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# A NEW EXPERIMENTAL R&D PROGRAM ASSOCIATED WITH THE CORIUM JET IMPINGEMENT ON THE ASTRID CORE CATCHER SACRIFICIAL MATERIAL

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*The strategy used in ASTRID Sodium Fast Reactor Demonstrator to mitigate the consequences of a postulated severe accident relies on the presence of dedicated corium discharge tubes between the active core region and the lower plenum and an in-vessel core catcher in the lower plenum to collect and cool the molten fuel. In this situation, the corium progression from the core towards the core catcher could lead to jet impingement on the core catcher surface and a subsequent degradation of the core-catcher material(s). After a review of the existing experimental database, it appeared necessary to define a dedicated experimental R&D program related to the long-lasting jet impingement on thick material plates. A particular behaviour will be studied when a molten pool is created (named “pool effect”) at the impingement point that reduces the heat transfer at the jet-material interface. In this scope, experimental tests with simulants and prototypic materials will be carried out by using the most possible representative conditions (e.g. Reynolds and Prandtl numbers) for ESFR (European Sodium Fast Reactor) severe accident conditions. Three R&D program have been proposed:*

- (i) Ice-water jet impingement, the few results in the literature show a good agreement between ice-water jet system and metal wall/metal jet system which justifies the use of such simulant materials for investigating the impingement behaviour. The JOLO facility will be designed at LEMTA Nancy University.*
- (ii) Molten steel jet impingement on the thick wall. The MOCKA facility in the Karlsruhe Institute of Technology will be used.*
- (iii) Dedicated test section PLINIUS-2 IMPACT will be designed in future PLINIUS 2 large-mass prototypic-corium experimental platform at CEA Cadarache.*

*First experiments have been carried out in the JOLO facility and provided dynamic ablation data before and during the formation of the pool. Additional JOLO tests and the MOCKA tests will be carried out in the frame of the ESFR-SMART European project starting by the end of 2017.*

*The MOCKA tests will be performed with steel at higher temperature than in JOLO, before running core catcher qualification tests with prototypal corium (depleted UO<sub>2</sub> and steel) and the ASTRID core catcher selected materials in PLINIUS-2 platform.*

*New correlations and models will be developed from the experimental results in order to estimate the heat transfer data between the jet and the impacted material taking into account the “pool effect” phenomenon.*

## I. Context

In France, in 2006, in the framework of the law on sustainable management of radioactive materials and waste, a coherent program towards the development of a 4<sup>th</sup> generation sodium-cooled fast neutron reactor was set-up. A collaborative R&D program was launched between CEA, AREVA and EDF, focusing on innovations derived from the experience of Sodium Fast Reactor (SFR) at French and international level. At the end of 2009, in a broader investment plan for the future, ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration, Ref. 1 and 2) was identified as one of the priorities to receive governmental funding. In 2010, the finance law put into place the multiannual budget for the ASTRID program. The CEA and its partners have been tasked with designing the reactor, taking into account of

the stringent safety requirements meeting generation IV requirement, and paying particular attention to the potential for a severe accident involving the partial or total meltdown of the reactor core, as later happened at Fukushima Daiichi (4<sup>th</sup> level of defense-in depth).

The main R&D safety focus areas for the ASTRID project in terms of severe accidents are as follows:

- Core meltdown accident prevention: to design a core with an optimum low void coefficient with the addition of complementary safety devices for severe accident prevention
- Additional complementary safety devices for severe accident mitigation to maintain the reactor in a stable safe state, even in the event of a control rod drop failure

The severe accident mitigation for the ASTRID reactor aims at maintaining the second barrier (Ref. 3) by taking into account the following events: core degradation, melt progression towards the core catcher, ablation of core catcher sacrificial materials by molten corium, energetic Fuel-Coolant Interactions (FCI), structure mechanical behavior during FCI, containment behavior, and fission production release and transport.

## II. ASTRID core catcher qualification needs

The severe accident mitigation for the ASTRID reactor is based on priority routes (see illustration in Fig 1) for the molten fuel that are designed to control its relocation in sub-critical and coolable configurations. For this reason, the CEA has recommended two important mitigation concepts:

- Discharge channels (DCS-M-TT: Complementary Safety Device – for Mitigation – Transfer Tubes; see Ref. 2) to carry the molten fuel away from the core region, thus reducing the risk of prompt criticality and mechanical loading. These channels are located in the core in the form of empty fuel sub-assemblies, filled with sodium (three in the inner zone and eighteen on the outer perimeter). These sub-assemblies are extended below the core by tubes (~80 mm for the shortest internal diameter) which pass through the diagrid/strongback leading into ASTRID's lower head in order to channel the molten fuel towards the core catcher.
- A core catcher in the vessel lower head to collect the corium and remove its decay heat (Ref. 4). The design of the core catcher and its protective material are being studied in order to

comply with the technical specifications<sup>1</sup>. It should be noted that ASTRID Core catcher materials defined during the Conceptual Design phase are under review and must be updated during the Basic Design phase.

The robustness of the safety case relies on the qualification of these components and on the use of assessed simulation tools by means of experiments (in-pile and out-of-pile, more or less integral or separate-effects experiments) using prototypic materials and simulants, in order to understand the physics and validate the related computational tools. With regard to the corium progression during the course of the accident, the CEA will partially rely on a wide range of experiments carried out in the past to support the safety cases of SPX or EFR in particular. However, the phenomena depend on the design to be taken into consideration and the materials used and conditions applied. The safety requirements have also changed, requiring greater control of uncertainties and in particular demonstration of extrapolation to the "reactor" case. This involves ensuring that all the significant phenomena and their interactions are covered, and checking the cliff edge or scale effects.

The ASTRID design therefore includes provision for discharge tubes for the molten fuel (i.e. corium) to be installed as complementary devices for severe accident mitigation in the ASTRID core to transfer the corium quickly from the core to the core catcher in the vessel lower head. The jet of molten fuel discharged from the tube could impact the structures of the ASTRID core catcher under certain conditions. The scope of R&D program proposed here is to study the impact mechanism of a jet of oxidic or metal corium on the surface (metal or shielding structure) of a core catcher to support the ASTRID core catcher design and the safety demonstration.

The impact of coherent jets of corium or simply the arrival of debris on the core catcher is difficult to predict

<sup>1</sup> Technical specifications of the ASTRID core catcher:

- Can fit all the relocated fuel and structural materials
- Optimises the management of criticality
- Cools the corium and removes its decay heat
- Protects the support structures of the core catcher from thermal and energy shocks
- Performance of the core catcher maintained despite the possible impact of a corium jet
- Delays the heating of the sodium and prevents a departure from nucleate boiling (film boiling)
- Core catcher material compatible with Na under normal operating conditions
- Cost, manufacture and forming of a core catcher.

with current calculation tools. If there is complete fragmentation of the jet (jet breakup length < way in the sodium) after it exits the DCS-M-TT, the jet impingement does not occur. If there is incomplete fragmentation of the jet (jet breakup length > way in the sodium) exiting the DCS-M-TT, a coherent jet could induce significant core catcher ablation due to the very high heat exchanges.

The past experimental data evaluating jet breakup length in sodium do not cover the range of expected ASTRID conditions. FARO-TERMOS (Ref. 5) experiments using a hundred kilograms of corium, have shown that corium jets (diameter: 50 mm, 80 mm) did not penetrate beyond 1 m in sodium. However, the initial temperature of the subcooled sodium (about 400°C in TERMOS) is expected to be a key factor during interaction phenomena, so experiments have to be performed at higher coolant temperatures to assess missing data in order to cover all possible situations involved in the ASTRID scenarios.

The identification of the severe accident events associated to the core catcher design showed that jet impingement and corium/sodium interaction are high-priority issues for which there is very little data. The review by Ref. 6 deplored the lack of consensus on fragmentation models or even on the hierarchical organisation of the phenomena. Little progress has been made since then. In the past, the phenomenon of the jet impingement has mainly been studied in relation to the interaction of metal or oxide jets on a relatively thin, planar wall in the context of safety studies for pressurised water reactors. Results from the literature (see Ref. 7 to 11) are insufficient to design the protective materials of the ASTRID core catcher which would have to be thicker to protect the metal structures from the effect of the corium jets. Besides, a few studies show that when the depth of the cavity created by the jet exceeds a few times its diameter (by a factor of ~ 4), the ablation is slowed by the presence of liquid in the cavity created by the ablation of the material. This phenomenon, which is referred to as the "pool effect", was evidenced by (Ref. 7) and is currently poorly modelled. The study of this phenomenon is a high priority for our situations in which the jet flows through pre-determined openings for long discharge times.

It is worth noting that very few experimental tests with prototype oxide materials (with a jet temperature over 2000°C) exist in the literature. It is important to point out here that extrapolating the results found in the literature obtained using simulants to ASTRID conditions is the source of significant uncertainties. The mechanisms leading to ablation of a thick, non-planar wall (made of metal or other material) by a prolonged high-temperature

liquid jet need to be studied in detail to quantify the ablation kinetics and qualify the design of the ASTRID core catcher. This ablation occurs when the temperature of the jet is higher than the melting point of the wall in question. The complexity of this problem lies not only in the fact that the physical phenomena which come into play are, by their very nature, multi-material, multi-phase and multi-scale, but also in the sheer difficulty of conducting experiments with nuclear fuel.

In addition, for jets (e.g. corium oxide) with a melting point greater than the melting point of the wall in question (e.g. a metal wall), the ablation rate decreases considerably when a crust layer forms at the jet impact point (see Ref. 7, 10 and 11). The stability of this crust layer is not known and depends on the cycles at which it forms and collapses and on its (unknown) mechanical and wetting properties. Some authors (including Ref. 7 and 8) propose to tackle this issue from a heat transfer perspective with a stable crust in steady state, however the validity of this approach has not been confirmed. Hence we are also proposing to study this phenomenon in our R&D program.

A large experimental phase will be assigned to this phenomenon to coincide with the recently-started ESFR-SMART project and the future PLINIUS-2 platform (see Ref. 12 and 13). To meet the ASTRID safety requirements, a 3-phase<sup>2</sup> experimental program was planned:

- (i) Water jet impingement on the ice. The JOLO (Jets Of Liquid Observation) facility will be designed at the university of Lorraine (LEMTA).
- (ii) Molten steel or simulant oxidic jet impingement on a thick wall. The MOCKA facility in the Karlsruhe Institute of Technology will be used.
- (iii) Dedicated test section PLINIUS-2 IMPACT will be designed in future PLINIUS 2 large-mass prototypic-corium experimental platform at CEA Cadarache.

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<sup>2</sup> The first two phases are part of the ESFR-SMART European project

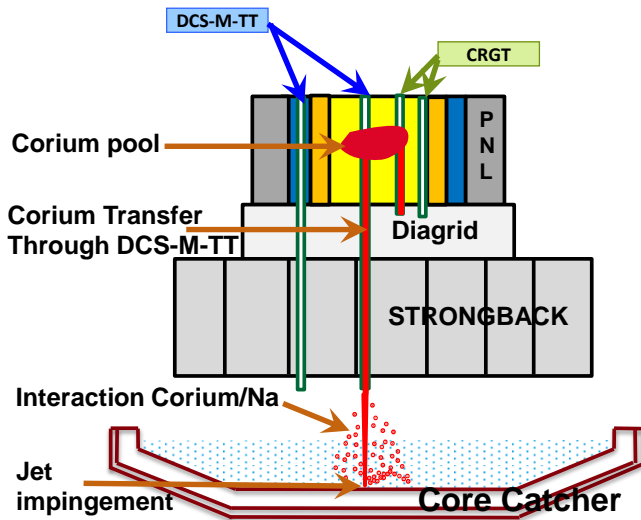


Fig. 1. ASTRID Core, with Control Rod Guiding Tubes, Corium Transfer Tubes, and Core Catcher together with corium relocation in severe accident situation

### III. Simulant experimental tests in the JOLO facility

The task presented in this section aims to plan and prepare the actions to be undertaken on a Europe-wide scale as part of the ESFR-SMART project (European Sodium Fast Reactor - Safety Measures Assessment and Research Tools) which was launched at the end of 2017 (see Ref 12).

From 2018, new experimental and modelling studies will be carried out to make a significant contribution to enhancing existing models and generally improving our knowledge about the jet impingement on the core catcher surface.

The aim of the task is to quantify the heat transfers associated with the hydrodynamic conditions for prolonged jets on a non-planar wall geometry, which are characteristic of conditions that could occur in the ASTRID reactor. Two points in particular will be studied in detail:

- When the depth of the cavity created by ablation of the jet exceeds several times the diameter of the jet itself (e.g. 3 to 4 times), ablation slows down. This phenomenon, known as the “pool effect”, was identified by Saito et al. (Ref. 7) and no model has been developed.
- A planar wall does not present the optimum geometry for limiting ablation kinetics. The impact of a high-temperature

liquid jet on solids with a more complex geometry is yet to be investigated.

Some preliminary experimental results have been obtained and exposed hereafter thanks to high speed visualizations by using:

- Water jet impinging transparent ice at different temperature and velocity. It is worth noting that, for the time being, the jet diameter is small i.e. 1 mm;
- Visualizations performed using a high speed camera (Phantom v701) and a powerful backlighting

Experiment tests were conducted in the JOLO facility (fig. 2), which consists of the sacrificial material (5: ice), the nozzle of the test section (4), the containment vessel (6) and the tank (1) at the controlled temperature with pump (2) and the mass flow rate (3). The erosion kinetics is measured thanks to a camera with a high speed video connected with a system control. The ice temperature is fixed at  $-5^{\circ}\text{C}$  and the jet diameter is of 1 mm which is perpendicular onto the ice surface. It is worth noting that for this ice/water jet system, no crust formation occurs on the eroded surface due to the ice melting temperature similar to the water solidification temperature. This configuration is representative for the steel jet / steel wall system.

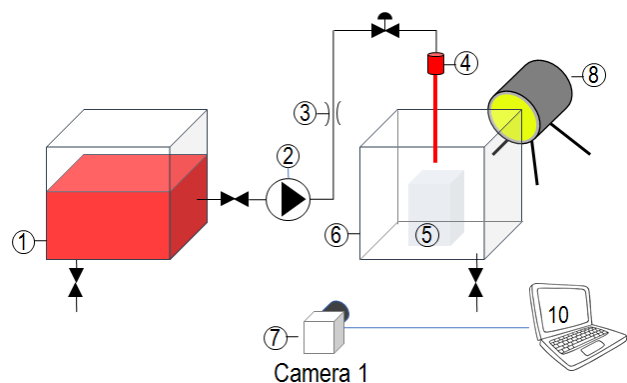


Fig. 2. JOLO Experimental facility

1. main tank at controlled temperature
2. pump
3. mass flowmeter
4. nozzle
5. sacrificial material (ice)
6. vessel
7. camera (high speed video)
8. back light illumination
9. laser source
10. system control

In the first series of the experiments, the water jet temperature ranges between 30°C and 70°C. The jet velocity lies between 2.5 m/s and 9.4 m/s. The experimental input data for this first series are displayed in table I.

For example, Fig. 3 shows the erosion measurements for test 6 with the following experimental conditions:  $T_{jet} = 70^\circ\text{C}$ ,  $V_{jet} = 4.8\text{ m/s}$ ,  $D_{jet} = 1\text{ mm}$ . It is important to underline that the erosion measurements start at 5 mm of depth. The beginning of the ice melting, when the jet is perpendicularly onto the solid plate, is not available. So, the first measurements start when the erosion process occurred in a cavity. At these first measurements, the cavity depth (5 mm) is clearly higher than the  $D_{jet}$  (1 mm). In these conditions, the erosion kinetics measurements evidence the enlargement of the cavity. The heat transfer to the cavity wall is assumed to perform by forced convection.

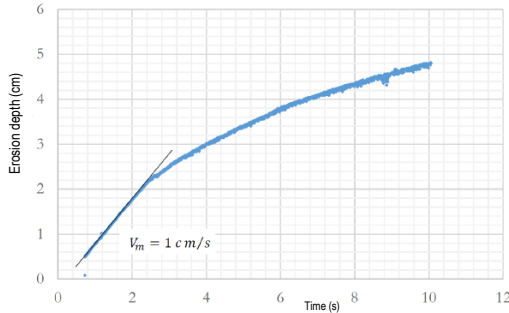


Fig. 3. Erosion depth as a function of the time  
Test 6 :  $T_{jet} = 70^\circ\text{C}$ ,  $V_{jet} = 4.8\text{ m/s}$ ,  $D_{jet} = 1\text{ mm}$

TABLE I. Experimental conditions of a water jet impinging on ice

Test	$T_{jet}$ ( $^\circ\text{C}$ )	$V_{jet}$ (m/s)	$V_{melting}$ (m/s)	Re	Pr	Nu
1	30	2.5	0.0031	3083	5.42	60
2	30	4.8	0.0050	5954	5.42	96
3	30	7.1	0.0055	8824	5.42	106
4	30	9.4	0.0071	11695	5.42	136
5	50	4.8	0.0070	8616	3.55	77
6	70	4.8	0.0100	11545	2.55	76

So, in this study, the erosion kinetics identifies the phenomenon called “pool effect” (as described by Saito in Ref. 7). The enlargement of the cavity leads to the decrease of the input heat flux of the jet to the solid

structure surface due to the interaction of the jet and the stagnant molten pool in the deeply eroded hole.

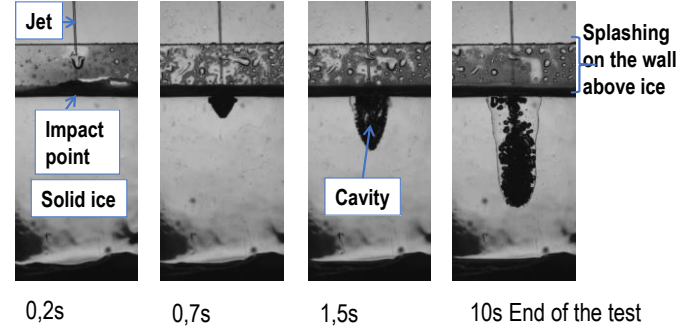


Fig. 4. Evolution of the cavity propagation as a function of the time: Test 6 :  $T_{jet} = 70^\circ\text{C}$ ,  $V_{jet} = 4.8\text{ m/s}$ ,  $D_{jet} = 1\text{ mm}$

From the results in Fig. 3, the erosion kinetics is observed to be steady over the first 2.2 cm measured. During this first erosion phase, the erosion velocity was evaluated to be 1cm/s. After this area, a slope break can be observed. In Fig. 4 we can see four pictures showing the evolution of the erosion cavity as a function of time. Up to 1.5s, the cavity is filled by a thin liquid film flowing upward (in black in Fig. 4, due to refraction of the light rays by the ice and the water film). Beyond this time, an air/liquid mixture is present in the cavity which can explain the slowing of the erosion ablation. Also, the erosion front is observed progress downward and sideward steadily with time. The eroded cavity is symmetrical at the impingement point.

The heat exchange coefficients during ablation of a thin surface by a high-temperature jet can be evaluated from the main empirical correlations derived from the literature on the basis of the formulation of Nusselt, Reynolds and Prandtl dimensionless numbers (See Ref. 7-11). In table I, the erosion velocity during the first phase are reported for six experimental tests together with the dimensionless numbers Re, Pr and Nu. The Nusselt number is evaluated from the heat transfer, which is itself measured from the melting velocity, as defined hereafter:

$$h = \frac{V_{melting} \cdot \rho_s \cdot (L + C_p (T_{melting} - T_s))}{(T_{jet} - T_{melting})}$$

$$Nu = \frac{h \cdot D_{jet}}{\lambda}$$

With:

h the heat transfer coefficient (W/m<sup>2</sup>/K)



$V_{\text{melting}}$  the melting velocity (m/s)  
 $L$  the latent heat of fusion (J/kg)  
 $C_p$  the heat capacity (J/kg/K)  
 $T_{\text{melting}}$  the melting point of the ice (K)  
 $T_s$  the temperature of the ice (K)  
 $T_{\text{jet}}$  the temperature of the jet (K)  
 $D_{\text{jet}}$  the diameter of the jet (D)  
 $\lambda$  the thermal conductivity (W/m/K)

From these results, the Fig. 5 shows the dependence of the Nusselt number for the impingement heat transfer with melting on the jet Reynolds and Prandtl numbers. The experimental results in our study could be simulated from a new correlation i.e.  $Nu = 0.121 \cdot Re^{0.6} \cdot Pr^{0.8}$ . Also, the Fig. 5 presents the comparison between the experimental results of the Nusselt number for the turbulent impinging jet with wall melting and the Sato's equation ( $Nu = 0.0152 \cdot Re^{0.92} \cdot Pr^{0.8}$  as reported in Ref 9).

So, Sato's equation cannot simulate these results. Also, it is worth noting that the validation area of the Sato equation (i.e.  $0.0095 < Pr < 0.20$  and  $4.1 \cdot 10^4 < Re < 4.9 \cdot 10^5$ ) departs from those of our experimental tests (i.e.  $2.55 < Pr < 5.42$  and  $3.8 \cdot 10^3 < Re < 1.2 \cdot 10^4$ ) and that our correlation is closer to Saito's correlation ( $Nu = 0.0033 \cdot Re \cdot Pr$  as reported in Ref. 7).

Consequently, we need to enhance these empirical correlations by varying the Reynolds number and the jet diameter. But we must also improve our knowledge of their origins. Ablation kinetics varies with the hydrodynamics of the impact in the cavity, which in turn depend on the boundary conditions of the problem and the geometry. Ablation behaviour is therefore controlled by a complex relationship between hydrodynamics and heat transfers with phase transformation.

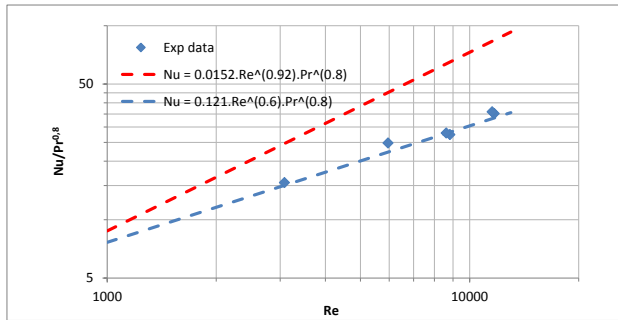


Fig. 5. Dependence of the Nusselt number for the impingement heat transfer with melting on the jet Reynolds and Prandtl numbers

In the future, these experiment results will be simulated by using a CFD approach. This will be performed with a numerical simulation tool designed to aid understanding of the phenomenon under investigation and will help to provide an insight into severe accident conditions for ASTRID.

Besides, in the frame of the ESFR-SMART project, a new design of the experimental facility will be shortly built at the University of Lorraine (LEMETA). The expected experimental results will relate to the evaluation of ablation kinetics of a solid structure with various shapes simulating the ASTRID core catcher geometry. The experimental conditions for these tests will replicate accident conditions as closely as possible in terms of the form and thickness of the solid structure, and the duration and speed of the jet. An experimental facility will be used to meet these test requirements. Analytical tests will be conducted using jets of water (and Field's metal) on ice. According to (Ref. 10), the study of this system is representative for a metal jet on a steel wall. Also, a fine optical instrumentation (Particle Image Velocimetry (PIV) device coupled with a Planar Laser Induced Fluorescence (PLIF) device) will be used to evaluate the evolution of the velocity field as well as the temperature fields during the impingement jet. The measuring equipment will allow us to evaluate the parietal flow, heat transfer coefficient and the velocity field. This will allow the ablation front to be monitored by an ultra-fast camera.

#### IV. Prototypical experimental tests in the MOCKA facility

In the frame of the ESFR-SMART project, two experimental tests about the interaction between a prototypical corium jet and a thick wall in presence of a "pool effect" will be performed in the MOCKA facility. The test conditions will take into account a relatively long duration of (oxidic or steel) corium jet release (with a jet diameter of some centimeters). One of the priority issues to be studied concerns ablation slowdown when a significant cavity height  $H_{\text{cavity}}$  is created in the material impacted, i.e. when the "pool effect" phenomenon occur. The result is that the heat transfer at the jet-material interface decreases which will be beneficial for the core catcher design. As already mentioned, this phenomenon has been studied very little in the past and the dimensionless number correlations do not exist in the literature. Experimental results in MOCKA facility will be used for developing new correlations which could be used in the codes for simulation of the core catcher ablation kinetics.

The MOCKA facility at KIT is designed to study the interaction between molten corium (oxide or steel) and sacrificial material in 2D and 3D geometry crucible (see Fig. 6). The oxidic and metallic melts are generated in a thermite reaction and the decay heat is simulated by adding the thermite briquettes and Zr into the melt from the top. The thermal ablation kinetics of the core catcher material by corium jet can be evaluated at the beginning of the interaction from dimensionless number correlations which were assessed on the past experimental tests using simulant and prototypal jets flowing over a short time (see in Ref. 13). For example, experimental tests were performed in the past in the KAJET facility at KIT (with experimental conditions close to those which will be used in the MOCKA facility) to evaluate the concrete ablation kinetics by metal and oxide jets for LWR severe accident conditions (see Ref 14).



Fig .6. Cross section of MOCKA crucible at KIT

## V. Prototypal experimental tests in the PLINIUS-2 facility

The future PLINIUS-2 platform for prototypal corium experimental R&D will be located at CEA Cadarache, as described in Ref. 15. The experimental facility will be devoted to the ASTRID SFR and the LWR severe accidents. It will be the successor of current PLINIUS platform (VULCANO, VITI, KROTOS).

Inside the PLINIUS2 experimental platform, three underground experimental halls (see Fig. 7) will be dedicated to study the phenomenon set linked to prototypal corium behavior: one for corium-sodium interaction (see Ref. 16), one for corium-water interaction

and one for long term experiments requiring decay heat simulation (Material Ablation, Molten Core Concrete Interaction, Corium Pool cooling ...). Above these three halls, a cold crucible induction furnace is designed to produce and flow up to 500 kg of prototypal corium in the experimental devices (see Ref. 18). Cold crucible induction technology allows to obtain very high corium temperatures which also prevents any significant melt pollution thanks to the formation of a self-crucible. This furnace could be moved, between experimental series, over the experimental halls above the selected test section. An alternative melting method (urathermitic reaction (Ref. 18)) could be used to provide particular corium compositions.

As described previously, R&D programs about the molten fuel progression for ASTRID reactor are currently under way, and the need for large masses (several hundred kilogrammes) of prototypal corium in PLINIUS-2 has been expressed. Two experimental phases were defined for validation of safety design options i.e. core catcher and DCS-M-TT:

- Before having PLINIUS-2 tests, experimental programs, in existing facilities or in facilities which might be prepared in the medium term, has been elaborated: it includes the R&D programme reported in this paper on the jet impingement issue;
- This first phase will be then supplemented by means of more representative tests (scale, materials) in the PLINIUS-2 facility to support the ASTRID safety report.

The need for PLINIUS-2 experiments involves "large masses" (expressed in Ref. 17) to:

- qualify the components of the two mitigation devices (i.e. DCS-M-TT tubes and core catcher) involved in the corium transfer between the core and the core catcher;
- validate the computer tools for severe accidents used at the CEA for ASTRID.

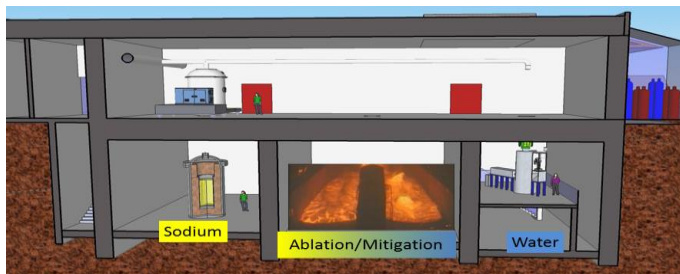
The design of the PLINIUS-2 test devices is currently studied to reproduce some severe accident sequences associated with various phenomena, as described in Ref. 17. Both medium to large scale experiments in the future PLINIUS2 facility and small scale separate effect experiments are needed. These test devices (currently at the conceptual design or feasibility study stage) will use corium volumes up to 40 litres that is to say 500 kg of fuel (i.e. more than the fuel mass of 3 ASTRID fuel sub-assemblies).



Associated with five key phenomena affecting the relocation of molten fuel in engineered discharge tubes between the core region and the core catcher plenum, various PLINIUS test devices are under study (experimental campaigns between 2023 and 2028) and calculation tools under development (presented in Ref. 15 and 16) as reported in Table II.

**TABLE II.** Description of the Plinius-2 devices together with phenomena and calculation tools

Phenomenon	PLINIUS-2 Device	Calculation tool	Qualification
Corium Transfer Through DCS-M-TT	PLINIUS-2 TR (TRansfert)	SIMMER V	DCS-M-TT
Sodium Boiling around a hot particle	SERUA (Sodium boiling Experimental Rig for Understanding of fuel-coolant interAction)	SCONE	Vessel lower head design
Interaction Corium/Na : Fragmentation and vapor explosion	-PLINIUS-2 DROP (Na Droplet Fragmentation) -PLINIUS-2 FR (Corium Jet FRagmentation) -PLINIUS-2 EXPLO (Vapor EXplosion)	SCONE	Vessel lower head design
Jet impingement on the core catcher material	PLINIUS-2 IMPACT (Corium Jet Impact)	Analytical correlations CFD tool	Core Catcher
Corium pool deposited on the Core Catcher Material	PLINIUS-2 CERAM (CERAMic/corium Interaction)	TOLBIAC-SFR	Core Catcher

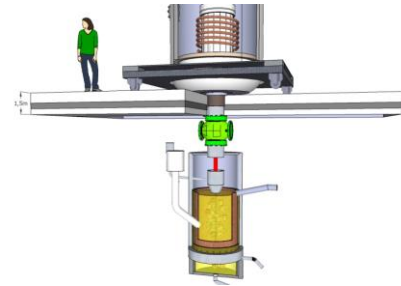


**Fig. 7.** Schematic view of PLINIUS2 platform

As described in introduction, it will therefore be important to have an experimental device (called PLINIUS-2 IMPACT as reported in this table above) studying the impact of a prototypic corium jet on the protective material of the core catcher with a time period,

a discharge velocity and corium superheating that are representative of accident conditions in ASTRID. To meet these requirements, the CEA is planning an experimental program without sodium based on a jet of corium perpendicular to the ASTRID core catcher material with the following conditions:

- A jet of liquid steel or prototypic oxide
- A jet velocity of approximately 10 m/s
- A jet diameter less than 8 cm
- An oxide jet temperature greater than its liquidus temperature (i.e. 2800°C). A metal jet temperature greater than that at which steel melts (i.e. 1450°C)



**Fig . 8.** Conceptual view of PLINIUS-2 EXPLO experimental layout with furnace

One of the priority subjects to be studied in the context of the associated R&D program at PLINIUS-2 concerns ablation slowdown when a significant cavity height  $H_{cavity}$  is created in the material impacted, i.e. when the "pool effect" phenomenon is triggered. The experiment on ablation by jets is currently being designed and will have the benefit of the results of the tests using simulants. Preliminary estimates indicate that masses of around 500 kg would be adequate for our requirements. These experimental tests could be performed without sodium by using the upper part of the PLINIUS-2 EXPLO device, as described in Ref. 16 and illustrated in Fig 8.

## VI. CONCLUSIONS

The safety approach established for the ASTRID reactor is to take events associated with a severe accident into account right from the Conceptual Design phase. The jet impingement on the core catcher material is one of key phenomenon to be studied in the scope of the safety requirements.

It will therefore be important to have experiments studying the impact of a prototypic corium jet on the protective material of the core catcher with a time period, a jet discharge velocity and corium superheating, which are representative of accident conditions in ASTRID. To meet these requirements, the CEA is planning a 3-phase<sup>3</sup> experimental program:

- Analytical tests in chilled water, in the JOLO (Jets Of Liquid Observation) device at the University of Lorraine (LEMTA)
- Large-mass tests, using high temperature oxide simulant (aluminium thermite) or prototypic steel carried out at KIT
- Large-mass tests, with prototypic oxide materials in the PLINIUS-2 facility

The two first experimental phases assigned to this task will be carried out in the frame of the European ESFR-SMART project. The third phase will occur in the future PLINIUS-2 platform. The expected experimental results will relate to the evaluation of ablation kinetics of solid structure simulating the ASTRID core catcher. The experimental conditions for these tests will replicate accident conditions as closely as possible in terms of the form and thickness of the core catcher materials, and the jet velocity and diameter.

Some main correlations derived from the literature to estimate the heat exchange coefficients during ablation of a surface by a high-temperature jet use the formulation of Nusselt, Reynolds and Prandtl dimensionless numbers. However, the validation areas are limited to jet impingement on thin and planar walls. For the more complex, non-planar geometry configurations with thick core catcher material in the ASTRID conditions, we need to enhance these models and improve our knowledge. Also, these future studies will involve multi-phase simulations to take into account of the melting/solidification processes using CFD software.

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