State of the art of the conceptual designs for ASTRID control and shutdown rods

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Abstract. A critical look at the conceptual designs of control and shutdown rods and absorber elements, along with the lessons learnt from the operation of French fast reactors (Phénix and Super-Phénix especially) and the associated irradiation tests, has yielded improved and even innovative absorber assembly design concepts which are presented in this paper. To comply with the GEN IV objectives set for the 600 MWe Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID), these design concepts have been researched with a view to improved economy/sustainability and enhanced safety.

The two main measures undertaken to achieve economy, among many others, have been to reduce the absorber subassembly dimensions and boron carbide enrichment, as well as to extend the residence time. To achieve enhanced safety, measures could include improved components and/or structural materials and guidance surface coatings/hard-facings in active shutdown systems. As part of these measures, a new kind of absorber assembly has also been designed – called SEPIA[1] – pertaining to safety devices for the passive insertion of negative reactivity in the core.

Preliminary thermal-hydraulic and structural mechanical analyses have been carried out with the CADET and LICOS project codes to show their feasibility. Further detailed analyses need to be carried out to achieve optimum dimensions that comply with the RAMSES II design rules.

The paper discusses the basis of the conceptual designs, giving due consideration to emerging design concepts, analysis backups and further R&D required for design qualification.

1. Preliminary discussions

In 2010, the CEA started the first phase of conceptual design for the 600 MWe Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) prototype to define innovative technical options.

Designed with a defence-in-depth approach based on redundancy, diversity and independence, ASTRID has two distinct and independent fast-acting 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. The absorber subassembly of the first system dedicated to power regulation, compensation for the reactivity change during the lifetime and normal or emergency shutdown is called RBC subassembly, and that of the second system dedicated to emergency shutdown, RBS subassembly. The respective drive mechanisms, RBC-BK and RBS-BK, are housed in the control plug, which is a part of the reactor's top shield.

With a view to a more robust design and safety demonstration, additional core safety features/systems, called SEPIA, are designed as potential options based on passive insertion of negative reactivity equivalent to a 3rd shutdown system, allowing the return to a safe state in case of a loss of coolant accident without scram [1].

[1] This is an abbreviation for "SEntinal for Passive Insertion of Antireactivity".

2. Major design options

2.1. Itemising ASTRID specifications

The following main improvement objectives and related topics for subsequent investigation stemming from ASTRID specifications motivated the structure of RBC, RBS and SEPIA subassembly design activities:

(1) enhanced safety
- (a) lessons learned from previous fast-reactors operations
- (b) structural materials and guidance surface coatings/hard-facings

(2) projected cost savings
- (a) reducing absorber subassembly length
- (b) extending residence time: it is economically desirable to match the residence cycle and, if possible, life span of the absorber elements with those for the fuel cycles (4 runs of 360 or 400 effective full power days, or EFPD, each)
- (c) reducing the total number of absorber subassemblies
- (d) keeping the enriched absorber material requirement as low as possible

2.2. Value engineering

As regards RBC and RBS subassemblies within first phase of ASTRID conceptual design, it was decided to use the same design principles as for the French Phénix, Super-Phénix and EFR systems:

- alignment of all (fuel and absorber) subassembly heads in the core,
- retention of the mobile absorber rod inside the wrapper and maintaining its gravity actuation;
- for the RBS subassemblies, disconnection in case of scram, via an in-sodium electromagnet that does not extend beyond the absorber subassembly lifting head. This constitutes a diversification against common mode failure of insertion of control rods into the subassemblies that makes it possible to guarantee safe core shutdown in case of significant deformation of the reactor block that would be likely to block the RBC mobile rods in their wrappers (disconnection of the RBC rods takes place at the level of the slab).

With reducing the height of the subassemblies as an objective, the following options for the absorber subassemblies were chosen:

- RBC subassembly with lower guide bush and olive-shaped rod spike linked to an absorber drive mechanism with a bayonet-type gripper;
- RBS subassembly with a dashpot located in the lower part and an unsegmented absorber bundle linked to an electromagnetic gripper.

The current standard generic absorber element for the French RNR reactor type has been renewed as the reference option for the start-up core. This absorber element consists of a vented pin with a permanent sodium bond between the stainless steel cladding and the absorber column, which is equipped with a confining shroud (to prevent migration of the absorber fragments). The main absorber rods consist of bundles of such pins, which may or may not be enclosed within a cylindrical pin bundle wrapper depending on the cooling requirements. Boron carbide (B_4C), which may or may not be enriched in ^{10}B (the neutron-capturing isotope of the neutron-absorbing boron element) is currently the only neutron-absorbing material and is not currently being reassessed for the first cores. Most of the R&D and qualification requirements mentioned further on stem from the operating issues inherent to this type of design and/or absorber material. However, both the search for more durable standard absorber elements and the specific requirements for SEPIA system operational modes fully justify requirements that tend to break with current feedback on design/absorber type. Alternative absorber materials like HfB_2 and TiB_2, whether or not they are enriched in ^{10}B, and even Hf are all being considered for the longer term, along with a single- or double-donut shaped absorber column design.

As for the structural materials, the first ASTRID cores will be based on a choice of known and already tested materials, some of which have even been tested in Phénix cores, e.g. EM10 for the hexagonal tube material and

AIM1 for the cladding. All this helps to increase the reliability of rod insertion due to a better understanding and integration of irradiation swelling.

2.3. Design features – Description

2.3.1. RBC subassembly

The RBC subassembly consists of a mobile control rod in a stationary hexagonal wrapper tube identical to the fuel subassembly wrapper, as shown in Fig. 1. Its length is 4.5m and it is supported on grid plate. Nineteen absorber pins housed in the mobile RBC rod are held by guide rails and hang freely from the top. They are arranged in triangular pitch as a bundle, covered by a cylindrical wrapper. B_4C boron carbide pellets are stacked and shrouded in the absorber pin clad tubes. Sodium enters at the foot of the subassembly, passes through the absorber pin bundle and through the annular gap between the mobile RBC rod and stationary wrapper, and exits through the top of the cylindrical wrapper. RBC rod movement inside the stationary wrapper is guided at two levels: at the lower end of the rod spike (mobile guidance along a guide bush located over the spike) and along the entire length of the pin bundle wrapper (stationary guidance by means of pads located in the upper part of the subassembly). The parts of the wrapper in contact with the mobile rod (guide bush and pads) have a hard-faced surface to ensure the durability of guidance throughout the life of the subassembly.

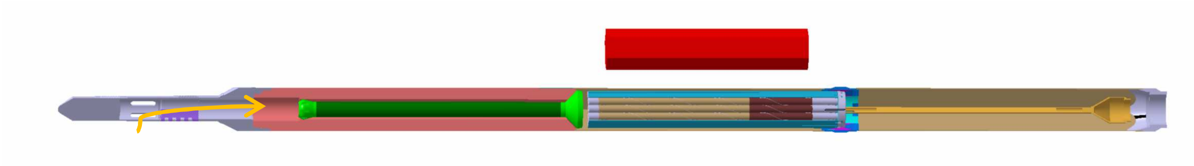

FIG. 1. RBC subassembly
(red part representing the position of fissile core; orange arrow showing sodium flow entry)

A bayonet-type gripper at the bottom end of RBC-BK may be used to hold/release the head of the mobile RBC rod, as illustrated in Fig. 2.

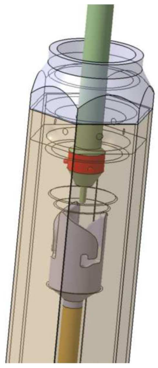

FIG. 2. How the RBC rod could be connected to a bayonet-type gripper
(courtesy of AREVA-NP)

2.3.2. RBS subassembly

The RBS subassembly consists of a mobile rod in a stationary hexagonal wrapper tube identical to the fuel subassembly wrapper, as shown in Fig. 3. The rod's mechanical structure is maintained by a central anchor shaft linking the connecting surface to the electromagnet (in the upper part of the rod) to the dashpot piston (in the lower part). A collar is attached to the anchor shaft, from which the pins are hung along with a centring grid at the lower end of the pins. Unlike for the RBC rods, the objective is not to optimize pin bundle cooling by channelling most of the sodium into a pin bundle wrapper, inasmuch as the absorber material here is not introduced into the core during operation. When the rod has dropped, shock absorption is activated by the piston, which enters a cylinder attached to the wrapper. A wide diametrical gap is engineered between the wrapper and the rod along the entire length of the rod's stroke to ensure rod insertion even in conditions where the wrapper is significantly deformed (bending and/or crushing in the across-flat area).

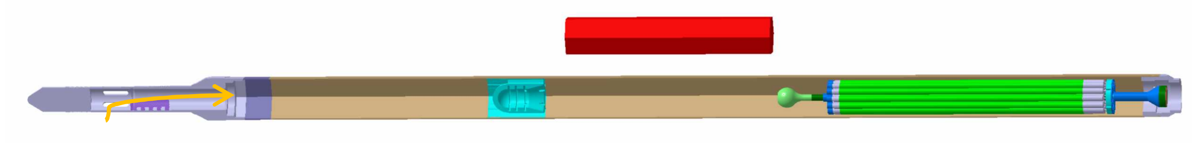

FIG. 3. RBS subassembly
(red part representing the position of fissile core; orange arrow showing sodium flow entry)

2.3.3. SEPIA subassembly

The safety directives for ASTRID are to develop a diversified negative reactivity insertion system that is independent from the two shutdown systems to ensure that if these fail, the hot zero power state in the core will occur at temperatures compatible with the thermal criteria for the fuel melting margin, the boiling point of sodium and the resistance of the structures. To the extent that the failure of the first two systems can be linked to the instrumentation and control system, a requirement is that the third system can be actuated directly in response to a physical phenomenon. A number of different concepts are under study, including a hydraulic actuation system (in response to a drop in flow rate) and a heat-actuated system (in response to an increase in temperature). The research on this last concept is more advanced; actuation is triggered by the differential expansion of two cylindrical shells under temperature transient caused by the loss of the primary flow and/or the secondary flow which is not protected due to the failure of the first two systems. This device, called SEPIA, is illustrated in Fig. 4.

SEPIA consists of a capsule inserted into the centre of a fuel subassembly pin bundle. The differential expansion of the two shells, which are located in the upper part of the capsule, causes several locking fingers on a column of spherical absorber pellets to rotate and thus the absorber elements to fall inside the capsule. This set of design options allows developing a system that is:

- completely independent and distinct from the first two shutdown systems;
- highly responsive to temperature transients, since the actuating system benefits directly from the fuel subassembly flow rate;
- robust from the operational point of view, because the mechanical principle for the actuating system allows out-of-reactor qualification, a locking capability to avoid any risk of untimely triggering at handling temperatures, the development of sufficiently wide movement for the required actuating precision, and the possibility to use mechanical means to ensure reliable actuation. The system is also far enough away from the neutron flux that it is unaffected by irradiation swelling, and remains operational for conditions in which the subassemblies would be significantly deformed due to the mechanical decoupling of the capsule and the central wrapper, to the form of the absorber elements (column of spherical pellets) or to the wide diametral gap created between the absorber elements and the capsule;
- not particularly significant in the core design because:
  a) it requires no absorber drive mechanism and therefore no slab penetration,
  b) it has a very low impact on the core's fuel volume fraction (less than one per cent),
  c) the design concept for the capsule-carrying fuel subassembly is qualified (DCC Phénix) and it is also required for irradiation experiments in ASTRID.

Studies have shown that the thermocouples placed over the subassemblies enable the detection and localisation of the absorber column insertion in a SEPIA subassembly. An ultrasonic detection system is also being investigated.

The main points that remain to investigate in terms of feasibility practically all have to do with qualification, in-pile tests for absorber elements and out-of-pile loop tests for the actuation technology.

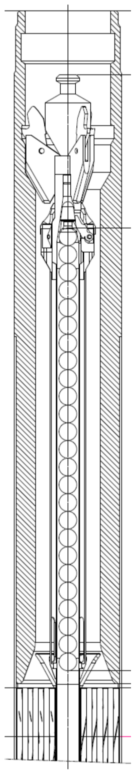

FIG. 4. Illustration of the SEPIA subassembly

3. Examples of studies carried out

3.1. Absorber element design methodology and topics/specific points to be investigated to match the required residence time

The generic design process aims to guarantee throughout the life of an absorber element both the integrity of the cladding in compliance with the RAMSES II design rules and with respect to the propagation of any internal cracks initiated by corrosion of the cladding material in connection with absorber cladding chemical interaction (ACCI), and the absence of: 1) melting of the absorber or of the shroud, 2) absorber cladding mechanical interaction (ACMI) or 3) interaction between absorber elements. Support calculations have been performed using the LICOS project code [4].

The issues relating to compliance with meltdown prevention criteria must be distinguished from life span issues. French feedback on these issues mostly concerns boron carbide (B_4C). Melting temperature and integral thermal conductivity under radiation are the parameters that, together with the geometry of the basic absorber entity (pellet, sphere, etc.), determine whether or not there is compliance with the meltdown prevention criterion. Currently, the most restrictive factor concerning B_4C is clearly the excessively conservative formalism describing the changes to its thermal conductivity under fast neutron flux.

The volumetric swelling of the absorber entity under irradiation and internal corrosion of the cladding material by the absorber material have been identified as the phenomena most likely to reduce the absorber element's life span. Independently, their kinetics determine the instant that ACMI occurs and the time it takes to reach the maximum acceptable corroded thickness relative to the cladding mechanical strength. Together, these phenomena determine the life span over and above which the loss of shroud ductility becomes incompatible with its containment function.

Due to the heavy production of helium when boron materials are subjected to neutron flux, the swelling kinetics are especially dependent on the changes in the capture density rate for ^{10}B. The absence of ACMI will then depend on not exceeding a certain capture density threshold. In the absence of a confining shroud, the appearance of ACMI is subject to the random behaviour of any fragments in the joint and to compression caused by macro-/micro-fracturing of the absorber entity. By holding fragments in place and preventing compression, the shroud significantly slows down ACMI. Achieving long service lives such as those sought for ASTRID and the Generation IV sodium-cooled fast reactors is subject to the reliability and performance of this component.

Strict compliance with the B_4C and shroud meltdown prevention criteria as regards conventional absorber elements has never led to a technological impasse. With respect to the ASTRID project, compliance presents less of a design optimisation problem than it used to, now that ^{10}B enrichment has been scaled down. A life span of at least two runs out of the four required for ASTRID is an accessible objective to start with, by renewing the components and materials that have been validated in the Phénix and with the added reliability of the shroud and the use of "carbothermal"-generated B_4C instead of the "magnesiothermal"-generated B_4C [5] that is the sole basis for the knowledge gleaned from Phénix feedback. Even if in this respect the presence of a shroud is supposed to cancel out the B_4C fabrication differences, it still is necessary to update a behavioural comparison of the two types of product, including for the corrosive potential. Due to the neutron volume requirements for SEPIA absorber entities (solid spheres), the current conservatism of the thermal conductivity law for B_4C turns out to be incompatible with compliance with the meltdown prevention requirement for the absorber. This obstacle alone fully justifies experimental efforts to do away with or at least to better define this conservative approach and find alternative absorber materials that are significantly more conductive and/or heat-resistant than boron carbide. Another major research and development challenge, practically as important as the nature of the absorber material, is to perfect a suitable shroud for SEPIA absorber entities.

3.2. Preliminary thermohydraulic analysis

This analysis is done using CADET [3] and LICOS design tools, based on the thermal criteria that apply to the above-mentioned design process. 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 carburisation of the cladding, to prevent meltdown of the absorber material and keep the sodium joint from reaching the boiling point.

3.2.1. RBC and RBS subassemblies

In the case of the RBC and RBS subassemblies, a flow rate of a few kg/s per subassembly enables compliance with all criteria in every scenario.

For both, the cavitation and fly-off risks still remain to be studied. Even so, the low flow rates required to cool these subassemblies makes it possible to significantly limit these two risks, so the feasibility studies reveal nothing that would disqualify the chosen designs. However, before launching a full thermohydraulic design for these two subassemblies, more thorough studies do need to be done.

3.2.2. SEPIA subassembly

A specific thermohydraulic feature of this subassembly is the column of spherical absorber pellets that are introduced into a device called the capsule, which is placed within a fuel pin bundle from which two rows of pins have been removed. The capsule has no internal flow rate for cooling the absorber spheres, so these are cooled by conduction and then by thermal coupling with the bundle coolant medium. The CADET code is used to do the design analysis to integrate the fuel pin bundle and the transverse thermocouples, while the LICOS code serves to assess the internal temperature of the designed absorber sphere. Two absorber materials are analysed: B_4C and hafnium diboride HfB_2. The limit value of thermal conductivity after irradiation is assumed for each one. The two above-mentioned scenarios are studied.

The design analysis shows that whatever the scenario, the fissile pin bundle is always correctly cooled with a flow rate of about 36 kg/s, even without flow inside the central wrapper. The most severe design scenario is the one featuring an untimely drop of the column of spherical absorber pellets with the reactor continuing nominal operation. Therefore, given the current knowledge on B_4C (especially on how its thermal conductivity changes under irradiation):

- for B_4C: it is not possible from the thermohydraulic viewpoint to ensure the meltdown prevention criterion, even with a flow inside the central wrapper or by increasing the flow rate in the fissile bundle;

- only by replacing B_4C with HfB_2 can the meltdown be avoided.

So, the results do show, however, that the feasibility of the SEPIA subassembly is linked more to the chosen absorber material solution (B_4C *versus* HfB_2) than to its thermohydraulic feasibility, which remains to be refined and validated but so far does not give reason to abandon this design concept.

3.3. Subassembly spikes with additional discriminatory feature

The goal is to keep the core sub-critical under all plant conditions, including design basis conditions and design extension conditions. In order to meet this goal, the normal operating reactivity will be defined so that the sum of all credible reactivity insertions during normal operation is insufficient to cause criticality. During refuelling, absorber rods will be used to reduce the reactivity still further, to account for the additional reactivity associated with possible handling errors.

Additional protection against handling error during refuelling will be provided by including discriminatory features (currently under study) on the subassembly spikes to prevent substitution errors, e.g. the wrong type of subassembly from being completely lowered into the wrong position.

4. Outlook

4.1. R&D and qualification requirements to support design options

In 2012, the different requirements for R&D and qualification of the absorber subassemblies (including the materials) for the CFV core (low sodium void fraction) were analysed, which made it possible to identify the more structurally significant ones with respect to the ASTRID plan. The analysis was based on lessons learnt and on the identification of lacunae in the state of the knowledge and the experimental databases.

Given the current knowledge, as we progress with the ASTRID specifications with the perspective of at least matching the life span of the absorber elements and subassemblies to that of an ASTRID reactor fuel core, it emerges that the main qualification issues concern:

- for absorber element R&D: shroud behaviour, structural corrosion (cladding and/or shroud), and absorber thermal behaviour, with the intent to use the most durable materials possible as a common thread,
- for absorber subassembly R&D: the behaviour of hard-faced parts that are implicated in guidance problems.

The qualification issues relating to SEPIA were discussed above.

4.1.1. Post-irradiation experiments on already irradiated objects

Generally speaking, the qualification of absorber elements and subassemblies will broadly rely on the post-irradiation examinations of irradiation experiments carried out in the Phénix reactor. The objects of interest for the ASTRID core and the testing requirements were identified in connection with the “Phénix Treasures” project [2].

4.1.2. R&D actions on shroud behaviour and cladding/shroud corrosion

The shroud and corrosion behaviour studies must be linked. Before start-up, these studies will consist of sodium loop tests, specific mechanical tests of corroded specimens and analytical irradiation experiments. As for the conventional absorber elements, they must first consolidate or confirm (relative to the “carbothermal” B_4C) what can already be considered as acquired (half-life span) and then reach at least the intended life span of the conventional absorber elements by assessing other types of shroud and/or cladding materials (coatings included) and other design options. If no integral or even representative irradiation occurs prior to the start-up of ASTRID, the scenario will aim for two cycles for the initial loading of ASTRID, based on what we already know. These two cycles would be subject to an appropriate monitoring plan and efforts to introduce, as soon as possible, some precursor materials with the potential for longer life spans (cf. the Superphenix approach).

4.1.3. R&D actions on absorber materials

Three main areas for research and development on absorber materials were identified:

- Consolidating and advancing the knowledge on boron carbide (B_4C) to improve phenomenological modelling and formalisation of its irradiation behaviour. The first step is to make the best use of the most relevant irradiated absorber entities from the "Phénix Treasures" project, in particular those fabricated from "carbothermal" B_4C.
- Studying the changes in the properties and behaviour of HfB_2 and TiB_2 under irradiation. These diborides have been identified among other boron materials as potentially and globally the most capable of meeting the operating requirements for SEPIA systems. They also show the right potential to be appropriate long-term substitutes for the use of B_4C in general. A preliminary R&D step is needed to confirm whether or not they are capable of maintaining under neutron flux the initial properties they were chosen for, i.e. a high and distinctly metallic thermal conductivity and high refractoriness.
- Hafnium metal, which is a robust and durable alternative under rapid flux to boron materials as long as its low intrinsic absorbing power does not constitute an unacceptable handicap. It also has excellent mitigation potential, which is an advantage. The main question is whether it is capable of remaining under rapid flux for long periods (ageing) without unacceptable loss of its geometric integrity.

4.1.4. Irradiation

With respect to absorber qualification, investigations will be launched to carry out:

- irradiation of specific materials to qualify the coatings/hard-facings for guidance parts that are exposed to neutron flux,
- irradiation of absorber elements, using design and flux conditions that are as representative as possible of the start-up core in support of 1) validating the overall design-fabrication-service load process, 2) qualifying "carbothermic" B_4C and 3) demonstrating the shroud life span.

ABBREVIATIONS

ACCI Absorber–cladding chemical interaction

ACMI Absorber–cladding mechanical interaction

AIM1 Austenitic improved material 1

ASTRID Advanced sodium technological reactor for industrial demonstration

EFPD Effective full power days

EM10 Martensitic alloy

RAMSES II Design rules for the fast breeder core structures embrittled by irradiation

RBC-BK Drive mechanism associated with RBC subassembly

RBS-BK Drive mechanism associated with RBS subassembly

SEPIA Sentinal for passive insertion of antireactivity

ACKNOWLEDGEMENTS

The authors wish to thank AREVA-NP teams involved in absorber assembly components and drive mechanisms design and both AREVA-NP and EDF for their financial support.

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