Design studies of the ASTRID nuclear island are conducted in accordance with GEN IV reactors criteria, in particular for safety and operability improvement. The latest configuration of ASTRID nuclear island (including primary and secondary circuits) has been produced by AREVA NP at the end of 2017 corresponding to the middle of the Basic Design phase.

This paper describes the main ASTRID safety and operational requirements and the up-to-date design options, focusing on innovative options.

The on-going phase is a phase of configuration consolidation. The consolidation of options relies on detailed computations (thermal hydraulics and thermal mechanics calculations), on experiments and on manufacturability studies. Some studies and experiments concerning specific structures or components are detailed in this paper.

II. ASTRID DESIGN OPTIONS

ASTRID is an integrated reactor of 1500 MW thermal power.

II.A. Main and safety vessels

The main vessel (MV) of the reactor, which contains all the primary sodium (approximately 2000t) except the sodium of the purification circuit, forms part of the second containment barrier. It has to resist a severe accident and the design must ensure creep and fatigue resistance of this vessel over 60 years in normal operation.

The safety vessel (SV) is outside the main vessel; it contributes to confinement and prevents core uncovering in case of sodium leakage outside the main vessel.

Because of the latter function, the gap between the two vessels should be reduced, so that the drop in sodium level in the main vessel is limited in case of leakage. However, the gap between the main vessel and safety vessel should be large enough to avoid main and safety vessels contact in case of Core Disruptive Accident and to allow the main vessel inspection thanks to a dedicated system.

This paper reports on the progress of the studies concerning:
- thermal hydraulics and thermal mechanics,
- evaluations of the seismic resistance,
- in-service inspection,
- qualification needs.

Lastly, it indicates the open options for materials, components and general architecture, which will continue to be studied in the second half of the Basic Design phase.
steel) and the support box (in ferritic steel), a forged flange is welded at the top of the main vessel to hang the vessel: this flange lays on wedges fixed to the support box. The security vessel is welded to the support box. Both vessel are in austenitic steel (316L(N)) and automatic welding is foreseen.

Main vessel cooling system is achieved using a derived cold flow from the strongback closed part through pipes routing the sodium to the main vessel cylindrical part. An immersed weir limits the risk of gas entrainment and ensures creep and fatigue resistance of the main vessel over 60 years. The device allowing inspection of all main vessel welds from the outside surface in gas (between main vessel and safety vessel) includes a supporting chain with an inspection trolley and precise sensor positioning. Core support structure welds can also be inspected from the outside. Periodic visual inspection of the safety vessel welded joints with the inspection system of the main vessel is planned as well.

II.B. Upper closers – ACS, rotating plugs and slab

Upper closures complete the envelope of the primary circuit at the top of the main vessel and participate in the confinement of the cover gas. They serve as support for components, for instrumentation and for control rod drive mechanisms. Another function of the upper closures is the radiological protection of the personnel in normal operation and during maintenance periods. The ACS, the rotating plugs, the slab and the support box are made of ferritic steel 18MND5. A safety requirement is that there should be no water in the on-roof area: the upper closures are cooled with air.

The above core structure (ACS) supports the 21 control rod drive mechanisms, core instrumentation and the Direct Lift Charge Machine. The instrumentation supported by the ACS includes:

- 351 temperature and flowrate measuring poles (1 above each fuel subassembly and each reflector subassembly of the first row) : 3 thermocouples + 1 Eddy Current Flowmeter,
- high temperature fission chambers to detect local reactivity effect (some are also located in core support structure),
- tubes for sodium sampling over each fuel subassembly to localize fuel cladding failure,
- high Temperature Ultra-Sonic Transducers : SONAR and US Acoustic Detection (active and passive detection)

The ACS is designed for the longest duration: it has to withstand thermo-mechanical loads created by emergency shut down, fast shut down and operational power variations. If necessary, its replacement shall be possible once; a cylindrical ACS has been chosen.

The slab supports the components, rotating plugs and Above Core Structure. The slab is part of the second containment barrier; the best sealing is therefore requested. It is cooled down to 120°C at the lower surface, to avoid sodium aerosols deposition. If the slab is no more cooled, a normal shutdown has to be sufficient to maintain the slab in an operational status. The slab is made of welded metallic plates: metal slab has enhanced resistance to CDA (Core Disruptive Accident). It also has to resist to a sodium fire.

Rotating plugs are made of thick plate steel. While rotating, they are cooled by embarked systems. Polymeric joints are envisaged for the dynamic sealing of rotating plugs because they offer a more compact design than liquefiable metal seals.

II.C. Core support structures

The support structures ensure the core stability, the core sodium supply, the reactivity control and the rods fall in normal and in any accidental conditions. Additionally, ASTRID core structures design aims to improve ISI&R, and the associated constraints to severe mitigation strategy accident such as corium course towards the core catcher.

The strongback is supported by a skirt welded onto the bottom of the main vessel, away from thermal loads. The safety supporting skirt, which is under the strongback lower base plate, is also welded onto the main vessel. These welds can be checked by an UltraSonic examination with guided waves from the inter vessel space. The leak collector is limited to an annular tight volume in the central part of the strongback. The cold plenum is extended to primary vessel bottom; the support skirts and the strongback are designed with large openings to allow a good natural coolability around the core catcher. The strongback design has been improved regarding ISI&R considerations. Inspection of the strongback is possible thanks to:

- the access to the cold pool through 3 slab penetrations and 3 internal ducts, and a possible access to the strongback from underneath (by a robot or a push-pull chain).
- 2 penetrations in the rotating plugs allowing to pass through the core (by removing some assemblies) and use the ISI holes in the crossing of the stiffeners to access the strongback internal welds.

The diagrid supports all the assemblies including lateral neutron shielding assemblies (in SPX, the neutronic shielding assemblies that had no flow rate were on a different structure); the consequence is the large size of this component. It collects and directs cold sodium to the core. It ensures cold sodium distribution through the assemblies, to the inter wrapper space and to the main vessel cooling system: labyrinths control leak flows to the inter wrapper space and to the leaks collector.

The flow rate in the different assemblies is not the same; the distribution is ensured by pressure reducing devices in the assemblies spikes.

The diagrid has to ensure the right position of the assemblies during their loading: there are unmisleading locks in the diagrid tubes to guaranty that each kind of assembly is in the right place. The diagrid tubes also ensure the fine orientation of the assemblies during their loading. A manufacturing study confirmed the feasibility of this component. Diagrid is able to slide onto the strongback, in order to limit the mechanical constraints in case of differential expansions between the two structures.

The inner vessel is welded on the diagrid which facilitates the connection of primary pumps to the diagrid: no bellows are needed.

The gas retention in the diagrid has to be minimized in order to avoid a large gas volume passage through the core that could result in an important insertion of reactivity: the gas is continuously removed by draining assemblies.

This equipment is not replaceable: it is designed for 60 years.

II.D. The core

The reactor configuration at the end of 2017 includes a CFV core (low void sodium worth) referenced ‘CFV BD 16-10’ (Ref. 5). In CFV cores, low sodium void effect is achieved by a heterogeneous fissile zone with sodium plenum in the upper part of the assemblies, Upper Neutron Shielding in boron carbide and an axial fertile plate in the internal core.

The “CFV BD 16-10” core incorporates an innovative architecture of the control and shutdown rods called “RID” architecture. This architecture is composed of 2 kinds of rods, RBC (control and shutdown device) and RBD (diverse control and shutdown device). They both manage the core reactivity during the cycle of irradiation. Three RBC rods contribute to the power regulation.

Complementary safety devices for prevention (DCS-P) and for severe accidents mitigation (DCS-M) have been implemented in the core:
- three hydraulic absorber rods which fall if the core sodium flow decreases under a given threshold (DCS-P-H)
- Curie point electromagnet will release RBD control rod by loss of bearing capacity if the core temperature increases too much.
- 21 crossing tubes (DCS-M-TT) to discharge the corium towards the core catcher in case of core disruptive accident.

Lateral neutron shielding is provided by 11 sub-assemblies rows with MgO sub-assemblies and B4C sub-assemblies. Upper neutron shielding is made of B4C pins, the lower part of which is enriched to 90% in 10B.

The CFV BD 16-10 core includes an internal storage for spent fuels and positions for fuel sub-assemblies with cladding failure.

II.E. The core catcher

The main core catcher function is to collect and manage the corium (melted fuel and metallic structure) coming from the 21 corium guides after the Core Disruptive Accident, contributing to the three main safety requirements: confinement (collection of the whole corium, preventing any uncontrolled scattering of corium solid fragments or liquid phase), control of reactivity (by corium spreading), and efficient and long term post-accidental DHR (cooling by sodium natural convection around the core-catcher).

The core catcher is inside the main vessel; its design includes the tray to collect the corium, plus one or more material layer(s) to protect the component. The choice of this material is still to be made.

Mechanical structure shall resist to the highest energetic accident considered (CDA) and to external aggressions (earthquake, plane crash…). Lifetime of 60 years, plus post-accident management period is integrated in design studies. All materials shall be compatible with its environment in normal and accidental conditions (sodium, gas, corium).

The corium guides that cross the core end under the diagrid in the central part of the strongback which is open, in communication with the cold collector, in order to benefit from a significant height for the corium to fragment before reaching the core catcher plate.

In mitigation situation with low mechanical energy, the Decay Heat Removal Systems inside the primary vessel cool down the corium by primary sodium natural convection.

In mitigation situation with higher mechanical energy, the Decay Heat Removal System outside
the primary vessel also cools down the corium by primary sodium natural convection.

II.F. Intermediate Heat Exchangers

The IHX are the components where heat resulting from nuclear reactions is transferred from the primary sodium to the secondary sodium. The Intermediate Heat Exchangers are part of the second containment barrier (they must ensure tightness between the primary and the secondary circuits); they have to resist to a severe accident and they are designed to meet the specified secondary circuit pressure in normal operating and accidental conditions.

Each of the four IHX is required to transfer 375 MW of heat at normal operating conditions and power operation with one Intermediate Heat Exchanger isolated should be possible.

This replaceable equipment must be designed for the longest duration.

The IHX are counter flow heat exchanger with primary sodium on the shell side of the tubes. The ASTRID IHX thermomechanical behavior is improved thanks to the presence of a bend on the tubes and the suppression of the connection between the central tube and the lower tubular plate.

In order to limit secondary sodium activation, there’s a skirt made of boron steel in front of the upper window devoted to radiological protection; neutronic protections inside the IHX also contribute to limit the activation of the secondary sodium.

IHX / Inner vessel tightness is ensured by mechanical seals (seals with argon have been abandoned in order to limit the risk of gas entrainment into the core).

IHX shutters are manually controlled.

Concerning maturity, this component will be in the same way than those conceived for Phenix and Superphenix, with thermo-hydraulic and thermomechanic optimizations. A manufacturing study has allowed to bring out a solution for the tubes beam mounting (with bends on the tubes).

At last, the design takes into account the need for welding examination on both sides.

II.G. Primary mechanical pumps

Primary pumps force the circulation of the sodium from the cold plenum to the diagrid to ensure sodium supply of the core.

Intrinsic halving time (duration to reach half of the normal flow rate) shall be as long as possible.

Normal power operation with one primary pump stopped is not required but in shutdown states the functioning with 2 pumps shall be possible.

This replaceable equipment is designed for the longest duration (20 - 30 years).

Each of the three pumps delivers 2837 kg/s. The normal rotation speed is 470rpm and the intrinsic mechanical inertia guarantees that the pump flow is at least 50% of the nominal flow 10s after the pumps stop.

The three pumps are supported by the slab (embedded connection of the pump casing).

The main features of the primary pumps are: a single flow impeller (the aspiration flow to the impeller is radial), a subcritical drive-shaft, an asynchronous drive motor with a variable speed, a top oil bearing and an hydrostatic sodium bearing located at the bottom of the shaft above the impeller and fed with high pressure sodium from the pump outlet.

The pumps suction side (inlet to the impeller) communicates directly with the reactor’s cold pool via a suction skirt.

The connection between a pump and the diagrid include:

- a collector at the pump outlet; this collector is fixed to the strongback,
- a Tee and 2 optimized pipes connected to the diagrid (called LIPOSO).

The LIPOSO are designed to absorb the differential expansions between the diagrid and the strongback. Mechanical seals between the pump outlet and the collector shall absorb the displacements between the pump fixed to the slab and the collector fixed to the strongback.

There are no non-return valves at the pumps outlet but anti-reverse devices prevent counter-rotation in case of inverse flow in a pump (case when one pump is stopped while the two others are operating).

II.H. Decay heat removal systems

Requirements and justification of the ASTRID decay heat removal systems architecture are provided in Ref. 6; ASTRID options for DHRS architecture are briefly recalled beneath.

From shutdown down to 10MWth, the normal Energy Conversion System is used for decay heat removal. When the power is lower than 10 MWth, a dedicated system for normal shutdown (NDA) using a water cold sink is implemented on the tertiary circuit.

Two safety systems remove decay heat in the primary vessel:

- the RRB passive system comprises 2 trains of a capacity of 100% with sodium/sodium exchangers located in the hot pool,
- the RRA active system comprise 2 trains of a capacity of 100% with sodium/sodium exchangers located in the cold pool.

A third safety system (RRC) removes decay heat through the vessels (oil circuit outside the safety vessel).
II.I. Fuel handling systems

In-vessel transfer machines are based on well-known components; the principle is to load / unload the subassemblies with two rotating plugs, one direct lift charge machine on the little rotating plug and one fixed arm charge machine on the large rotating plug.

The primary vessel refueling machine is a concept with two ramps and a loading/unloading airlock. The system transfers the subassemblies into a double position sodium pot filled with sodium. The maximum subassembly power for this transfer is about 40kW. The double position sodium pot has been chosen to optimize the availability factor, by exchanging fresh fuel and spent fuel in primary and buffer zone vessels. This device takes opportunity to operate in parallel ramps transfer and in vessels transfer.

It has been chosen to implement an in-sodium external buffer zone, similar with an external storage but associated with an internal vessel storage to reduce its size and its allowable residual power.

The fresh subassembly storage is merged with the spent fuel subassembly storage, which allows both reduction of size and number of equipment.

II.J. Primary sodium purification

In SPX, cold traps were located inside the primary vessel whereas they were outside the primary vessel in PX; both concepts have provided satisfactory results. The main requirements for ASTRID are to try to limit the Reactor Vessel diameter (better with outside cold trap), to try to limit the risk of gas entrainment (better with outside cold trap because it is not necessary to inject gas in the primary vessel to cool the cold trap) and to try to limit the maintenance time (better with outside and large capacity cold traps with internal cartridges). The option of outside cold traps has been retained for ASTRID at this stage of the project but the risk of primary Na leak must be taken into account, that’s why the pipes are doubled and the cold traps are in an inerted dedicated bunker.

II.K. Secondary loops

The secondary loops transfer the thermal power from the primary circuit to the power conversion system (PCS). They ensure a forced circulation of the secondary sodium from the IHX to the steam generators or the sodium-gas heat exchanger according to PCS selection; loops architecture depends on the PCS type. Indeed, two options are studied for ASTRID power conversion system: a Rankine steam water cycle and a Brayton gas cycle. Since 2015, studies focused on the Brayton gas cycle with pure nitrogen. The configuration described in this paper, corresponding to the ASTRID configuration at the end of 2017, is based on a gas conversion system.

In case of IHX tubes leak, secondary loops must prevent secondary loop contamination and reconstitute the radiological confinement. They must protect the Intermediate Heat eXchanger (IHX) in case of Sodium Gas Heat Exchanger (SGHE) leak by limiting the pressure at the IHX’ secondary side.

They must prevent large sodium leak and resist to fire, load drop and seism.

They must accommodate the density variation of the sodium due to temperature change for all operating conditions: loops operate even in cold stop (200°C).

At last, secondary loops must be designed to ensure natural convection onset in the primary circuit in case of loss of supply station power: the loop architecture shall allow to benefit from the thermal inertia of the loop (by natural convection after the secondary pumps stop) during a few hundred seconds in order to cool the primary sodium in the IHX.

Four loops are implemented, that lead to a maximum flow rate of 1594 kg/s for each loop. In the reference loop layout, the secondary pumps are Electro Magnetic Pumps (EMP); this choice is motivated by a simpler technology than mechanical pump, a higher reliability and a reduced maintenance.

A “compact sodium-gas heat exchanger”, based on compact plates modules in a pressure vessel, has been developed for gas power conversion system.

In the latest configuration, secondary loops include 2 sodium-gas heat exchangers per loop that exchange 187.5 MW.

In order to meet requirements concerning confinement, the secondary loops are maintained in overpressure with regard to the primary circuit and isolating valves are implemented on hot and cold legs. Expansion tanks are placed on both sides of these isolating valves.

Loops are automatically drained in case of sodium leak and drained thanks to disruptive valves in case of overpressure due to gas leak.

Innovative multilayer detectors are developed for sodium leak detection as an alternative to pearl wires.

The quality of sodium is controlled (sodium purification is needed).
III. VALIDATION OF ASTRID PRIMARY CIRCUIT THERMAL HYDRAULICS

III.A. Thermal hydraulics calculations

Thermal hydraulics studies issues in ASTRID are:
- for normal operating conditions, the validation of design options, according to the thermal hydraulic behavior of the primary circuit, in order to minimize the thermal loadings on the structures and the components of the circuit,
- for dimensioning transients, to provide input data for damage evaluation,
- for accidental conditions, in particular those leading to decay heat removal in natural convection, to check the respect of criteria of tightness or integrity.

Thermal hydraulics studies of the hot plenum in normal operating conditions aim to verify the thermal hydraulic stability of the jet coming from the core (for nominal and partial loads) and evaluate the thermal fluctuations on the ACS grid (mix of hot and colder temperatures at the core outlet). The objective is to avoid creep fatigue and thermal stripping on structures like the inner vessel, the above core structure and the RRA exchangers. These studies have led to the adjustment of the ACS porosity.

Thermal hydraulics studies of the hot plenum also aim to verify the position of the thermal stratification at the bottom of the hot plenum: due to heat exchanges with the cold plenum through the inner vessel and the cold flowrate coming from the diagrid (upper leakage) the lower part of the hot plenum is cold. It is important that the stratification front should not be situated on some parts of the inner vessel with a complex geometry (stress concentration). Following these studies, a core shell has been added round the core to locate the stratification front on the current part of the inner vessel. It has been checked that the thermal gradient is not too high locally.

Thermal hydraulics studies of the hot plenum also aim to verify:
- the IHX flow supply : the flow supply at the intermediate heat exchangers inlet for the nominal operating conditions must be the most homogeneous possible to guarantee optimal performances and limit the thermomechanical damage on the component,
- the location of instrumentation (DND behind the IHX, thermocouple detectors above the core).

Thermal hydraulics studies of the cold plenum in normal operating conditions aim to:
- verify the lack of thermal stress on LIPOSO and strongback due to heterogeneities of temperatures at the IHX outlet (the outlet window has been redesigned),
- determine temperatures stratification in the upper part of the cold plenum and in the components ducts.

Thermal studies of the cover gas in normal operating conditions aim to:
- evaluate the power received by the upper closing for the sizing of the cooling circuit
- evaluate the temperatures of the gas and the structures for the thermomechanical analyses of the emerged structures.

Thermal hydraulic calculations of normal transients and OC2 transients are conducted to determine the evolution of the main thermal hydraulic parameters in the primary circuit (velocities, temperatures, pressure) to establish thermal loads on main structures and components and evaluate damages. Dimensioning operating conditions (OC1 and OC2 such as automatic and fast trip, stop of a primary pump, increase of secondary flow, stop of an EMP, draining of a secondary loop, loss of power ( delay <2h) …) and number of transients during the plant lifetime are defined for each structure and component. The objective is to analyze the integrity of the major components against thermal loads during lifetime.

The main challenges relative to life duration in ASTRID concern some parts of the intermediate heat exchangers, the ACS and the inner vessel.

The capacity to evacuate the decay heat in natural convection is a strong objective for ASTRID

In the situations of loss of flow, in particular in case of a loss of supply station power, it is necessary to be able to demonstrate:
- the initiating of the natural convection in the primary circuit,
- the establishment of a generalized natural convection maintained by the power extraction by the decay heat removal systems

This demonstration is done by using the coupling of codes at different scales (system scale, sub channel scale in the fuel assemblies and CFD scale).

III.B. Experimental program in the PLATEAU facility

The PLATEAU loop (Ref. 7) has been built in 2012; it provides the experimental conditions, in terms of flow rate and temperature, to various in-water mock-ups. Different tests are being or will be performed in the PLATEAU facility with different
mock-ups to study ASTRID primary circuit thermal hydraulics.

The MICAS mock-up (Ref. 8) represents the ASTRID upper plenum (360°, scale 1/6). The mock-up is placed into a water pool to perform Laser velocimetry in order to get a 3D representation of the flow distribution.

MICAS is used to (tests are on-going):
- confirm the overall thermal hydraulics behavior of the hot plenum (with possibility to realize transients),
- validate CFD simulation tools,
- investigate the presence of local vortex on free surface in order to evaluate the risk of gas entrainment.

The MILIPISO mock-up (Ref. 9), which is currently being tested, represents the Pump / Diagrid connection (360°, scale 1/6). In this mock-up, will be studied:
- the hydraulic stability of the outlet flow coming from the pump /diagrid connections,
- the hydraulics in the diagrid in normal conditions and asymmetrical situations (break of a pipe, pump shutdown),
- the behavior of the gas in the diagrid (identification of the accumulation zones).

The MISHOCO mock-up [9] will represent a part of the core and the hot plenum. It is currently in the definition design phase and could be a 120° sector and a 1/3 scale. Representative of an up-to-date design of ASTRID and on a bigger scale compared to the MICAS mock-up, it will allow to study thermal hydraulics in the hot plenum, thermal fluctuations at the core outlet and inter wrapper flows. It will also bring new data for the validation of CFD (Computational Fluid Dynamic) simulation tools.

A hot and cold plenum integral mock-up is foreseen for the study of the natural convection initiating. The scale is to be defined; it could be about 1/10.

Some other experiments will require a sodium environment.

IV. SEISMIC RESISTANCE EVALUATION

In the reference configuration, there’s a horizontal seismic isolation by seismic pads under the nuclear island buildings. Evaluation of the seismic resistance of the primary structures and components has been realized.

Weak points are:
- some parts of the ACS, that will be reinforced,
- pumps (risk of contact in the hydrostatic bearing): shake table tests are planned to evaluate the risk of pump seizure.

Other structures meet buckling resistance criteria with or without margins

V. CONCLUSION AND FUTURE WORK

The latter ASTRID options are described in this paper. Some options have been validated by thermal hydraulics and thermal mechanics calculations, experiments of manufacturing studies. Work on life duration increase and seismic resistance improvement will continue. Alternative materials are studied for hardfacing deposits, for core catcher structure and layer, for upper closures seals and eventually for SGHE.

REFERENCES


7. D. Guenadou et al. “PLATEAU facility in support to ASTRID and the SFR program: an overview of the first mock-up of the ASTRID upper plenum, MICAS”
Proceedings of NURETH-16, Chicago, USA, August 30-September 4, 2015 – Paper 12895

Proceedings of NUTHOS-11, Gyeongju, Korea, October 9-13, 2016 - N11A0118 1/11

9. G. Gaillard-Groleas et al. “The qualification processes of simulation tools, components and systems within the framework of the ASTRID project – Description and examples”
Proceedings of ICAPP 2017 - Fukui and Kyoto, Japan, April 24-28, 2017 - ID 17407