THE INNOVATIVE RBH COMPLEMENTARY SAFETY DEVICE FOR ASTRID TO ADDRESS UNPROTECTED LOSS OF FLOW TRANSIENTS: FROM DESIGN TO QUALIFICATION

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To comply with the GEN IV objectives, the design of the 600 MWe Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) includes enhanced safety compared to current generation II or III reactors. One of the most important safety aspects is the ability to shut down the reactor in any condition.

In the early stage of the ASTRID conceptual design phase (2013), it was decided to support a robust safety demonstration by complementing ASTRID low void fraction (CFV) design core natural behavior with two types of Complementary Safety Devices dedicated to core damage prevention that would passively shutdown the reactor. The first type is based on the exploitation of the Curie point of the electromagnetic delatch system of one of the diversified reactor shutdown systems, to address unprotected loss of heat sink transients. The second type is a hydraulically suspended absorber rod subassembly, called RBH, dedicated to unprotected loss of flow (ULOF) transients.

Concepts of the latter type are innovative for a French sodium-cooled fast reactor. Their operating principle is simple. Under normal operation, the absorber rod is hydraulically suspended above the core by the upward flow of the sodium coolant. Should an ULOF event and the associated drop in flow rate occur, this upward force would become insufficient, thus allowing the absorber material insertion into the active core region by gravity.

Based on the ASTRID functional specifications and safety requirements, the structured process of value engineering that led to the selected options/designs of ASTRID RBH concepts is presented in this paper. Several RBH subassembly concepts specifically designed by CEA are under investigation whose design features and main parameters involved in their operation are described. Their current study/development status as well as related experimental and simulation support are finally discussed with regard to how they could match the ASTRID framework and future milestones.

I. INTRODUCTION/BACKGROUND

Late 2015, the three-years conceptual design phase (AVP2) for the 600 MWe Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) prototype drew to an end. During this phase, main reference innovative technical options to improve the safety level with progress made in SFR-specific fields and to thus comply with the GEN IV objectives were provided with greater consistency and confirmed with a view to a consistent preliminary design.[1]

Designed with a defence-in-depth approach based on redundancy, diversity and independence, ASTRID has two distinct, diversified and independent fast-acting automatic reactor shutdown systems. Each shutdown system consists of sensors, logic circuit, drive mechanisms and mobile neutron absorber rods in stationary wrappers. The rod and wrapper form the absorber subassemblies distributed in the core.

In ASTRID innovative reactivity control architecture, these systems are respectively called RBC (control and shutdown device) and RBD (diverse control and shutdown device). Both RBC and RBD systems are dedicated to the core reactivity management (power regulation, compensation for the reactivity change with time and normal or emergency shutdown) during the cycle.

Complementary safety devices dedicated to core damage prevention that would shut down the reactor passively have been implemented in ASTRID low void fraction (CFV) design core.[2] They aim at complementing its natural behavior in case of some unprotected (i.e. with complete failure of all automatic shutdown systems)

transients in order to meet temperature criteria on coolant, core and primary circuit structures within a robust margin and safety demonstration.
Since the reactor shall be shut down passively, the actuation of these complementary safety devices has to be triggered directly by the sole physical effect induced by the accidental transient.
ASTRID functional specifications and safety requirements for such complementary safety devices have been detailed in a previous paper,[3] as well as the structured process of value engineering. As a result of this process, two types of Complementary Safety Devices have been selected as the concepts the most capable to cope with both unprotected loss of flow (ULOF) and unprotected loss of heat sink (ULOHS) transients. The first type is based on the exploitation of the Curie point of the electromagnetic delatch system of ASTRID RBD shutdown system to address ULOHS transients. The second type is a hydraulically suspended absorber rod subassembly, called RBH, dedicated to ULOF transients. Both constitute the reference choice made for ASTRID reactor.[3]

In this paper:

- the outlines of the value engineering process that led to the selected options/designs of ASTRID RBH concept are reminded in chapter II;
- design features of several under investigation variants of RBH concept specifically designed by CEA and main parameters involved in their operation are described in chapter III;
- their current studies/development status to reach appropriate Technology Readiness Levels[4] as well as related experimental and simulation support are presented in chapter IV and V and discussed with regard to how they could match ASTRID framework and future milestones[5].

II. REMINDER ON SELECTED OPTIONS AND DESIGNS

II.A. State of the art

CEA patented an active/passive safety system in 1973, where the absorber rod is at once held by an electromagnet and hydraulically suspended.[6] Other CEA studies were performed in the 80s related to a pure hydraulically self-resettable system. The hydraulically suspended concept was also explored late in the 70s in the United States.[7]
The most actual emphasis is being given to this concept in Russia.[8] It has in particular been chosen for BN-800 and may be implemented in BN-1200 sodium-cooled fast reactors.[9]
This concept is innovative for a French sodium fast reactor.

II.B. Results of the value engineering

II.B.1. RBH concept selected for ASTRID

The RBH concept/device specifically designed by CEA consists of a mobile absorber rod in a stationary hexagonal wrapper tube almost identical to the fuel subassembly wrapper; the mobile rod is entirely contained within the wrapper tube at any time.
It operates with a sodium flow path reduced section called “working zone” that creates an important pressure drop giving rise to hydrodynamic force intended to support totally the mobile rod above the core under the upward flow of the sodium coolant associated to normal operation.
Should a ULOF event and the associated drop in flow rate occur, this upward force would become insufficient, making the rod drop hydraulically actuated and allowing the absorber material to get inserted by gravity into the active core region.
A mechanism *via* an electromagnetic grip is developed that aims only at actively cocking/resetting the absorber rod before divergence. During normal operation, the absorber rod would be disconnected from the grip.

This set of design options allows developing a system that is:

- completely independent of and distinct from the automatic shutdown systems;
- diversified with respect to the automatic shutdown systems; this allows to fight against common mode failures of triggering and/or insertion. Indeed, the accidents which might affect all automatic shutdown systems could result from the failure of sensors or logic circuit, or from the mechanical inability to insert the absorber rods into the core, consecutive to rod and/or drive mechanism jamming or malfunction. Thus:
    - the way of triggering (passive instead of active) is a first source of diversification;
    - since RBH is engineered to have the head of its mobile rod permanently housed in the subassembly, it is diversified with respect to RBC in terms of insertion (i.e. it could ensure reactor shutdown in case of significant deformation of the reactor block that would be likely to block the RBC mobile rods in their wrappers);
    - since the RBH rod would be disconnected from the electromagnetic grip of the mechanism during normal operation, it is diversified with respect to RBD in terms of triggering (i.e. any self-welding between the rod head and the grip would be avoided);
- as far as possible independent of the slab and of the main control room:

- any risk of re-connection under power between the rod and the grip, whether intentional or not, that could lead to the inhibition of passive actuation has to be eliminated by design. Management of operator interpretation fault and/or failure in mechanism grip state and/or failure of control system is the key point;
- with a view to that, all the following measures may be contemplated:
  - once RBH cocking is effective, the grip has to be put at such a distant parked position from the rod head that re-connection would not be possible even in case of electromagnet power supply;
  - the mechanism kinematic line might include a component that would be supplied solely during reactor start-up phases (with pin-out outside the main control room)
  - the grip parked position might be continuously monitored and an alarm could be triggered in case this position would not be respected anymore;
  - the electromagnet power supply control knob might be deported outside the main control room;

- *in situ* resettable after actuation, which allows *in situ* testability and rod worth measurement capability;
- not likely to introduce additional risks:
  - because the working zone is not active as the rod is in its lower position (during handling situations or after spurious drop during operation), any unexpected rod ascent from its lower position and subsequent reactivity insertion is avoided;
  - during operation, the wrapper ascent under the rod upthrust might be counteracted thanks to the mechanism;
- of no particular impact on reactor operation recovery in case of spurious actuation, which would be detectable anyway;
- not particularly significant in the core design[2] (as shown on Fig. 1) and the reactor integration because:
  - the slab design can accommodate the penetrations dedicated to the cocking mechanism of the limited number (i.e. 3) of required RBH in order to comply with requirement of about 1000 pcm to be inserted into the core after actuation of all RBH (with natural boron carbide B_4C as absorber material),
  - it has a very low impact on the core's fuel volume fraction (less than one per cent); its impact on neutronics performance would be negligible;

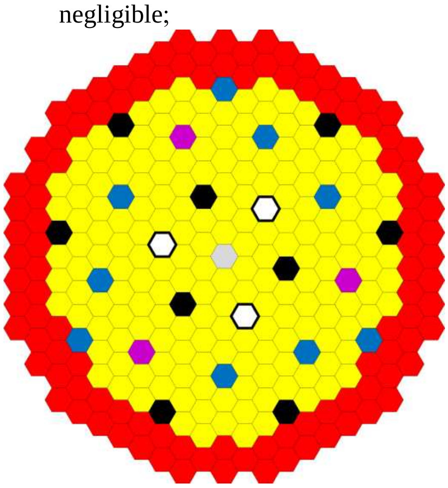

Fig.1. Configuration of ASTRID core including RBH S/As (fuel S/As in yellow and red; RBC and RBD S/As in blue and black; RBH S/As in pink ; dummy S/As in white and grey)

- provided studies and R&D confirm the feasibility and the robustness of this system (it is the purpose of chapters IV and V to report the progress made in this field), likely to comply with hydraulics performance requirements such as an actuation coolant flow rate of 45 % of the flow rate nominal value and a response/drop time (accounting for the duration between the time at which the coolant flow rate in the subassembly reaches the actuation value and the time at which absorber rods are fully inserted in the core) in the 1 to 30 s range (as suggested by some preliminary parametric thermal hydraulics calculations performed with the CATHARE system code[10], which have shown that the response time is not a first-order parameter in the management of the ULOF transient).
  Actually, the value of the actuation coolant flow rate of 45 % of the flow rate nominal value has been chosen to satisfy at the same time:
  - the need for a hydrodynamic force high enough to support the rod above the core under the upward flow of the sodium coolant associated to normal operation condition,
  - the need for compatibility with all operational conditions and reactor availability factor that dictates following requirements:
    - not to actuate before automatic reactor scram, should this works;
    - not to interfere with any normal mode of operation including start-up and divergence, partial power operation (the associated minimum flow rate contemplated equals 55 % of the flow rate nominal value), shutdown and

handling/refueling (the associated flow rate equals 30 % of the flow rate nominal value);
  - safety purposes (the earlier the actuation, the better the management of the ULOF transient and the avoidance of sodium boiling).

As such, this system abides satisfactorily by ASTRID specifications including functional specifications, safety and performance requirements to allow a safe state in the core to be achievable at temperatures compatible with the thermal criteria for the boiling point of sodium and the resistance of the structures, with a view to the short- and long-term management of the reactor.

II.B.2. Abandoned RBH concepts

Concepts based upon a self-resettable rod, on the one hand, and concepts involving a drive mechanism with a Curie point (electro)magnetic grip that would support the absorber rod in conjunction with hydrodynamic force, on the other hand, have been set aside.
As regards the former:

- potential additional risks are deemed to be associated to uncertainty on the rod position (uncontrollable in all situations):
  - spurious ascent of the rod would not be detectable during handling phase;
  - under operation, reactivity insertion might occur in case a decrease in coolant flow rate would be followed by a sharp increase, inducing the rod ascent.

As regards the latter:

- fine regulation of (electro)magnetic force that would equilibrate hydrodynamic force seems inconceivable on the whole lifespan:
  - with a permanent magnet whose magnetic properties would be sensitive to neutron flux,
  - based on operating experience from Phénix French reactor, the (electro)magnetic lifting force may decrease (as was the case within the backup control rod installed on Phénix; the cause of this decrease is not fully confirmed);
- passive actuation could anyway be inhibited, intentionally or not, through increase of the magnetic force.

III. DESIGN FEATURES OF ASTRID RBH

III.A.1. RBH subassembly

The RBH subassembly whose stationary hexagonal wrapper tube is almost identical to the fuel subassembly wrapper is supported on the reactor grid plate. In the upper part of the rod, a shaft links the connecting surface to the electromagnet to the rod body which houses a bundle of vented absorber pins. In the lower part, the rod body is linked to the rod spike. In the rod body, the absorber pins are arranged on two circular arrays around a central pin as a bundle, covered by a cylindrical wrapper. They are hung from a collar attached to the rod shaft along with a centering grid at their lower end. B_4C boron carbide pellets are stacked and shrouded in the absorber pin cladding tubes.

The working zone is developed thanks to the cooperation between a female piece (called “virole”) supported by the stationary wrapper and a solid surface component (male piece) of the mobile rod. When both pieces are placed beside each other, the resulting reduced clearance (of about a few millimeters) awards the expected important pressure drop giving rise to the rod hydrodynamic support capability under sodium nominal flow rate. When both pieces are not facing each other anymore, the working zone is disabled (this configuration is exploited either to initiate the rod drop in the core or to avoid any expected ascent of the rod from its lower position in the subassembly).
Here, as illustrated on Fig. 2, it has been chosen to develop the working zone under the fissile core, the male piece (called “pion”) being supported on some given height by the lower end of the rod spike. Apart the “pion”, the rod spike consists of a central shaft bearing some radial stiffeners.[11]
Among the parameters involved in the hydrodynamic force phenomenon are the geometrical characteristics of the working zone (“pion” diameter and shape; working zone length; clearance between “pion” and “virole”; surface roughness).

Sodium enters at the foot of the subassembly, runs through the working zone, the absorber pin bundle and the annular gap between the mobile rod and stationary wrapper, and exits through the top of the cylindrical wrapper.

The rod movement inside the stationary wrapper during cocking or drop is guided/restrained at two levels at least: along the length of the rod spike (the working zone “virole” acting as a guide bush) and along the entire length of the pin bundle wrapper (guidance and/or angular movement restriction by means of pads located in the upper part of the subassembly). The parts of the wrapper in contact with the mobile rod (“virole” and pads) may have a hardfacing surface to ensure the durability of guidance throughout the life of the subassembly.

Once actuated, the RBH rod falls freely into the reactor core until it reaches a stop supported by the stationary wrapper. However, in the last part of the rod stroke, rod velocity is smoothly decreased using a passive

device called "hydraulic dashpot" in which sodium is allowed to flow from one chamber to another through narrow clearances. The associated damping action provides some shock absorption; the final impact at the end of the stroke may however challenge the mechanical integrity of the rod and sleeve structures, especially the connections between their respective components.
Two main types of dashpot design are currently under study for ASTRID RBH S/As:

- the first one (named _1) consists of an annular flange at the bottom of the rod body which penetrates in an annular groove provided from the upper face of the working zone "virole". Due to its radial design to be included in a given internal across flats dimension, this type of dashpot is a limitation to the development of a "virole" with high diameter; however the whole axial space between the altitudes of the fissile core bottom and the top grid plate can be made the most of to develop long "pion";
- the second one (named _2) consists of the rod spike lower end interacting with a component supported by the subassembly spike. This type of design allows the development of a "virole" with high diameter; however the axial space available to develop "pion" is reduced due to the axial dimension of the above-mentioned component.

All in all, two main variants of RBH conceptual designs are currently under study at CEA:

- the RBH_1 variant, as partially illustrated on Fig. 2, with a thin and long "pion" (i.e. the "pion" length is maximized),
- the RBH_2 variant with a thick and short "pion (i.e. the "pion" diameter is maximized).

In both cases, the sodium apparent mass of the rod is similar.
In particular, the RBH_1 variant allows the decoupling of the lift and dashpot functions by differentiating the associated surfaces. This is highly suitable to avoid that the surfaces implied in the lift function be distorted/damaged because of the shock in the dashpot at the end of each rod drop stroke.[12]
In particular, the RBH_1 variant presents some concave component (cf. its annular flange which is furthermore under neutron flux during normal operation) whose impact in terms of rod vibrations and/or hydraulic instabilities needs to be checked.

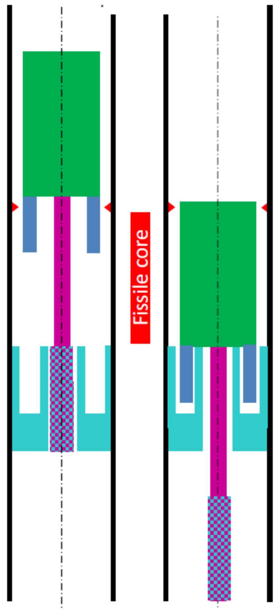

Fig.2. Illustration of ASTRID RBH_1 S/A variant
[Rod upper position on the left (with working zone activated) and lower position on the right (with working zone deactivated)
Working zone "virole" in turquoise
Working zone "pion" in checkered turquoise/magenta
Rod spike in magenta
Dashpot components in royal blue
Rod body in green
Upper guidance level illustrated by red triangles]

III.A.2. RBH cocking mechanism

A cocking mechanism with an in-sodium electromagnetic grip (as is the case for RBD drive mechanism) has been chosen as reference option, a mechanical grip being the alternative.

The main advantages are:

- a simplified mechanism since no mechanical transmission to the grip is necessary,
- a better protection against potential blockage of the rod in its wrapper (the disconnection would be easier),
- an easier instrumentation configuration to detect the rod presence if need be.

Some technical difficulties identified with the RBD drive mechanism in-sodium electromagnet would be less sensitive:

- no safety function is attributed to the RBH electromagnet whose development is thus easier ;
- it can be made the most of the development actions of the RBD electromagnet;
- RBH ambient conditions are less stringent than RBD ones as regards the electromagnet.

On the contrary, the potential behavior of the electromagnet in normal operation with the rod disconnected needs to be investigated as it both:

- would be placed at the core outlet in a sodium flow mixing zone,
- could be a ferromagnetic particle trap.

IV. DEVELOPMENT STATUS AND ONGOING STUDIES

Final choices between RBH variants will be guided by:

- hydraulics performance: coolant actuation flow rate, hydrodynamic force, drop time;
- management of other performance: neutronics efficiency, absorber rod cooling, reliability of rod insertion, cavitation, dashpot ability, subassembly integration…

Actually, all these topics are intrinsically related to each other and need a strongly iterative management. The hydraulics topic is multi-parametric (cf. geometrical characteristics of the working zone, sodium flow rate value, rod mass) and cannot be decoupled from:

- the mechanical topic that aims at ensuring on the one hand the correct cocking of the rod, on the other hand the correct insertion of the rod in the core after actuation (especially the clearance between "pion" and "virole" is here involved that dictates in return the flow rate value in the RBH subassembly),
- the damping topic (from hydraulics and mechanics point of view) that aims at ensuring the integrity of the components implied in the rod drop and shock (especially the design of the dashpot has consequences on the geometrical characteristics of the working zone *via* the axial and radial subassembly integration and on the pressure drop compilation in the RBH subassembly),
- the safety topic that aims at ensuring no self-resettability capability to the rod,
- the subassembly integration topic according to the limitation of the length of all ASTRID core subassemblies,
- the within RBH subassembly pressure drop compilation topic that encompasses both:
  - o the search for a maximization of the working zone pressure drop that must however remain consistent with the core pressure drop,
  - o the compliance, via the flow rate value available for the lift function (deduced from the RBH subassembly pressure drop compilation), with other core thermal hydraulics criteria (for instance in terms of what part of the core flow rate RBH subassemblies could withdraw) or other hydraulics criteria (such as subassembly upthrust, cavitation, vibrations and thermal stripping),
- the operational conditions of ASTRID reactor.

Hereafter are some focuses on ongoing related studies performed with a view to find an RBH operating point that would abide by all these topics and criteria.
This operating point needs to be supported by water-loop experimental results to confirm/bring into question preliminary design features, to provide more information and greater consistency and to optimize the design. Related R&D is presented in chapter V along with the features of the RBH mock-up to be built.

IV.A. Hydraulics calculations

As regards the hydrodynamic force (assuming appropriate coolant actuation flow rate):

- it has been calculated through a one-dimensional modelling based upon Euler-Bernoulli theorems associated to the RBH subassembly pressure drop compilation. The rod apparent mass, the core pressure drop, the coolant actuation flow rate and the « pion » diameter are the first order parameters;
- CFD calculations are ongoing.

As regards drop:

- the rod drop kinetics has been studied based on a simplified analytical modelling on a preliminary RBH design. Drop time obtained complied with requirements;
- this analysis needs to be deepened as regards RBH_1 and RBH_2 variants. Following approaches will be used:
  - o first, a classical approach based on CFD static calculations for various positions of the rod along its drop stroke to be integrated in a more global model to reproduce the free drop kinetics (before arrival in the dashpot);
  - o then an innovative approach based on smooth particle hydrodynamics featuring the flow, to treat the drop kinetics in the dashpot (through a two-dimensional axisymmetric modelling of it). Optimization of the dashpot design is also expected.

IV.B. Other hydraulics topics

As regards cavitation and subassembly upthrust (N.B. both are treated through the same one-dimensional modelling as the one used to determine the lift force on the rod):

- the risk of cavitation may be significant at the working zone level where sodium flow mean velocity values can be high. If operating conditions in this zone can be computed through some operating Thoma criterion, only an experimental determination of the cavitation Thoma criterion is possible, the final comparison between these criteria showing whether cavitation can be expected or not.

- the risk of subassembly upthrust, which may be high at nominal power and flow rate, can be managed by weighing down the subassembly stationary wrapper, by hydraulically locking it in the grid and by correctly designing the above the grid internal part of the subassembly spike.

IV.C. **Absorber rod cooling**

The objective is to determine the flow rate that is necessary to cool the absorber pins of the RBH bundle in such a way that their mechanical integrity would be guaranteed.

This analysis is performed using a design tool based on a subchannel model of subassemblies and is based on some thermal criteria. Nominal operation scenarios and incidental scenarios involving the untimely dropping of a rod during nominal reactor operation are being considered.

The aims for the chosen criteria are to minimize carburization of the cladding, to prevent meltdown of the absorber material and to keep the pellet/clad sodium bond from reaching the boiling point.

A flow rate of a few kg/s per RBH subassembly enables compliance with all criteria in all scenarios. Finally the RBH subassembly flow rate is dictated less by the rod cooling requirements than by the rod lift needs.

IV.D. **Reliability of rod insertion**

Even if the rod is disconnected from its mechanism apart during cocking, problems regarding reliability of rod insertion might occur:

- the potential guide levels being quite distant from one another with regard to their functional reduced clearances, the risk of blockage/slowing down of the rod drop has to be investigated, taking account of the possibilities of misalignment between the rod and the stationary wrapper (for instance due to the manufacturing/mounting tolerances of the structures or the irradiation-induced subassembly bending). A preliminary simplified analysis needs to be revisited in light of RBH_1 and RBH_2 characteristics;
- the risk of blockage by bracing and/or stick-slip has also to be taken into account because of the rod body weight deported away from the working zone at the beginning of the rod drop. A preliminary analysis of bracing showed that no blockage had to be feared and that an increase of the radial clearance at the upper guide level would even be beneficial.

IV.E. **Subassembly integration**

Functional criteria and constraints to be complied with within the subassembly integration process are related to:

- the core reactivity management, that dictates the relative positioning between the absorber and fissile columns,
- the rod stroke management, that dictates the positioning of stops in the wrapper and the guide provisions,
- the management of differential deformations due to multiplicity of structural materials involved, that dictates the expansion provisions,
- the keeping of functional guide clearances, that dictates the relative positioning between the guide levels and the fissile core and/or the selection of materials.

A calculation tool has been developed to perform the optimization of the subassembly integration in a multi-parameters and multi-criteria framework (apart from the above-mentioned functional criteria and constraints, input data include especially the target subassembly length, the elevation of the fissile core imposed by ASTRID fuel subassembly design and the relevant material and design features of the components and their connections).

Uncertainties (cf. manufacturing/mounting tolerances, material properties…) will be included in an upgraded version of this tool.

V. **EXPERIMENTAL INVESTIGATIONS OF RBH MOCK-UP HYDROMECHANICAL FEATURES**

V.A. **Objectives**

It has been explained above how much experimental support is needed to understand the hydro-mechanical behavior of RBH concept depending on the numerous parameters and design features identified and to confirm its feasibility and robustness as regards the actuation technology, whose sensitivity to environmental variations (flow rate, deflections, vibrations…) has especially to be assessed.

This is the purpose of out-of-pile loop tests scheduled in CEA Cadarache BACCARA facility[13] on a RBH mock-up whose main design options and development phases have been chosen in order that it be an analytical support to the RBH design and allow the qualification with sodium/water similitude conditions of the RBH hydro-mechanical behavior to reach Technology Readiness Level 4-5 in 2016-2017 (TRL 4 = analytical validation of lift phenomenon; TRL 5 = almost analytical validation of the complete hydro-mechanical behavior in a representative environment).

V.B. BACCARA facility and RBH mock-up

The BACCARA facility (see Fig. 3) is part of the GISEH platform.[4,13] It has recently been refurbished with a view to RBH mock-up tests.

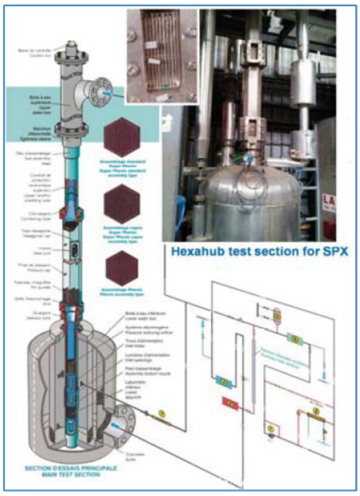

Fig.3. Sketch and picture of the BACCARA facility

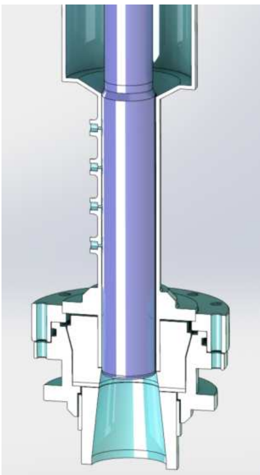

Fig.4. RBH mock-up
Zoom on the working zone

The commissioning of the mock-up shall be made by mid-2016.

Two configurations of the RBH mock-up are contemplated that correspond respectively to two types of tests, static and dynamic, to be performed chronologically:

- in the first step, mainly dummy stationary wrapper and rod are included, that build some working zone as illustrated on Fig. 4; the modular design aims at testing various geometrical configurations of the working zone; the rod mass is representative;
- in the second step, with a view to test the whole operation scheme (cocking and release of the rod by the mechanism; lift; drop) of the RBH, some cocking grip and dashpot features will be added to the RBH mock-up.

V.C. Test program and schedule

As regards static tests:

- some aim at characterizing the effect of the “pion” diameter and of the clearance between the “pion” and the “virole” on the rod lift and at following the evolution of the required flow rate;
- some others aim at optimizing the rod lift by investigating on the one hand the effects of the surface roughness and the working zone length on the required flow rate and on the other hand the effect of the “pion” form on the rod lift (via the regular and singular pressure drops it will induce in the working zone);
- some others aim finally at characterizing the effect of some misalignment between “pion” and “virole” on the rod lift.

First tests should be done in the second half of 2016.

As regards dynamic tests, to be performed on a reference configuration (rod mass, “pion” diameter and form, nominal flow rate) of the RBH mock-up that will be chosen on the basis of the static test results:

- rod cocking, increase of flow rate to the nominal value and rod release will first be simulated;
- the rod behavior (with the rod either in natural position or submitted to some misalignment) will then be monitored while decreasing the flow rate until triggering of the rod drop.

Check and measurements of the mock-up behaviour/movements are to be performed with the help of following sensors:

- laser Doppler vibrometers aim at measuring the working zone output flow velocity;
- an accelerometer (plus a window) located at the working zone output aim at detecting cavitation acoustically and visually;
- several pressure sensors are foreseen distributed between the working zone and the rest of the test section;
- force sensors aim at measuring the hydrodynamic force.

VI. CONCLUSIONS

In this paper, the design activities of the ASTRID RBH complementary safety device dedicated to ULOF transient management have been described. Several variants of RBH concept specifically designed by CEA are under study whose design features need experimental and simulation support to be confirmed or revised and optimized. Scheduled out-of-pile water loop tests are part of the global qualification plan towards licensing of ASTRID start-up core.

Most relevant issues to be addressed in parallel or thereafter in a R&D program:

- Try to benefit from international hydraulically suspended rod design/test feedback experience.
- Hydraulics calculations vs test results
  - BACCARA test results will constitute a validation database for the hydraulics modelling.

ACKNOWLEDGMENTS

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NOMENCLATURE

ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration
CFV	French abbreviation for “Coeur à Faible effet de Vide sodium”, meaning low void effect core
RBC, RBD	ASTRID two distinct and independent fast-acting automatic reactor shutdown systems
RBH S/A	ASTRID concept of hydraulically suspended absorber rod subassembly
ULOF	unprotected loss of flow
ULOHS	unprotected loss of heat sink

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