Alexandrov Research Institute of Technology in Saint Petersburg on behalf of IRSN, EDF, AREVA and the CEA. The CORDEB programme includes around 15 experiments using simulator materials in various configurations in order to observe and qualify the main phenomena involved: physical-chemical separation of phases, inversion of layers by turbulent instability, interactions between debris and layers, etc.

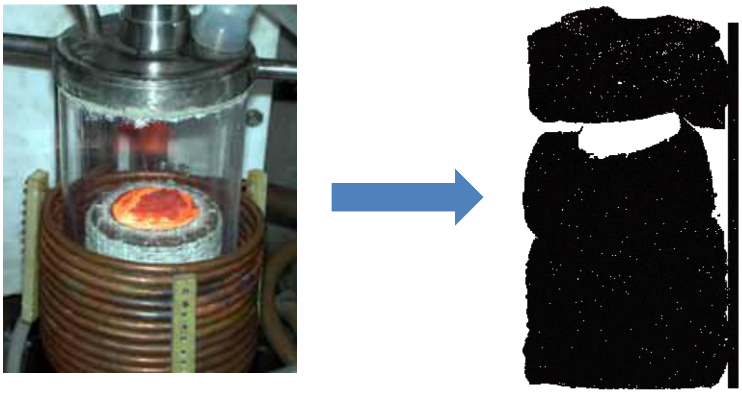


Illustration of an experiment performed within CORDEB programme to study corium pools stratification kinetics.

Finally, the last area of research is managed within the ANR-RSNR (French National Research Agency-Nuclear Safety and Radiation Protection Research) project "ICE", focused on the interaction between corium and water, and draws on the conclusions of the OECD programme SERENA 2. The work concerns:

- intrinsic fragmentation mechanisms of the jet, which drives the interaction;
- impact of the oxidation and solidification of the materials;
- processes of pressure increase in the explosion phase;
- three-dimensional effects (non-vertical jets, off-centre flows, etc.).

The three research areas include experimental activities as well as interpretation and modelling.

More generally, on in-vessel retention, IRSN is coordinating a project proposal for the European call for proposals H2020. This project, which involves more than 20 partners, aims to examine all of the scientific issues in question. As part of this effort, IRSN will continue its work on debris bed cooling to address the cooling of compact areas surrounded by debris. It will benefit from the work conducted by the other partners, notably on external vessel cooling (including technological developments) and the mechanical resistance of a partially ablated vessel. An important part of the project is the inter-comparison calculations for the different designs and reactors, with the aim of defining a shared methodology for evaluating the robustness of an in-vessel retention solution.

VI. Conclusion

For reactors at or below 600 MWe, current knowledge makes it possible to adopt an in-vessel corium retention strategy, even in the absence of water injection into the vessel, provided that the vessel geometry and external cooling system design are suitable.

Beyond this level of power, given the current state of knowledge, the capacity to cool the corium in the vessel cannot be demonstrated for all accident situations, and the risks of vessel failure are even greater for higher power levels; this in turn increases the steam explosion risks due to interaction of corium and the external cooling system water.

An in-vessel corium retention strategy for reactor powers greater than 600 MWe would require R&D, and perhaps technological improvements, more significant at higher powers, **with a difficult safety demonstration, given the variety of scenarios to cover and the complexity of physical phenomena to consider.**

IRSN has initiated several research efforts to improve its knowledge and effectively evaluate the robustness of a solution for corium retention in the reactor vessel that could be proposed by operators or designers **for existing reactors or as part of new reactor designs.**