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Evaluation results of core catcher innovation measures

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Summary

Characterisation of heat transfer ? Proposal of innovative concepts or measures to be tested in subtasks 6.2.2 and 6.2.3.

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Summary

This report deals with the proposal, within the framework of the ESFR-SIMPLE project, of innovative mitigation features related to the core-catcher integrity. To propose such new features, past core catcher design history has been summarized. Then, based on this knowledge, innovative features have been discussed between KIT, LEMTA and CEA. Some new mitigation features have been proposed that are experimentally accessible during the course of this project. They promote the beneficial effect of the pool effect at the corium jet impingement on the core-catcher. This effect was already revealed by the former JIMEC and HANSOLO experiment and slows down the core-catcher ablation. It has thus been proposed pods located directly under the transfer tubes to better protect the core-catcher from ablation. The influence of the inclination or shape and roughness of the upper surface of these pods are of primary interest to control the pool effect appearance. With this objective, representative experimental tests are proposed by the LEMTA. They will be carried out during the course of this project in order to confirm which pod design would be the best to protect the core catcher. This work would be performed during the subtask of 6.2.2 of the project. Furthermore, such addition of pods on the core catcher, which would be partially ablated during the short-term corium relocation, would have then an influence on the corium long term cooling mainly by influencing the corium natural convection flow and its related heat transfers or by inducing preferential crust formation. This second issue related to long-term cooling will be studied by the KIT through various experiments in the LIVE facility. This work would be performed during the subtask of 6.2.3 of the project.

Keywords

SFR Severe Accident, Core-catcher, Innovative mitigation devices

Abbreviations and acronyms

Acronym	Description
CDA	Core Disruptive Accident
DHR	Decay Heat Removal
FCI	Fuel Coolant Interaction
SFR	Sodium Fast Reactor
WP	Work Package

Introduction

It is important to account for the consequences of a hypothetical severe accident very early in the pre-conceptual design phase of a fast reactor, in order to reduce them as much as possible. In particular, it is of fundamental importance to ensure the containment of Fission products and long-term cooling without radiological damages.

In case of hypothetical severe accident, the reactor ultimately melts down and the degraded fuel, or corium, releases a decay heat that must be evacuated on the short and long terms to preserve the containment of the radioactive materials. Past studies (Rineiski, 2008) have evaluated the decay heat to roughly 3% of nominal power one minute after shutdown. After one hour, this ratio reduces to almost 1%, while after one day it is between 0.4 and 0.7%, depending on the fraction of minor actinides in the fuel.

To ensure long-term coolability of the corium, a dedicated mitigation device is generally installed below the core, called the “core catcher” to collect the molten corium or debris material (including the fissile material), spread it to better insure its coolability and avoid a neutonic recriticality. In GEN-II reactor designs, the corium pool had to melt its path from the core region within the diagrid and strongback to the lower plenum (Figure 1 left). This process could last some hours, which is relatively slow considering that the core degradation may occur within a few minutes after the initiator of the accident, and increases the risk of violent supercritical power excursions in the degraded core. In Sodium Fast Reactor (SFR) most recent designs (French and Japan), innovative devices called corium “transfer tubes” (Tobita et al., 2008) (Bachrata et al., 2021) have been installed to mitigate this risk by fastening the fissile material relocation (in about 1 minute) of core material from the core region to the lower plenum (Figure 1 center and right). However the decay heat is about 3 times higher at time of arrival in this case compared to the slower GEN-II relocation process, which increases the importance of the modelling of the phenomenology associated to the arrival of the corium onto the core catcher.

In this ESFR-SIMPLE project, the objective is to strengthen the SFR safety demonstration and the aim of studies of the task 6.2 is manly directed on the core catcher performances. The typical functions of a core catcher are:

- Contain the corium (debris or liquid pool), even in case of whole core melting accident;
- Ensure the cooling of core debris / corium melt and dissipation of decay heat,
- Guarantee the neutron sub-criticality,
- Be mechanically robust, especially during the accident transient when corium reaches the core catcher, leading to transient contact of high temperatures ~3000 K, and important masses ~100 t
- Protect its supporting structures; to limit the release of radioactive products.
- Of course, the core catcher should also not disturb plant normal operation.

Several options could be considered concerning the location and general architecture of the core catchers:

- In-vessel core catchers in the lower plenum of the internal vessel. In the past several designs have been considered: a single tray as in Superphenix or ASTRID (Figure 1 left and center) or multilayered as in JSFR (Nakai et al., 2009) depending in particular on the space available at this location.
- Inter-vessel core catchers between the internal and safety vessel,
- External core catchers below the safety vessel.

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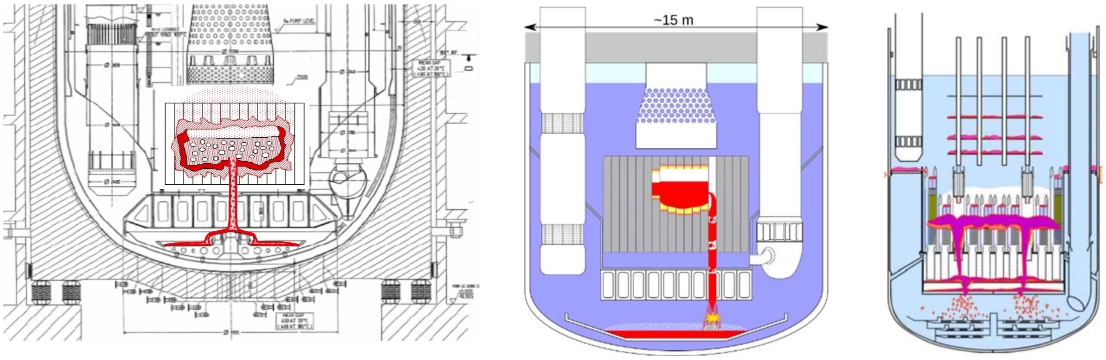

Figure 1 : Sketch of corium relocation from core region to core catcher in lower plenum
(Left: in Gen 2 SFR such as Superphénix – in Gen4 SFR such as ASTRID [center] or JSFR [right]
(Nakai, 2009)

Insuring the integrity of the chosen type of core catcher demands a proper characterization of the main physical phenomena that may impact it.

Indeed, if the relocation of the corium from the core to the lower plenum occurs through transfer tubes, localized corium jets with velocity of about 10 m/s would penetrate into the cold sodium of the lower plenum . This induces on one hand, a high risk of molten Fuel Coolant Interactions (FCI). These energetic interactions may result in mechanical loads on the vessel structure (in particular when the sodium temperature in the lower plenum approaches the boiling point) and an important jet fragmentation into small debris/particles (Figure 2 left). It is likely that the heaviest particles would eventually settle down and form a debris bed that would self level as sodium around the debris particles will boil (Xu and Cheng, 2022). Moreover, depending on the heat balance between heat removal and power decay, this debris could melt and form a pool.

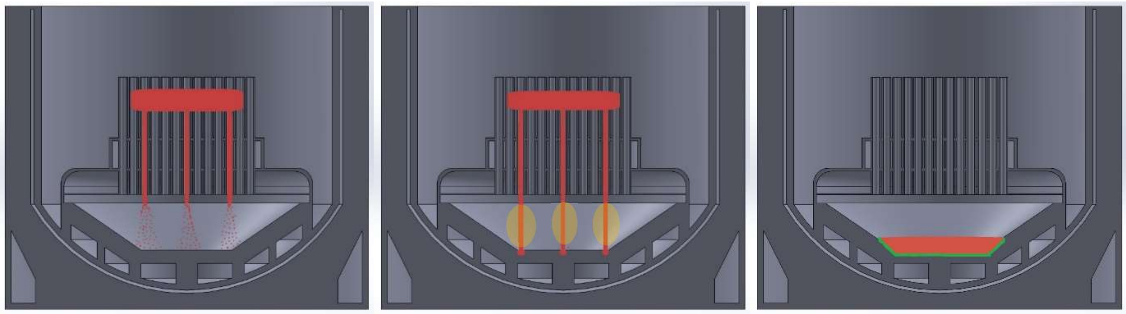

Figure 2 : Configurations of interest for melt relocation above core catcher:
Left: Fuel Coolant Interaction - center: jet ablation of core catcher – right: corium in the core catcher

Another configuration of higher interest for the core catcher integrity is the case of a no-fragmented liquid jet. This would be most probable in the case a large vapor bubble is formed below a transfer tube due to previous heat exchanges between the corium and the sodium which vaporizes; Figure 2 center. In this case, the core catcher upper material can be thermally ablated by the jet and the ablated thickness should be studied to certify the non-drilling of the core catcher (Lecoanet et al, 2021).

Non-criticality must be guaranteed at all stages of relocation. After the end of relocation processes, there will be a debris bed and/or a pool inside the core catcher (Figure 2 right). Due to decay heat generation in the fuel, the surroundings (core catcher, sodium) will be heated. If heat transfer is not sufficient, debris bed may partially or totally melt into a corium pool. Convective heat transfer in a melt pool may lead to some thermal ablation of the core catcher material and should be studied. The heat release from the vessel is provided by a Decay Heat Removal (DHR) system. The heat exchanger could be inside the vessel or through the main vessel. In all cases, convection loops in sodium will ensure heat transfer from the core catcher area to the DHR heat exchanger. Different ultimate cold sources can ensure necessary redundancy and diversity.

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1 Core catcher design history

Core catcher have been first designed for Sodium Fast Reactors before they have been considered for Light Water Reactors. In this section, we are reviewing various designs that have been proposed (and often constructed) during the history of SFRs. This section is divided into two parts, the first one dealing with past projects (from DFR to JSFR) and the second one with ASTRID and its follow-ups, including ESFR-SMART.

1.1 In the past projects

In this section, the core catcher designs from DFR, PFR, SNR-300, SuperPhénix, EFR, BN-800, CDFR, DRF, PFBR, CFBR and JSFR are presented and their main characteristics are discussed. References are also proposed for further information.

1.1.1 DFR (Scotland)

In the Dounreay Fast Reactor (DFR), a "catch pot" consisting of a 1.7-m diameter niobium-sprayed stainless steel "saucer" and "splash plates" had been installed below the core to collect molten or frozen debris (Serre et al, 2013). A conical deflector at the centre was intended to deflect solid debris and prevent critical geometries (Figure 3 - left).

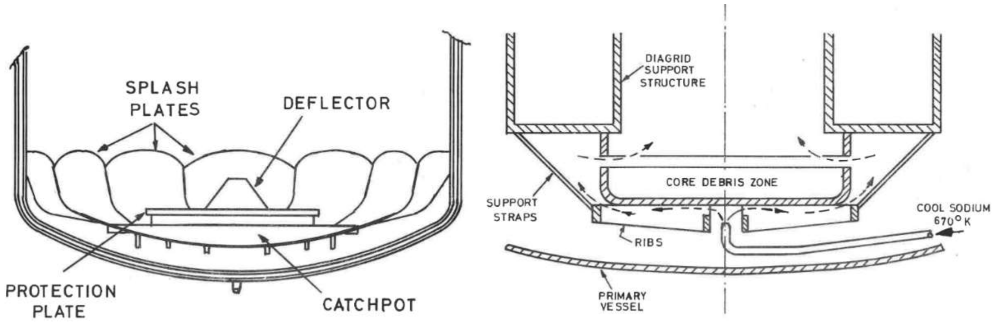

Figure 3 : Design of DFR (left) and PFR (right) core catchers (Serre et al, 2013)

1.1.2 PFR (Scotland)

In the Prototype Fast Reactor (PFR), a 3-m diameter, 35-mm thick flat plate core catcher (Figure 3 - right) had been installed below the core region. It is supported by ribs designed to withstand the large thermal gradient that could occur in case of core relocation. A forced sodium convection has been designed to cool the core catcher underside (Serre et al, 2013).

1.1.3 SNR-300 (Germany)

The external core catcher (Figure 4) was installed below the reactor vessel and guard vessel in the reactor pit (Friedrich, 1977). Depleted uranium had been selected for an eight-cm thick protective layer on the core catcher tray (Mueller & Schulenberg, 1983). The core catcher was dimensioned for the whole material of the core and avoid recricticality thank to the retention crucible. The plateau is protected by bricks of depleted Uranium and cooled by a dedicated system of NaK and an emergency system of nitrogen. Experience from the SNR-300 core catcher indicated that, although an external core catcher has the advantage of being separated from daily reactor operations and avoiding interaction between core catcher material and sodium in normal conditions, it leads to difficulties. In particular, it requests to design the reactor pit and the support systems to withstand both short-term and long-term loadings due to the dropping of molten core, structure debris and sodium in order to ensure the containment integrity, and avoid containment bypasses. It must be noted that the plans for a German follow-up reactor SNR-2 were to implement an in-vessel core catcher (Vossebrecker & Friedrich, 1982).

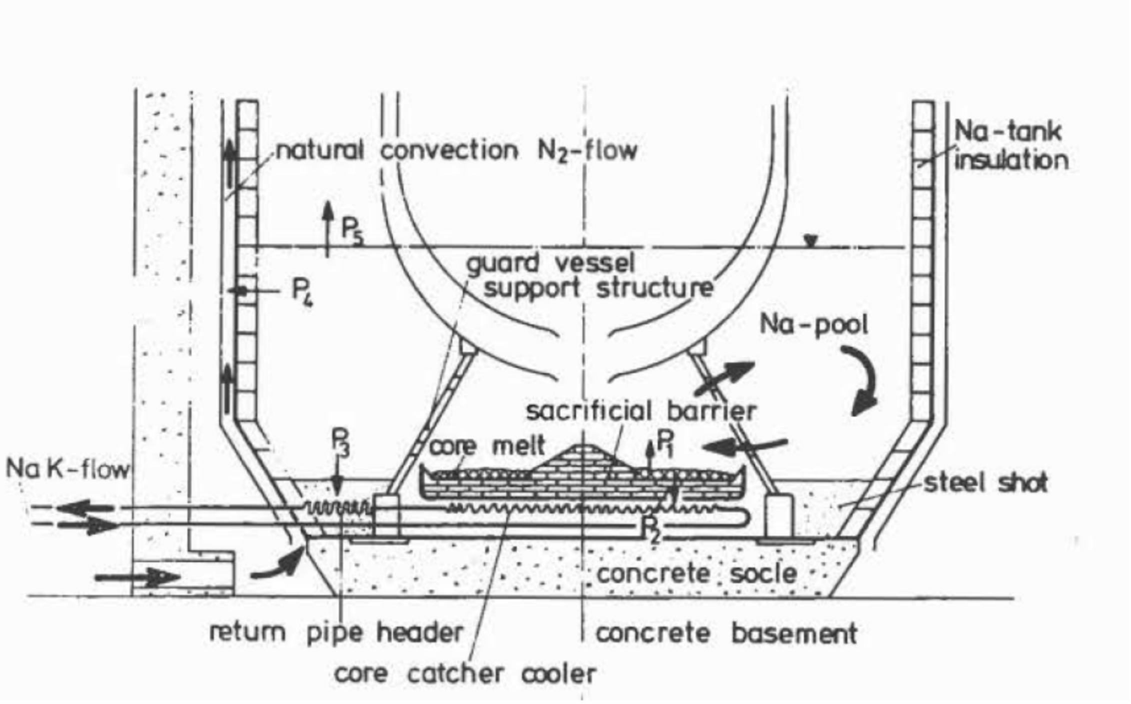

Figure 4: SNR-300 external core catcher (Friedrich, 1977)

1.1.4 SuperPhenix (France)

On the contrary to the Phenix reactor where there was no core catcher, an internal core catcher called ‘debris core catcher’ was installed in SuperPhenix. It was able to collect 100% of core debris. For its design, it was supposed no corium jet but only debris arrival for this design extension configuration. However, the core catcher was sized from a thermomechanical point of view to collect the molten materials of seven fuel assemblies which was the scenario of “reference plausible accident”. It was composed of a plateau of 7 700 mm of diameter with a central chimney of 700 mm of diameter. This arrangement leads, when hot material is on the tray, to the formation of a natural convection loop as depicted in Figure 5 right. The sodium flows below the core catcher from the outer edge towards the chimney and back in the upper volume (Chenaud et al., 2018) where it can be cooled by decay heat removal heat exchangers implemented in the hot plenum of the primary circuit. The plateau is protected by a conic thermal screen in steel not directly on the plateau (a gap is in between). This core catcher weighs 64 t.

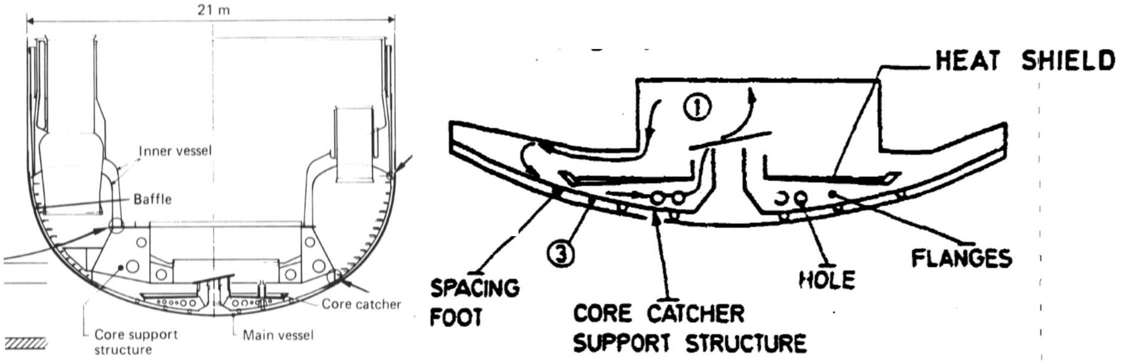

Figure 5 : Superphénix core catcher. Left: position in lower vessel (Broadley et al. 1982)
Right: detailed scheme with sodium flow (Le Rigoleur et Kayser, 1979)

1.1.5 EFR

The internal core catcher is quasi similar to the SuperPhenix one. The objective is to collect the whole core material. The core catcher is installed below the strongback and presents a central chimney with a circular upper plate (Figure 6). A small slope has been designed to promote core debris spreading on the upper plate and to evacuate the sodium vapor from the downside (Polidoro et Parozzi, 2012).

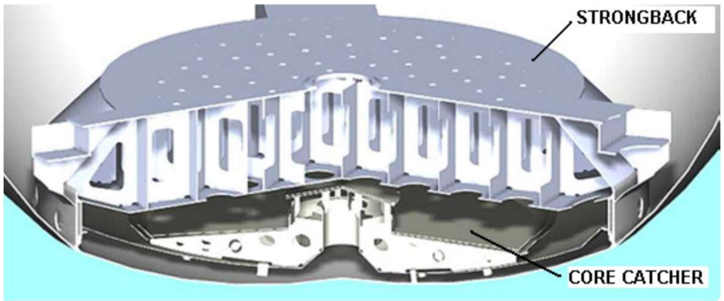

Figure 6 : EFR Code catcher (EFR, 1998)

1.1.6 BN-800 (Russia)

In BN-800 the core catcher has been designed for the safe retention of one fourth of the core assemblies (Rogozhkin et al., 2013). It is also a cylindrical tray with a slight slope towards the periphery and limited by a conical structure number 1 in Figure 7. The tray upper surface is lined with molybdenum. There are 7 chimneys (see elements number 2 in Figure 7).

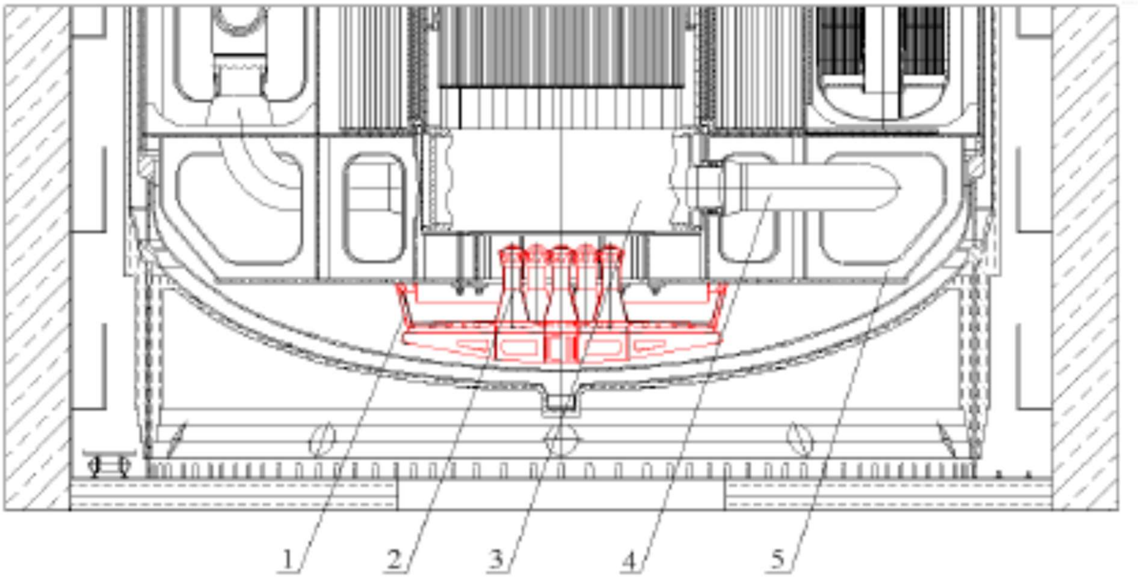

Figure 7: BN-800 core catcher design (Rogozhkin et al., 2013)
1 : cone barrel, 2 : 7 draft tubes 3 : discharge chamber, 4 : pump tube, 5 : support structure

1.1.7 CDFR, DRF, PFBR, CFBR (india)

These types of reactors have an internal-catcher (Bohje et al. 2000) below the core support structure. This is designed for retention of core debris arising out of meltdown of seven molten sub-assembly (SA) based on the SCARABEE tests, which have indicated melt propagation at the most to the neighboring six SA.

For future Indian FBR, Jhade et al. (Jhade et al, 2020) recommend a core catcher with Stainless-Steel-clad sacrificial material layer and Boron carbon (neutron absorbed) filled stainless steel spikes and a central chimney (Figure 8).

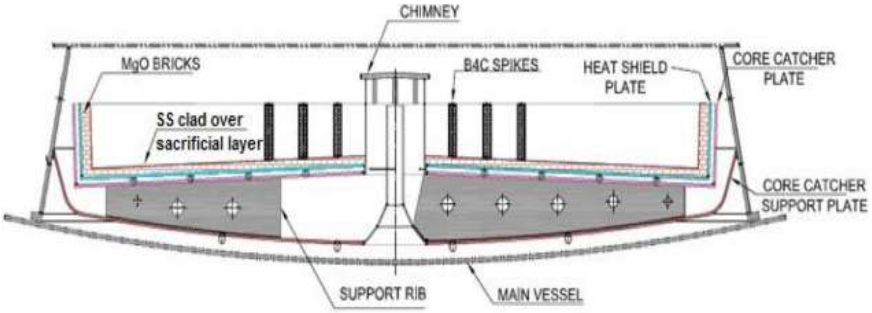

Figure 8 : Schematic of Indian design with sacrificial layer and B4C spikes. (Jhade et al, 2020)

1.1.8 JSFR (Japan)

For JSFR, as loop-type can accommodate a taller vessel. Therefore, for JSFR, an internal multiple tray designed has been chosen. This geometry can prevent critical configuration and enhance the surface to volume ratio, favoring coolability.

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Figure 9 : JSFR multilayered core catchers – Left: sketch of relocation phase – Right: Sketch of DHR phase (Matsuba et al., 2012)

1.2 In the recent projects

1.2.1 ASTRID

During the Conceptual Design phase 1 of the ASTRID project, various designs of core catchers have been studied :

- No external core catcher (i.e. outside of the safety vessel) because of major issues linked to corium and radiological confinement managements.
- Two inter-vessel core catchers cooled by a system integrated to a posed safety vessel or posed safety vessel, which is cooled and protected. However, these designs have been eliminated due to their ‘active’ features; passive systems having been preferred.
- An inter-vessel core catcher cooled by a passive system based on natural convection associated to a posed safety vessel.
- An internal core catcher, under the reactor core under the diagrid and the strongback.

After considering ex-vessel and inter-vessel (i.e. between the main vessel and the safety vessel) core catcher configurations (Serre et al., 2013), an internal core catcher has been selected due to its beneficial feature to mitigate a wide range of accident scenarios from the non-energetic ones (the most probable considering the ASTRID CFV core) and the most energetic ones and because its ability to confine corium inside the reactor vessel. The design (Figure 10Figure 10: Cut view of ASTRID showing core catcher in orange (CEA and AREVA NP Property design; (Chanteclair et al., 2017) includes a tray for the collection of corium either as debris or as melt. It must be noted that this core catcher design does not include any chimney at the tray center.

Mechanical structure shall withstand the highest energetic accident considered (CDA) and external aggressions (earthquake, plane crash…). Lifetime of 60 years, plus post-accident management period is considered in design studies (Chenaud et al., 2018). Firstly, a ceramic sacrificial material had been studied, but ceramics are not sufficiently stable in sodium for the whole reactor life-time and this option was replaced by metallic sacrificial materials, such as molybdenum or stainless steel.

Additional mitigation measures are integrated in the reactor design. In mitigation situation with low mechanical energy, the Decay Heat Removal Systems inside the primary vessel cool down the corium by primary sodium natural convection. In mitigation situation with higher mechanical energy, the Decay Heat Removal System outside the primary vessel also cools down the corium by primary sodium natural convection (Chenaud et al., 2018).

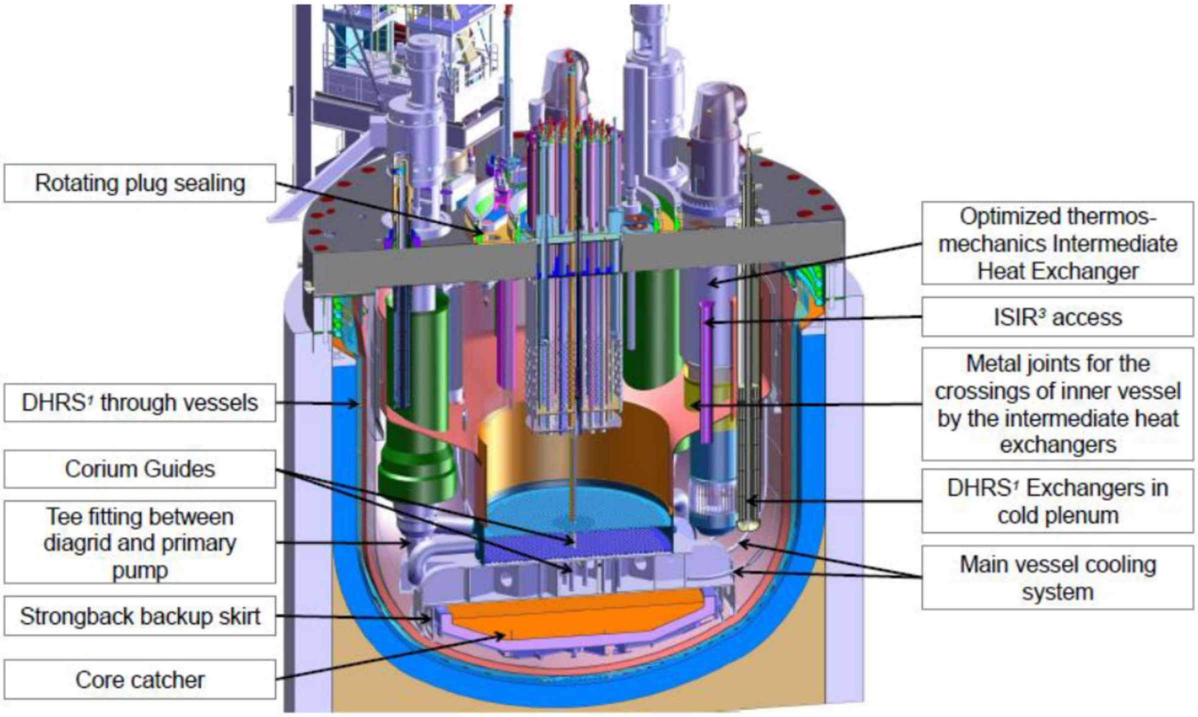

Figure 10: Cut view of ASTRID showing core catcher in orange (CEA and AREVA NP Property design; (Chanteclair et al., 2017)

After numerous studies, the main features of this internal core catcher are:

- A monolayer protective material of molybdenum as reference, or stainless steel as option.
- No cooling chimney and no central cone. The strategy to keep a sub-critical corium relies on the dilution of sacrificial material.
- The core catcher has a flat bottom,
- An anti-flying dish in 316L stainless steel to protect from seismic solicitations and enable the filtration of hypothetical released zirconia debris,
- Optimization of the core catcher support structure.

It can collect the entire core plus the three first rows of the reflector, and the core support structure that amounts totally 57.4 m^3 (356 t), on more than 60m^2, residual power of about 20 MWth at 1h after shutdown

1.2.2 Smaller SFR following ASTRID

Following the ASTRID project, a smaller SFR of power 400 MWth (150 MWe) has been considered in France (ASTRID was 1500 MWth and 600 MWe). In this new concept, the internal transfer tubes have been conserved, although their number has been reduced, as well as the inner core catcher. The following Information comes mainly from internal communications (Bachrata and Bertrand, 2019). Comparison between large-scale and small-

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scale SFRs degradation during ULOF are given in Table 1. The masses provided in the table come from simulations performed in both 2D and 3D with SIMMER-IV SU (Bachrata, 2018) and (Bertrand, 2016).

	Large scale reactor (Astrid)	Small scale reactor
Total fuel mass	~40000 kg (Bertrand, 2016)	~8400 kg (Bachrata, 2018)
Number of Transfer Tubes	21	7
Transfer Tubes diameter (cm)	~16	~16
Fuel mass discharged into Core Catcher	2D: 16000 kg (~40 %) in ~10 s 3D: 9200 kg (~23 %) in ~19 s	2D: 840 kg (~10 %) in ~15 s 3D: 1100 kg (~13 %) in ~5 s
Liquid fuel fraction and fuel mean temperature after power excursion	2D: 16000 kg (~40 %) at ~3500 K	2D: 5500 kg (~66 %) at ~4700 K 3D: Mass not reported, at ~3500 K (3D)

Table 1: Comparison between large-scale and small-scale SFRs in ULOF

The small-scale reactor adopts a design with homogeneous fuel assemblies, which leads to larger power excursions during the primary phase, upwards fuel relocation, and subsequently less fuel relocated into the core catcher (both in absolute value and in proportion). This also explains why the temperature of the fuel is much higher (4700 K vs 3500 K) than in the large-scale case. However, there is also a large difference between 2D and 3D calculations, 3D calculations predicting generally less severe events during the primary phase, and slower relocations. All these studies results highlight that the core catcher design highly depends on the core design.

1.2.3 ESFR-SMART Project

Within ESFR-SMART project, corium discharge tubes are arranged above the core catcher to channel the molten corium from core directly to core catcher. Cylinder objects on the core catcher bottom with conical top endings are installed under these tubes to allow a good dispersion of the corium inside the core catcher (Figure 11) and to mitigate local ablation, during transitory periods. The volume available in the core catcher allows receiving the whole core fissile inventory (Guidez et al., 2022). The cylinders could be, if necessary, replaced by chimneys to improve the natural convection of sodium under the core catcher, flowing through the chimneys (as in the BN-800 design). The core catcher must be equipped with a refractory material for which a number of properties are required: compatibility with sodium (for 60 years), good mechanical resistance during a thermal shock, high melting point, good resistance to ablation under a corium jet, easy to machine or to weld, available, and affordable. Molybdenum had been selected by ESFR-SMART designers (Guidez et al., 2022). The drawback of this material raised lately great concern that the creation of a molybdenum-steel eutectic at a temperature (1450 °C), which is much lower than pure molybdenum melting point (~2600°C). The eutectic could form when a jet of pure liquid steel ablates the core catcher.

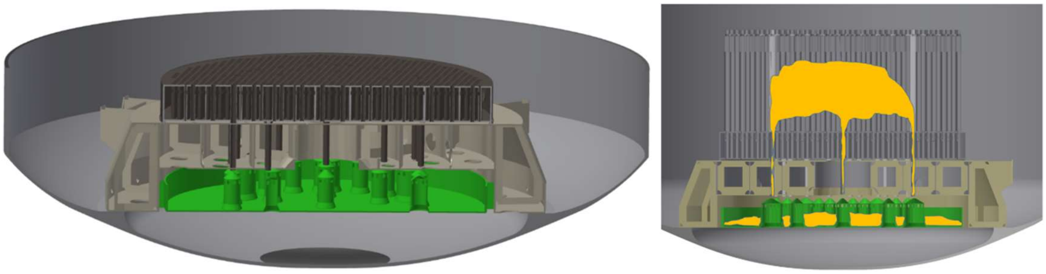

Figure 11 : Views of ESFR-SMART core catcher (Guidez et al., 2022)
(Left: drawing of core catcher within reactor vessel – Right: “artistic view” of the relocation from core region to core catcher through transfer tubes)

Within the framework of the ESFR-SIMPLE project, a core design will be proposed as well as associated innovative measures to preserve the core catcher integrity.

Since the details of this core design geometry been not yet known, propositions of innovative mitigation features will be roughly sketched to analyze its basic concept that can mitigate short term and long term corium ablations. At this very early stage of the project advancement, the above considerations do not account for design-dependent aspects such as the mass of the relocated corium, the nature of the corium or even the number of mitigation tubes. Later on, during the project course, when the core design will be defined, these propositions could be updated.

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2 Propositions of mitigation features

The propositions of mitigation features depending on the considered time scale are divided into short- and long-term events:

- The mitigation features for short-term events aim at preventing the ablation of the core catcher by corium jet. This phenomenon occurs during the corium relocation period from the core toward the core catcher via the corium transfer tubes that are assessed within 15 sec for a small scale reactor (See Table 1)
- Regarding long-term ablation, no additional mitigation measures are proposed but the consequences of the previous short-term mitigation features are evaluate to assess the core-catcher robustness. This evaluation is done on the long-term cooling which starts as soon as a large amount of molten material mass is relocated into the core catcher. The ablation of the core catcher structure due to convective heat transfers inside the molten pool should be studied in details.

Furthermore, from past reviews on existing core catcher designs the corner stone of the innovative measures which are the chimney design and the basic material of the core catcher have been discussed. As the size of the ESFR-SIMPLE reactor would be probably small compared to the other project described in previous section, the option of a central chimney on the core catcher has been eliminated. The arguments that support this choice are the following:

- Cooling by chimney effect works by natural convection: if cold sodium, from beneath the core catcher, flows upwards, it is warmed up (that cools the sodium down). Since the chimney design becomes a high safety issue for the integrity of core catcher, the cooling effect of the chimney effect should be studied carefully. The balance between the potential mitigation effect and the high risk in case of its malfunction must be carefully considered.
- If a chimney feature is considered on the core catcher, studies should be carried out to insure that no corium could flow through the holes of chimney to the outside of the core catcher, e.g. as a result of the ablation/molten down of chimney or just because the density difference between corium and liquid sodium.
- The temperature of sodium inside the chimney and in the ambient shall be carefully assessed to judge whether an upward flow of sodium can really occur in the accident situation.
- To evaluate the beneficial contribution of the chimney, the heat removed by this mitigation device should be compared to the heat removed at the border (essentially upper surfaces) of the pool. The pool natural convection should be very efficient to transfer heat flux at the pool boundary towards the sodium. It is comparatively doubtable that the chimney would have a decisive better cooling effect.

Concerning the core catcher material, bearing with the point view of water cooled reactor that a protective ceramic layer (like ZrO_2), either pure or in a metallic casing, could have advantage to withstand melting process, ceramic material has indeed drawbacks in sodium cooled reactor. The mechanical stability of this ceramic in contact to sodium during the lifetime of the reactor (~60 years) is difficult to demonstrate. Due to its dissolution in sodium, e. g. in case of degradation (e.g. by scratching) of the metallic casing envisioned to protect the ceramic from sodium, the sodium of the primary circuit would be polluted. It must be reminded that it would be impossible to replace any part of the core catcher and its support structures once they have been installed. That is key argument that metallic protective layers are considered. In case that a ceramic layer envisaged under few centimeters of a metallic layer, it raises a new issue on the durability of the bonding between these layers. In this case, a neutron absorber material, such as hafnium oxide might be added to the ceramic layer in order to better manage the recriticality (alloying the steel with metallic hafnium is another possibility for this issue). Another important point, which is not discussed in the following sections is the mechanical resistance of the ceramic or duplex layer core catcher as well as its supporting plate on the mechanical load originated by Fuel Coolant Interaction (FCI). As the chemical and physical instabilities of such material combination are complex and depend on the relocated corium mass and the core catcher geometry, their knowledge are not available in the current stage of the project. Thus, this study only treats a simple case of a pure metallic core catcher. This issue could be addressed later on during this project.

2.1 Prevention of core catcher ablation in jet configuration

Considering the mitigation of short-term events, the innovation features should minimize the core catcher ablation following a corium jet impingement from the transfer tubes as well as be beneficial against the long term ablation by a corium pool

2.1.1 Context

On the course of the accident, the corium jets coming out of the transfer tubes encounter the initially cold sodium in the lower plenum and undergo FCI (Fuel Coolant Interactions which are fast Na vaporizations, even explosive) (Armstrong et al., 1971), (Magallon et al., 1992). Indeed, this vaporization leads to pressure wave propagation and jet destabilization and fragmentation. This process increases the heat transfer and induces mechanical loads on the structure. A related safety criteria shall count this mechanical energy release. Many of the SFR safety evaluations consider currently decoupled thermal and mechanical safety issues. The thermal issues include the core catcher thermal strain due to a hot jet impact and, in the longer term, to the evacuation of the pool thermal power and its cooling. The mechanical issues, in short term, are related to the mechanical strain of the core structures due to the pressure peaks induced by the FCI. The raised issues related to the evaluation of the mechanical energy on the vessel structures are currently only treated by assuming simplified extreme conditions cases (i.e involving large masses of corium and sodium in interaction issued of the simulations of postulated very severe accidents). The vapor pressure and volume evolutions are calculated in order to derive the mechanical energy. In the future, these evaluations should be made more precise.

As no core design is specified (and thus no mass transfer) at this point of the ESFR-SIMPLE project, only the thermal issues (and not the mechanical energy) will be treated in the following.

So, if we resume the course of the accidental transient, after the first FCIs occurrence, the sodium is vaporized in the lower plenum and the pressure is high, temporarily preventing sodium liquid from flowing back inside this plenum. Thus, concerning the risk linked to the jet impact, the more unfavorable case regarding the core-catcher ablation and thus the safety is coherent impingements of corium jets on the core catcher, without been perturbed and fragmented by subsequent FCIs. Moreover, depending on the accidental scenario, and more precisely its kinetics, the corium composition would be different. In case of fast kinetics

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accident, the flowing corium might be rather composed on mixed fuel and steel, whereas in case of slow degradation kinetics, the lighter steel might be relocated before the heavier fuel, because phase decantation had time to take place inside the core before the transfer tube failure and opening.

Regarding more precisely the jet impingement issue, the jet destabilization and fragmentation before its arrival on the core catcher bottom plate are the more relevant topics. Earlier studies have shown different fragmentation and pressure increase mechanisms between UO2 melt and steel melt in contact with liquid Na (Armstrong et al., 1991), (Johnson & Journeau, 2020). Steel jet induces smaller energy increase than UO2 does, however the pressure increase of FCI with steel jets occurs immediately after the melt release, where a large delay on the pressure increase occurs in UO2 jet. The fragmentation seems to be lesser when the contact temperature of melt and Na is lower than the melting point of melt due to the formation of a stable crust.

Indeed, there are contrary effects between:

- Increasing the jet fragmentation reduces the jet coherency and thus thermal loads (by jet impingement) on the core catcher but increases the FCI which in turns increases the mechanical loads on the core catcher;
- Reducing the jet fragmentation and promoting its coherence, will reduce the mechanical loads on the core catcher due to FCI but increase the thermal loads due to jet impingement.

So to assess the safety and the related integrity of the core catcher, it seems important to have more knowledge and models on FCI. But it is very difficult to model the preliminary 'interaction zone' which highly depends on the masses of corium and sodium in contact, the size of the particles, and so on… The mechanistic model of Cho et al. (Cho et al. 1972) is widely used but highly depends on this mixing in the first interaction zone. CEA is developing the SCONE code for a mechanistic model of the whole FCI processes in sodium. In particular, it requires new experiments to be carried out in its future newPLINIUS experimental platform. So, because it is a very complex phenomenon and requires dedicated complex experiments, it is not proposed to experimentally investigate them during the ESFR-SIMPLE project. Others approaches to reduce the risk of degradation of the structures and core catcher, others than increasing the FCIs will be studied.

2.1.2 Proposed mitigation concepts

In the first approach, a plug with open lateral windows (Figure 12) at the bottom of each transfer tube was considered. The goal was to disperse the corium jet and so that to reduce its kinetics energy on the core catcher. However, it is predictable that some corium debris might block these windows and prevent the corium from flowing downward. Considering such device will thus further complicate the safety demonstration. For this reason, it has been preferred to consider open-end transfer tubes.

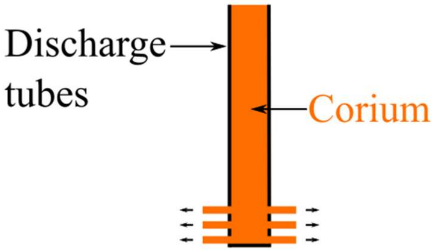

Figure 12: envisaged plugs with windows at the lower outlet of the transfer tubes

The innovative measures shall be then reinforcement pods installed on the core catcher.

2.1.2.1 Solid pods below the jets

A proposition to reduce the thermal loads on the core catcher, due to coherent jet impingement, would be solid pods located on the core catcher surface. The shape and state of the pods upper surface would be designed to promote the pool effect[1] which leads to a reduction of the ablation velocity (Lecoanet et al., 2021 b) (Figure 13). Several geometries have been proposed to withstand the core-catcher melting process (Figure 14).

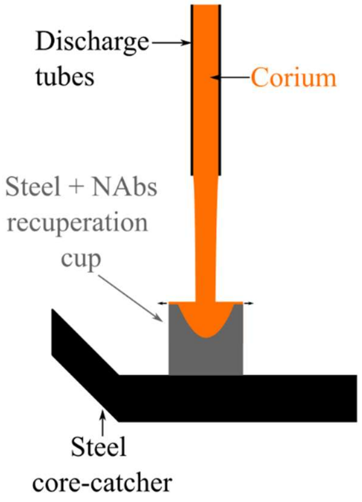

Figure 13: envisaged pods with a curved surface.

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[1] During ablation of a solid structure by a liquid jet, the liquid exits the cavity its digs into the solid as a liquid film during the first stage of ablation (this is the film regime), then when the cavity is deep enough the liquid film collapses and the cavity becomes filled with liquid (this is the pool regime). In the latter configuration heat transfers may be reduced. (Lecoanet et al. 2021 a&b)

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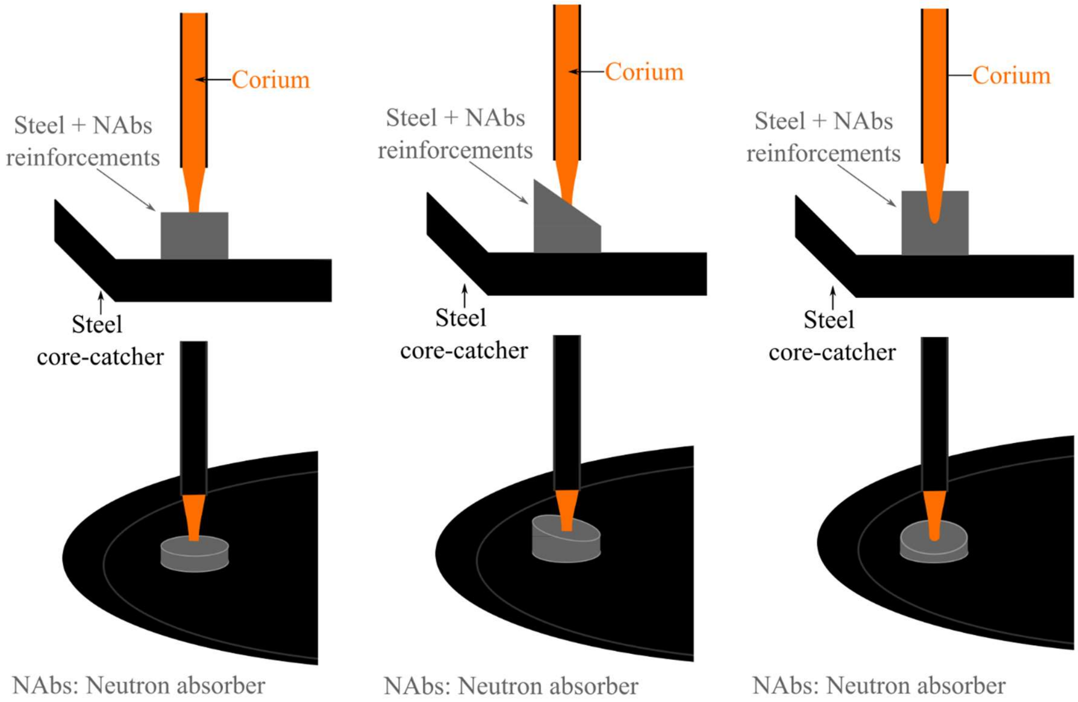

Figure 14: Propositions of flat reinforcement pods (top left) and inclined reinforcement pods with two different orientations, toward the center (top right) and toward the azimuth (bottom)

These designs implement metallic reinforcement pods which may contain additive neutron absorber materials (for example Hafnium) under discharge tubes to protect the core catcher. As the pool effect may slow down the ablation process, their height and diameter should be large enough to early allow the apparition of the pool effect regime during their ablation by an impinging jet. In a first order of magnitude (which will be detailed as soon as the final core design will be released), the height and diameter of these pods should be of at least 5 to 8 times the jet diameter. More details on the corium flow coming from the transfer tube is needed to give a better estimate using modelling represented in Lecoanet et al. (Lecoanet et al. 2021 a). These pods size will be defined by the core design.

2.1.2.2 Proposed shape and state of pod surfaces

Several options regarding their upper surface shape and state could be investigated following literature results. Upper surface of these reinforcement pods could be flat, inclined or curve like a hole of sufficient height to promote pool effect.

Furthermore, due to the very high temperature of the jet (~2000K) the lateral surface of this pods may finish to melt like observed in JIMEC experiments during the ESFR-SMART project, enabling the corium to flow down on the core-catcher. In this configuration, on arrival, the corium on the catcher would have a small inertia that would not more jeopardize the core-catcher.

The possible design improvements of these pods, which would be experimentally studied during the framework of the ESFR-SIMPLE project by the LEMTA team, are related to the size and the shape and state of their upper surface.

The effects of the shape of this upper surface could be studied. A priori, an inclination directed towards the inner part of the core catcher will concentrate the fuel and may lead to recriticaticity issues whereas an inclination towards the core vessel would lead to corium outwards projection, which could jeopardize the structures. A curve surface (with a certain height) could concentrate the fuel and enhance the pool effect. Finally, a slope surface towards more tangent direction than the center could be envisioned. The ablation of thick solid with an inclined surface has rarely been studied, and it should be done through experimental tests performed at LEMTA in comparison to a flat upper surface. The length and intensity of the corium projections should be characterized as well as the effects of the surface inclination on the pool regime transition. Some authors suggested that the slope of the impacted surface may increase the ablation velocity (Furutani et al. 1991).

In addition, as the core-catcher will remain decades in sodium, its surface state could not be very well known and controlled. Indeed, during fuel coolant interactions, some solidified corium droplet (i.e. debris) could be deposit on the surface or locally ablate the surface and modify its state making it rougher. Another parameter, namely the surface state may play an important role on ablation velocity (Lecoanet, 2021 c). So it could be studied by considering various states of upper surface of these reinforcement pods. Furthermore, it might be interesting to have a certain part of the pod that is faster ablated (for instance to deliver some neutron absorbing material). Thus, the influence of the surface state on the ablation phenomenology should be understood and be modelled with the aim at taking advantage of it in the design of mitigation features.

The proposed experimentations on the inclination and roughness of the pod surface will be supported by preliminary global ablation evaluations using correlations issued from literature. This work will be carried out as soon as the core design will be released. Indeed ablation kinetics depend on the nature of the corium, which could be estimated, at first insight from literature review, composed of 70 to 100% of fuel and 0 to 30% of steel. But as already said, it is difficult to predict which material, or mix of both, would firstly reach the core catcher. Thus diverse configurations of materials jets will be studied. However, the most penalizing case, regarding the ablation velocity, is the ablation of a material with a jet of the same composition. As the core catcher would probably be metallic, the most penalizing case is with steel jets. In case of oxide fuel jet on a metallic core catcher a protective crust is created at the interface reducing the jet ablation velocity (Saito et al. 1990, Lecoanet, 2021 c). Furthermore, this is a tough issue because this crust stability is not insured and should be studied. This will not be done during the framework of the ESFR-SIMPLE project but would be worth to be studying in the future. As a first estimation, Sato's *et al.* (Sato et al, 1991) correlation will be used if the metallic phase of the corium impacts the core catcher (metallic itself). On the contrary, if it is the oxide phase of the corium that is relocated, the ablation will be studied thanks to the *Saito's et al*. correlation (Saito et al, 1990). Likewise, the number of discharge tubes and their design themselves will be settled during the project developments.

Another issue is the melting of the lateral wall of the cup which should be studied in the long term (see paragraph 2.2). Also recriticality issue induced by the confinement of the corium within the pod should be keep in mind and might be studied for the final pods design.

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2.1.3 Proposed jet experiments during ESFR-SIMPLE project

During the PhD of Alexandre Lecoanet, LEMTA laboratory designed and built a new experimental facility named HAnSoLO (Hot Ablation of a Solid by a liquid jet – Observation). This set-up, although quite simple, allows the visualization of the ablation of a solid (transparent ice) by a liquid jet (hot liquid jet of water). The analysis of pictures coming from a high speed camera allows the estimation of the ablation velocity (by capturing the deepest position of the hole) and further the calculation of the heat transfer (also at that critical point). A complete analysis of the cavity formation process is also available and can be used for CFD code validation.

In this project, LEMTA team will study the ablation of different configuration of the proposed pods varying the inclination/shape of their surface as well as the effect of its initial state. A recent work done at LEMTA (not yet published) shows that heat transfer can be critically increased by some rough sate but this phenomenon is not completely understood and should be further analysed. Using HAnSoLO facility, the surface state could be shaped quite easily. For that, aluminium pads for indenting the ice blocks can be used. The pad would be a 4 or 5 cm square with cylinders of different heights, different diameters and also different centre to centre spacing. This type of tests varying the surface state of the pods are still in discussion.

A preliminary test matrix of tests is under discussion and will be refined and completed in the future. The proposed conditions are close to the ones studied in A. Lecoanet’s thesis which would be taken as reference for comparison purpose. Range of parameters are representative of industrial cases.

2.2 Prevention of thermal erosion in pool configuration

Based on the knowledge of the LIVE-CC experiments on the long term ablation of a core catcher by a corium pool in the ESFR-SMART project without the local reinforcement as described in the previous paragraph, the long-term ablation test in the frame of this new project ESFR-SIMPLE will focus on the influence of ablation cavities, resulting from the short-term jet impingement on the core-catcher, or the presence of the reinforcement pods inside the corium pool on the long term ablation of core catcher.

2.2.1 Long-term behaviour of an ablated cavity in core catcher

Long-term ablation of a core catcher occurs when a large corium pool is formed in the core catcher in which the decay heat maintains or increases the pool temperature to the extent that the core catcher wall is gradually molten and eventually lose its integrity, when the cooling capacity of liquid Na on the top and on the external wall boundary is less than the decay heat power. The LIVE-CC experiments were designed to examine the ablation characteristics of such a pool. The height scaling is 1:1 and radius scaling of 1:10, the simulant material is the eutectic KNO3-NaNO3 mixture, so that the Ra number is fully representative to the oxide corium in prototypical case. The experiments performed in the frame of ESFR-SMART project have shown a strong cooling efficiency at the upper surface. The highest heat flux on the core catcher wall is always near the melt upper surface.

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The experiments in the ESFR-SIMPLE project has one of the objectives to study in what extent the ablated cavities influences the core catcher safety. Assuming that the jet impingement on the core catcher during the short term transient creates local cavities on the core catcher bottom plate, (Figure 15), the long-term issue of the local cavity will be an interesting topic for the answers of whether the cavity on the core catcher bottom could be more vulnerable location of the whole core catcher. Could the cavities be filled gradually by the corium solidification due to the bottom cooling of Na? Or enlarged by the decay heat inside the corium? What is the time scale of the solidification or further ablation?

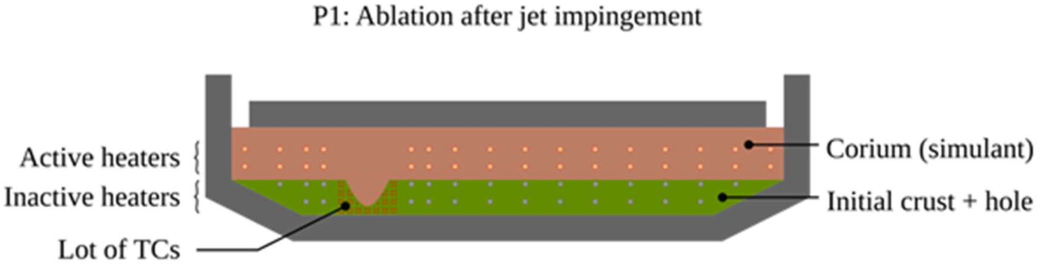

Figure 15: scheme of the core catcher with an local cavity

2.2.2 Long-term ablation behaviour with pods

The second proposed type of experimental studies is related to the presence of the reinforcement pod which has been proposed for short-term mitigation and whose presence would have an influence on long term cooling, especially corium flow circulation and the related heat transfers. If the solid pods remain intact or are not completely eroded during the short term period, how they influence the local and global flow of corium? When it is gradually melting, how does the melting process positively mitigate the recriticality of molten material by the gradually addition of absorbing material in the molten pool, and evolution of the fraction of liquid metal in the corium and the temperature in the whole pool concerning the contribution of the latent heat. The melting of the pods is in this point of view also an innovative measure for the long term ablation.

2.2.3 Proposed long-term cooling experiments in LIVE CC facility

The long term ablation experiments in LIVE-CC facility will investigate the phenomena described in Section 2.2.1 and Section 2.2.2. Three test configurations are foreseen:

- LIVE-CC cavity
- LIVE-CC non-melting pods
- LIVE-CC melting pods

For all the three test configurations, eutectic nitrate salt of KNO_3-$NaNO_3$ with the melting temperature of 220 °C will be used as simulant melt and also as the simulant of bottom plate of core catcher. Irregularities at two local positions with a diameter of about 80 mm for each one will be created. The irregularities are either cavities in a bottom nitrate salt crust simulating the core catcher bottom plate, or cylinder pods installed or created on the core catcher bottom plate. For the non-melting pod material, stainless steel will be used. The experiment with the

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non-melting pods aims to understand the heat transfer process inside and in the vicinity of the pods. For the melting pods, solid cylinder block of nitrate salt with the same composition of the liquid salt will be used. The ablation kinetic and its global influence on the temperature and heat transfer will be measured.

The height of the pods, the number of temperature instrumentation inside and near the irregularities are under discussion within the partners in this task. Also the power level and the boundary cooling conditions are to be defined during the Subtask of 6.2.3: LIVE-CC experiments on core catcher long term ablation. The experimental data will be simulated by numerical codes in CEA, which could be enable to extrapolate the heat transfer and ablation behaviour in the prototypical core catcher.

Conclusion

Designing a new SFR reactor, it is essential to account for the consequences of a hypothetical severe accident very early in its pre-conceptual design phase in order to reduce them as much as possible. In case of hypothetical severe accident, the reactor ultimately melts down and the degraded corium releases a decay heat that must be evacuated on the short and long terms to preserve the containment of the radioactive materials.

To ensure short-term control and retention and long-term coolability of this corium, dedicated mitigation devices are included inside the core. One of them, called the “core catcher” aims at collecting the molten or debris materials (including the fissile material) and spread them to better insure its coolability and avoid a neutonic recriticality.

This report deals with the proposal, within the framework of the design a new SFR reactor for the ESFR-SIMPLE project, of innovative mitigation features related to the core-catcher integrity. To propose such new features, past core-catcher design history has been summarized. Then, based on this knowledge, innovative features have been discussed between KIT, LEMTA and CEA. However, regarding that, at this very beginning stage of this project (which has started 4 months ago) the core design is not fully defined and owing to the little time period allows to this work, not all the important issues could have been treated in depth. Indeed, if more time and means would be allocated, very tough but important subjects such as Fuel Coolant Interaction occurring during the corium jet impingement, the natural convection around the core-catcher with a chimney or the presence of a protective material layer (the choice of this material and of the deposit method for this layer)… would have been worth studying experimentally. However, some new mitigation features have been proposed that are experimentally accessible during the course of this project to promote the beneficial effect of some phenomena that can be taken advantage to insure the core-catcher integrity. This is the case of the pool effect at the corium jet impingement on the core-catcher (already revealed by the former JIMEC and HANSOLO experiment) which slows down the core-catcher ablation. It has thus been proposed to promote this effect on pods located directly under the transfer tubes to better protect the core-catcher from ablation. The influence of the inclination or shape and roughness of the upper surface of these pods are of primary interest to control the pool effect appearance. With this objective, representative experimental tests are proposed by the LEMTA. They will be carried out during the course of this project in order to confirm which pod design would be the best to promote the pool effect. This work would be performed during the subtask of 6.2.2 of the project. Furthermore, such addition of pods on the core catcher, which would be partially ablated during the short-term corium relocation, would have then an influence on the corium long term cooling (mainly by influencing the corium natural convection flow and its related heat transfers or by inducing preferential crust formation). This second issue, related to long-term cooling, will be studied by the KIT through various experiments in the LIVE facility. This work would be performed during the subtask of 6.2.3 of the project. Various preliminary mitigation solutions were proposed by several project partners during the discussion but have not been fully evaluated them during the time allocated to this task. This will be done in the future within the framework of ESFR-SIMPLE project.

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