PLINIUS-2: a new corium facility and programs to support the safety demonstration of the ASTRID mitigation provisions under Severe Accident Conditions

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Abstract

The ASTRID reactor (Advanced Sodium Technological Reactor for Industrial Demonstration) is a technological demonstrator of sodium-cooled fast reactor (SFR) designed by the CEA with its industrial partners, with very high levels of requirements. Innovative options have been integrated to enhance the safety, to reduce the capital cost and improve the reliability and operability, making the Generation IV SFR an attractive option for electricity production.

In the ASTRID project, the safety objectives are first to prevent the core melting, in particular by the development of an innovative core (named CFV core) with heterogeneous pins and complementary safety prevention devices, and second, to enhance the reactor resistance to severe accident by design. In order to mitigate the consequences of hypothetical core melting situations, specific dispositions or mitigation devices are added to the core and to the reactor: several corium Transfer Tubes are implemented, allowing molten corium discharge outside the core region toward a core catcher which insures sub-criticality, cooling and confinement of the relocated materials.

For a robust safety demonstration, CEA with its partners is improving or developing codes (SIMMER, SCONE and EUROPLEXUS) to simulate de Severe Accidents progression. These codes must be assessed, and the mitigation devices qualified against experiments. Since no facility is worldwide available allowing tests with sodium and large masses of prototypic corium (about 500 kg) to study corium discharge through full-scale Corium Transfer Tube, Fuel-Sodium-Interactions and subsequent sodium vapor explosion, and Corium Interactions with the sacrificial material which protects the Core-Catcher tray, CEA has decided to build a new versatile facility, called PLINIUS-2; this new experimental platform will extend the PLINIUS capabilities where the handled corium mass is limited to 50 kg of UO_2, and liquid sodium cannot be used.

After describing the ASTRID design options related to Severe Accidents and the main features of the PLINIUS-2, the paper will describe the analytical and global experimental programs planned in PLINIUS-2, supporting the ASTRID development; the used molten mass of UO_2 will range from few grams to 500 kg. The programs will be devoted to the study of Fuel-Sodium Interactions (Droplet fragmentation, Corium Jet Fragmentation, Sodium Vapor Explosion), of Corium-Sacrificial Material Interactions (corium jet impingement, long term sacrificial material ablation by the corium), and to the qualification of the corium Transfer Tubes.

Key Words: Severe Accident, Corium, Infrastructure, Sodium

1. Introduction

The ASTRID reactor (Advanced Sodium Technological Reactor for Industrial Demonstration) is a technological demonstrator designed by the 'Commissariat à l'Energie Atomique et aux Energies Alternatives' (CEA) with its industrial partners, with a very high level of requirements [1]. Compared to previous SFRs, innovative options have been integrated to enhance the safety, to reduce the capital cost and improve the reliability and operability, making the Generation IV SFR an attractive option for electricity production. The ASTRID project started in 2010. The Conceptual Design phase was finished end of 2015, and is followed by the Basic Design phase (BD phase, 2016-2019). For qualifying the innovative options of ASTRID, a Consolidation phase is foreseen after the BD phase. For a robust safety demonstration, CEA with its partners is also developing or improving models and codes dedicated to simulation of Severe Accident

sequences in Sodium cooled Fast Reactor which also needs to be qualified in situation similar as those expected in ASTRID.
After describing the ASTRID design options related to Severe Accidents and the main features of the PLINIUS-2 and the Severe Accident Codes used for the Safety Demonstration, the paper will describe the analytical and global experimental programs planned in PLINIUS-2 and associated Test Sections, supporting the ASTRID development.

2. ASTRID Mitigation Devices Qualification Needs

The ASTRID reactor is a 600MWe pool-type reactor. In order to prevent and mitigate the consequences of Severe Accidents, the ASTRID reactor has an innovative core (named CFV) and Complementary Safety Devices (DCS in French). The CFV core, designed in particular to have a low void worth, has an inner core composed of MOX heterogeneous large-diameter fuel pins (10mm diameter, with two layers of fissile pellets, and in-between, a layer of fertile pellets), small spacer-wires to reduce the sodium volume fraction, and an outer core with homogeneous fuel pins [2, 3] (Fig. 1).
For shutting down the reactor, in addition to the dual diversified systems, there are Complementary Safety Devices for severe accident Prevention (DCS-P in French): three passive hydraulic-suspended shutdown devices acting in case of loss of flow [4], and nine sodium temperature actuated devices based on Curie point electromagnet acting in case of loss of heat-sink accident. Thanks to the low sodium void worth of the CFV core (lower than 0$), the mechanical loading of the vessel in severe accident conditions is minimized. The Complementary Safety Devices for severe accident Mitigation (DCS-M in French) are Corium[1] Transfer Tubes (DCS-M-TT), implemented in the CFV core to allow corium discharge outside the core region [5], and a Core Catcher to collect the discharged corium [6] (Fig. 2). The DCS-M-TT is made of an in-core removable sub-assembly (hexagonal geometry similar to the fuel assembly), with a dedicated spike with a free internal section for corium flow-down, and a prolongation tube crossing the strong-back. At the end of the Conceptual design Phase the in-vessel core catcher is composed of a steel tray covered by a layer of sacrificial material made of ceramic materials. For a robust safety demonstration, one has to qualify these mitigation devices in conditions representative of those expected in ASTRID during severe accidents sequences.

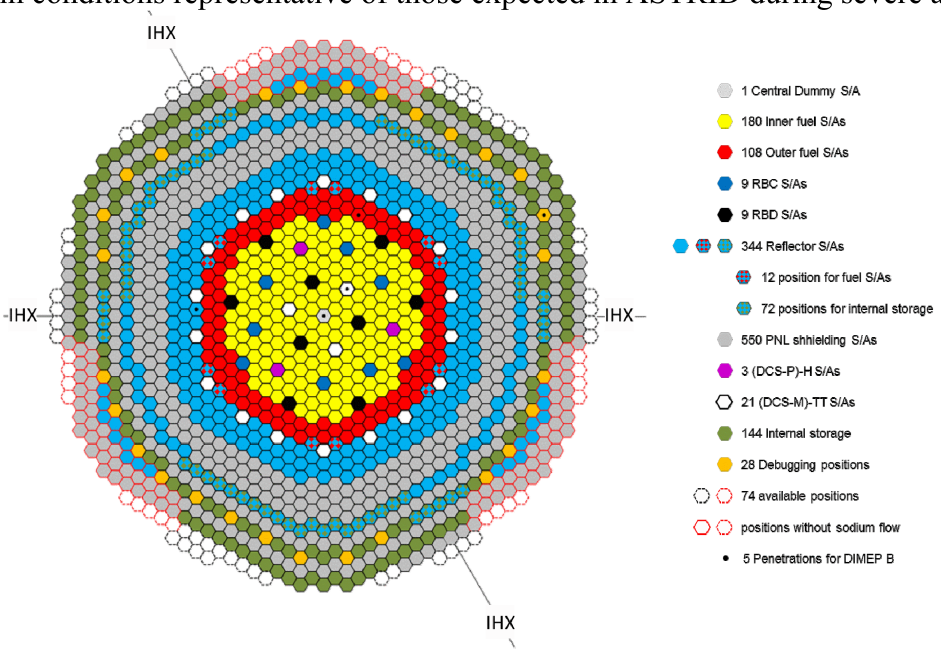

FIG. 1. ASTRID core main features (Active core in yellow and red; transfer tubes in white)

[1] "corium" is used as a general term for expressing degraded core materials mixture

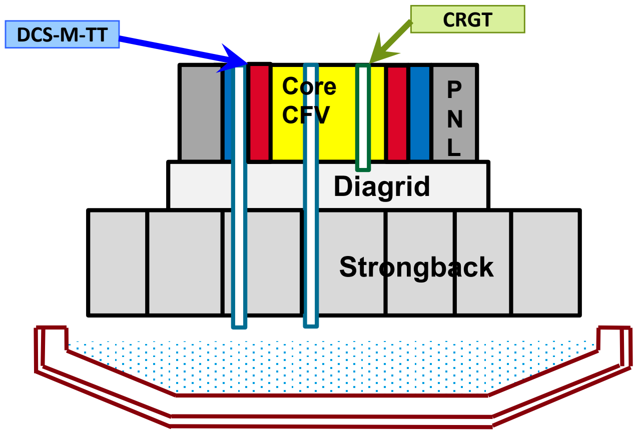

FIG. 2. ASTRID Core, with Control Rod Guiding Tubes, Corium Transfer Tubes, and Core Catcher

3. Severe Accident Code developments and Validation Needs

Severe accident scenarios of Sodium-cooled Fast Reactors (SFRs) involves various phenomena: 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. For robust safety demonstration, one needs to simulate the complete severe accident scenarios; to do that, the CEA strategy is relying on two chains of calculation codes: a reference mechanistic chain of codes and a chain of physical models with statistics and probabilistic capabilities.

The physical statistical chain of codes is composed of fast running models which will be implemented in the PROCOR [7] framework developed by CEA for simulating corium progression in light water reactors. This framework is very versatile and modular. It will be extended with models dedicated to SFR severe accidents.

The reference mechanistic simulation code is SIMMER [8, 9] to simulate core degradation and corium progression towards the core catcher. SIMMER will be coupled with an irradiation code (for example: CEA irradiation code named GERMINAL [10]) and a primary loop thermo-hydraulics code (for example: CEA primary loop thermo-hydraulics code named CATHARE [11]) thanks to a dedicated under development platform named SEASON.

The ablation of core catcher sacrificial materials by molten corium shows some similarities with molten corium concrete interaction (MCCI). So CEA plans to develop models to be implemented in PROCOR-Na [7]. The models will be derived from the models of the TOLBIAC-ICB code [12] used for MCCI for LWRs, with SFR capabilities in order to deal with core catcher sacrificial layer: more versatile geometry, 1D pool discretization, and sacrificial material properties.

The fuel-sodium interactions are quite different from fuel-water interactions. It is not possible to consider two separated phases (premixing phase and steam explosion phase), as for fuel-water interactions. CEA started recently the development of a code named SCONE (Simulation of COolant Na intEraction) [13], dealing with the whole fuel-sodium interaction processes.

The consequences of mechanical energy releases due to FCI are simulated with EUROPLEXUS (EPX) code [14], which is a CEA/JRC code dedicated to analysis of fast transient phenomena involving structures and fluids in interaction.

Assessment of the mechanistic codes is of prime importance to have a good confidence in the produced results. Physico-statistical models are benchmarked against the mechanistic code except when mechanistic model are yet not developed; in such case they are directly assessed against experimental data.

3.1 SIMMER code development and validation needs

SIMMER-IV (resp. SIMMER-III) is a three dimensions (resp. two dimensions), multi-velocity-field, multiphase, multicomponent, Eulerian fluid dynamic model coupled with a structure (pin and hexagonal can) model and a three dimension (resp. two dimension) space and energy-dependent neutron kinetics models.
A new version of SIMMER (SIMMER-V) derived from SIMMER-IV is jointly developed by JAEA (code manager) and CEA [15]; the numerical performance and the code robustness are being largely improved by CEA (the performance of the thermohydraulics and degradation module is 300 faster thanks to the improvement of the memory management and parallelization). SIMMER-V will allow to simulate all the phases of the severe accident, including primary phase thanks to a new pin degradation model developed by JAEA, and to simulate the ASTRID innovation options.
SIMMER-III and SIMMER-IV have been and are still intensively assessed. During the development of SIMMER-V, one verifies that there is no physical regression on a large bench of tests. The test matrix for SIMMER-V assessment is under specifications. It must cover model assessment related to the specificities of ASTRID such as CFV core degradation (degradation of heterogeneous pins and CFV fuel assemblies), and the corium discharge in the DCS-M-TT.

3.2 SCONE code development and validation needs

SCONE will have to calculate the pressure build-up generated by the interaction as well as the expansion of the pressure wave. In this aim, the physical phenomena involved in the intense vapor production will be precisely modeled: fragmentation of a coherent corium jet and of liquid corium particles, particle solidification, sodium boiling regimes and the associated heat transfers between the different constituents of the system, heat flux partition between liquid sodium heating and vaporization.
Knowledge gaps remain in the understanding of the physics of the interaction. To fill these gaps and implement the appropriate models in SCONE, experimental data are necessary:

- on the sodium boiling regimes and of the spontaneous triggering of the explosive phase of the interaction,
- on fragmentation mechanisms of a liquid corium droplet and corium jets,

and data from more global experiments at medium and large scales, involving larger masses of molten corium and liquid sodium.

4. Available Facilities for Corium Tests

Journeau et al. have shown in [16] that it is necessary to study Fuel Coolant Interaction phenomena with prototypic corium jet in steady state conditions, as expected at the outlet of the DCS-M-TT in the lower plenum of ASTRID; the mass of corium must be in the range of 500 kg. It is pointed out that this mass is also in the range of the total mass of one ASTRID fuel assembly. Therefore the ASTRID needs for Mitigation device qualifications and Severe Accidents model developments and validation requires carrying-out experiments in dedicated facilities able to handle this large masses of prototypic core materials in sodium environment. Experiments with large masses cannot be performed in in-pile facility. Therefore an out-of-pile facility survey has been carried-out by CEA to look for facilities meeting these requirements in sodium environment.
The PLINIUS platform of Cadarache CEA Center is limited to experiments with 50 kg of prototypic UO_2 [17] and cannot fit sodium (flooding risk).
Abroad, very few facilities are devoted to Corium Tests with sodium: EAGLE out-of-pile stand at NNC-RK but with moderated mass of simulant (20 kg of Alumina) [18], SOFI at IGCAR where the maximum planned masses of UO_2 will be limited to 20 kg [19], and PLUTON at IPPE but also with limited mass of fuel (in the range of 1 kg) [20].

5. PLINIUS-2 Platform

It was concluded that existing facilities cannot meet the needs for ASTRID development. It was then decided by CEA to launch the PLINIUS-2 Project to build a new corium test facility dedicated to resolution of SFR issues and also LWR issues [19].

The objectives of the PLINIUS-2 facility for SFRs will be:

- To study corium relocation through dedicated tubes and to validate the DCS-M-TT concept in sodium environment,
- To extend the knowledge on fuel coolant interaction in sodium environment,
- To study corium/core catcher sacrificial material interactions and qualify the core catcher design for ASTRID.

There are three folds on that project:

- design of the PLINIUS-2 facility,
- design and development of a furnace to melt up to 500 kg of UO_2,
- design and development of test sections and instrumentation to carry out R&D programs.

5.1 PLINIUS-2 Building

The PLINIUS-2 building has been designed in order to run tests with water, sodium or to run corium structure material tests in safe conditions sharing the same furnace.

The building is designed with two levels and three corium experimental halls in the basement:

- a Water Interaction hall with an associated steam processing hall,
- a Sodium Interaction hall with the associated sodium treatment hall,
- a Material and Mitigation hall in between.

The furnace hall, connected to the generator hall is at ground level, above the experimental halls. The furnace will be installed in an airtight enclosure that can be moved over the experimental halls above the selected test section (Fig. 3). Corium will be transferred through dedicated transfer devices to the test sections located underground in the experimental halls. A corium load preparation room is also located on the same floor.

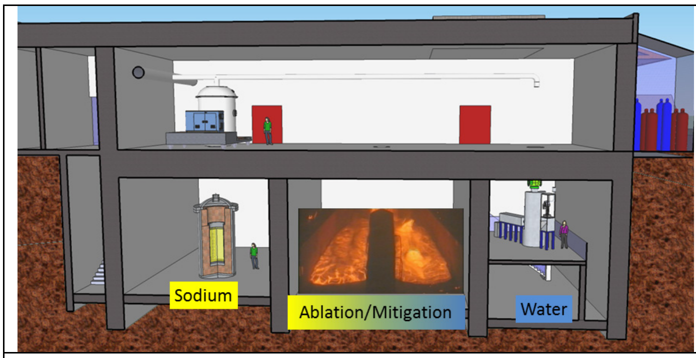

FIG. 3. Schematic cut view of PLINIUS-2 building

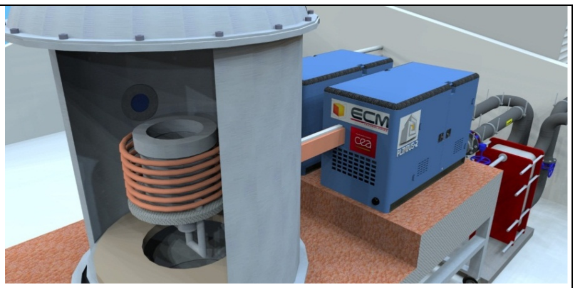

FIG. 4. 3D picture of the PLINIUS-2 furnace

The design of the facility enables the use of X-Ray devices in each experimental hall up to energies of 15 MeV in order to measure phase repartition during Fuel Coolant Interactions (FCI) as it is done in the KROTOS facility at Cadarache for Corium-Water Interaction experiments using the KIWI approach [22].

It must be pointed out that the PLINIUS-2 building will also fit a separate-effect tests hall.

5.2 PLINIUS-2 Furnaces

The furnace, based on cold crucible induction technology, widely used for prototypic corium melting experiments, is development by the ECM Company located in Grenoble with CEA. A prototype, able to melt 100 kg is first developed to assess the design before the large furnace to melt 500 kg (Fig. 4).

6. PLINIUS-2 Programs and Associated Test Sections

For the ASTRID development, six programs are under definition at CEA to be carried-out in PLINIUS-2 facility. In parallel to the definition of the programs, tests sections are developed, with high priority when their dimensions impact the PLINIUS-2 building, or when sizing is challenging due to possible high mechanical energy releases in case of FCI.

6.1 PLINIUS-2 DROP Program

The PLINIUS-2 DROP program will be dedicated to the study of hot corium droplet fragmentation for SCONE assessment; the program is composed of Analytical Tests with X-Ray instrumentation to track the droplet fragmentation. This program is very important to model the surface of the corium droplet exchanging with surrounding sodium for FCI modeling. In conjunction with the SERUA program dedicated to the study of heat transfer from a solid sphere in Na boiling conditions, one will be able to calculate the energy transferred from the corium droplets to the sodium.

The test section could be derived for the MISTEE test section used for study of binary oxide droplet interacting with water [23].

6.2 PLINIUS-2 FR Program

The PLINIUS-2 FR program (FR standing for ‘Fragmentation’) will be dedicated to corium jet fragmentation at the outlet of the DCS-M-TT to enlarge the MELT [21] and SOFI [19] database; X-Ray instrumentation will be used to track the jet fragmentation. The impact of sodium temperature, corium velocity and jet diameter will be studied.

A small test section derived from the PLINIUS-2 EXPLO Program test section (see next section, Fig 5 and 6) has been design in order to be able to use an X-Ray imaging system to capture corium droplets concentration and sodium bubbles concentration in the sodium environment.

The inner diameter of the test section will be 300mm and the useful length about 2.5 m. It will fit up to 50 kg of corium.

6.3 PLINIUS-2 EXPLO Program

The PLINIUS-2 EXPLO program (EXPLO standing for ‘Explosion’) will improve the knowledge on the sodium vapor explosion which will drive the mechanical dynamic loads of structures in the vicinity of the explosion. Large masses of corium will be poured in the sodium in order to have steady state jet in sodium. The impact of sodium temperature, corium velocity and corium jet diameter will be studied. To be representative of FCI at the outlet of the DCS-M-TT, the Corium will be injected below the sodium level.

The design of test sections for corium-sodium interaction studies reproduces the major outlines of the FARO-TERMOS [25] test section used in the past for similar studies. Since the test section must fit hot sodium (up to 850°C) and could withstand steam explosion, the Test Section design is based on a three part with different functions (Na tightness, insulation and mechanical robustness):

- A metallic liner to ensure sodium leak tightness;
- A ceramic thermal barrier;
- A pressure vessel.

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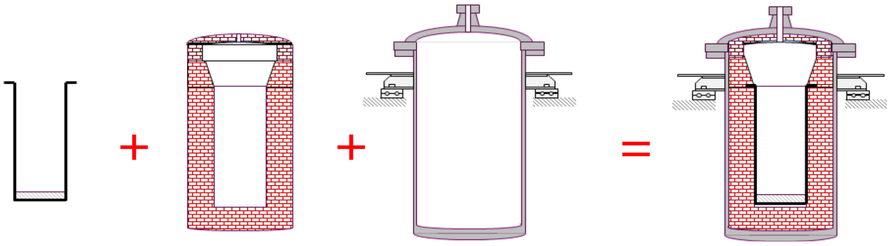
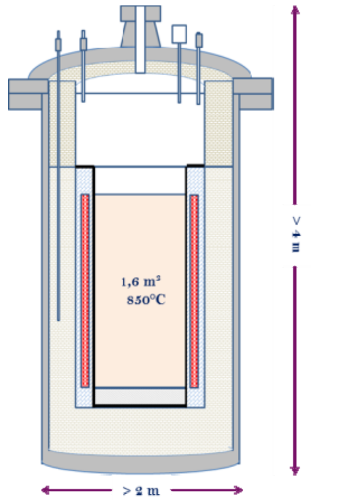
<td></td>
<td>
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<td>FIG. 5. Test Section for FR and EXPLO Tests</td>
<td>FIG. 6. EXPLO Test Section</td>
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It is assumed in this preliminary design stage, that the mechanical energy released by the vaporization of sodium can reach 16MJ. This will allow performing experiments with at least 200 kg of corium with sodium at 850°C, assuming that the mechanical energy release is 80J/Kg_{UO2}. With sodium at lower temperature (representative of sodium temperature in the lower plenum of ASTRID, not exceeding 600°C), and with improvement of our knowledge on FCI mechanical consequences, larger masses of corium will be used. The inner diameter of the test section will be 1000mm and the useful length about 2.5 m as for FR experiments.

6.4 PLINIUS-2 TR Program

The PLINIUS-2 TR program (TR standing for ‘Transfer’) will be dedicated to the DCS-M-TT qualification and the assessment of the related SIMMER models; the opening of the corium tube was largely studied in the EAGLE programs, so mainly the corium transfer in the corium tube with ASTRID geometry will be studied. These tests will enlarge EAGLE database with prototypic corium and large corium masses (up to about 500 kg), different corium compositions (Oxide uranium-iron-B4C), with representative geometry of the DCS-M-TT in sodium environment.
The preliminary design of the test section (Fig 7) is derived from the EAGLE out-of-pile test section used for the SBD series-tests.

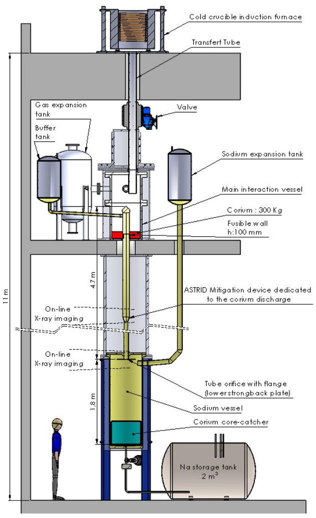

FIG. 7. Test Section for TT

6.5 PLINIUS-2 IMPACT Program

The PLINIUS-2 IMPACT program will be dedicated to the corium jet impact on the core catcher sacrificial materials for core catcher and model qualification. The impact of corium temperature, corium velocity, corium jet diameter and corium composition will be studied (Core catcher material will be fixed as chosen in design studies).

6.5 PLINIUS-2 CERAM Program

The PLINIUS-2 CERAM program will be dedicated to programs dedicated to the corium-sacrificial materials interactions, for core catcher and models qualification. The impact of corium temperature, corium composition will be studied (Core catcher material will be fixed as chosen in design studies).

Test sections will be derived from VULCANO test sections from the PLINIUS platform [16]. Corium heating by induction on the core catcher model will be possible to simulate de residual power (as done in VULCANO experiments)

8. CONCLUSIONS

The development of safer Sodium Fast Reactors with innovative systems, such as ASTRID, and meeting the GENIV objectives require having a robust safety demonstration. This requirement implies to develop and assess simulation tools against experimental data obtained in conditions similar as those expected in the reactor, and to qualify the innovative systems experimentally.

For SFR Severe Accidents, a large experimental database was developed to support development of SFRs worldwide, including the CEA database developed in France for Phenix and Superphenix with the in-pile experiments in CABRI and SCARABEE facilities, and out-of-pile programs in Grenoble.

However this database didn’t cover all phenomena involved in Corium-Sodium-Interactions with large masses of corium, the available measurements were not fine enough to build mechanistic models, and available present Corium facilities are not large enough to qualify the ASTRID innovative mitigation devices such as the Corium Transfer Tubes and the Core Catcher.

It is why the CEA is developing a new versatile platform PLINIUS-2 to perform corium tests able to handle large masses of prototypic corium for Corium-material studies, or for tests in sodium environment (as well as in Water environment for LWR studies).

In parallel of the PLINIUS-2 building design, six experimental programs are defined to meet the ASTRID needs and associated test sections are developed. At last, fine instrumentations are developed, including X-ray image system to visualize on-line phenomena involved in Corium-Coolant interactions.

The facility should be available for experimental programs in 2021, allowing to consolidate the ASTRID mitigation device designs, and to finalize the assessment of the simulation tools used for the ASTRID safety reports.

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