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Status of severe accident studies at the end of the conceptual design of ASTRID: Feedback on mitigation features

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ABSTRACT

The ASTRID reactor developed by the CEA with its industrial partners, will be used for demonstration of the safety and operability, at the industrial scale, of sodium fast reactors of the 4th generation. Among the goals assigned to ASTRID, one is to improve the safety and the reliability of such reactor (compared to previous built sodium-cooled fast reactors). Regarding the innovations promoted in the ASTRID design, a low sodium void worth core concept (CFV core) has been developed. By means of various design provisions enhancing the neutron leakage in case of sodium draining, the overall sodium void effect of the ASTRID core is near zero and could even be negative. Additionally, mitigation devices should be implemented into the core in order to limit the thermal energy released in the fuel during a severe accident. This paper deals with a synthesis of severe accident studies performed during the second period of the pre-conceptual design stage of the ASTRID project (2013–2015). The main insights of the studies in term of mitigation strategy and of mitigation device design are highlighted in the paper. The CFV core transient behavior has been investigated in case of generalized core melting situations initiated by postulated reactivity insertion ramps (UTOP) and unprotected loss of flow (ULOF). In case of UTOP transients, according to our calculations, the mechanical energy released by molten fuel vapor expansion does not exceed several tenths of megajoule. Simulated ULOF transients do not lead to energetic power excursions thanks to the mitigation provisions and to the core design. Regarding ULOF transients, early boiling phase leads to core power decrease and the primary phase of the accident is not governed by a power excursion. The paper deals with the approach and the presentation of preliminary findings regarding mitigation provisions. Those provisions are investigated by considering a postulated core degraded state representative of the end of the transition phase. The possible scenario evolutions from this degraded state provide the following parameters: mass and temperature of molten materials, mass and flow rates of materials relocated on the core catcher and possible ejected material mass above the core. Those parameters are used for the determination of approximate loadings for the primary vessel and for the core catcher.

1. Introduction

The status of the severe accident studies carried out during the conceptual design of ASTRID is presented in this paper. The main findings of these studies in terms of core and reactor behaviour and in terms of design definition, in particular regarding the mitigation devices implemented in the core (DCS-M-TT), are highlighted in the paper. After a brief presentation of the core design investigated in the studies, the whole study approach is described. First, the objective of severe accident studies, the considered initiating event families and the evolution of severe accident scenarios are presented. Then, the natural behaviour of the CFV core is described and illustrated by study results. Then the mitigation strategy is exposed as well as the adopted approach to preliminarily define the mitigation devices. In the next part the improvement of core behaviour provided by the mitigation devices is described. Finally, the verification process of the acceptability of severe accident consequences in a reactor including mitigation devices is presented even if the verification studies are not done yet.

2. Overview of the reactor design

ASTRID is being designed to fulfill the Gen IV criteria in terms of

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Nomenclature

(U)TOP	(unprotected) transient overpower
C2	outer fissile zone
CAI	lower neutronic axial protection
CFV	low void worth core
CRGT	control rod guide tube
DCS-M-TT	Complementary safety device devoted to mitigation (transfer tube)
DHR	decay heat removal
FCAM	median fertile zone
FCI	fuel coolant interaction
HT	hexagonal tubes
IHX	Intermediate heat exchanger
MOX	mixed uranium/plutonium oxide fuel
PNS	core upper shielding
SA	sub-assembly
SFR	sodium fast reactor
ULOF	unprotected loss of flow accident
ULOHS	unprotected loss of heat sink
USAF	unprotected sub-assembly fault
VEI	lower gas expansion zone
VES	upper gas expansion zone

safety, sustainability, economy and proliferation resistance (GIF, 2002). This reactor consists in a 1500 MWth SFR pool type reactor of about 600 MWe that is an integrated technology prototype designed for industrial-scale demonstration of 4th generation SFR safety and operation (Le Coz et al., 2013). The main objective of ASTRID is to test advances at an industrial scale in dedicated areas (in particular safety, operability, in-service inspection and repair). ASTRID will also be designed to investigate waste transmutation. Fuel type is oxide. Beyond the CFV core design already mentioned before, other innovative options have been investigated during the conceptual design period carried out between 2011 and 2015 in order to improve safety on the following points, for example:

- elimination of the possibility of sodium/water reaction at the interface between secondary loops and ternary circuit (investigation on the feasibility of a gas power conversion system instead of a water/steam system);
- enhancement of the reliability of the decay heat removal system (DHR).

2.1. Primary and secondary system layout and nominal operating point

The ASTRID pool type primary circuit includes three primary pumps and four secondary loops, each one being equipped with an intermediate heat exchanger (IHX) immersed in the reactor vessel (Fig. 1).

Each secondary loop delivers a fourth of the core power (375 MWth) to steam generators or to sodium/gas heat exchangers. The main features of the nominal reactor operating point are provided in Table 1. Moreover, a core catcher is foreseen in order to collect the core materials inside the primary vessel (Fig. 1). The aim of the core catcher is to spread the core materials in case of core meltdown to enable their cooling and to protect the lower head of the vessel. The design of this component is still under way and thus, only general features regarding its design and the severe accident scenario considerations used for its preliminary design are provided in this paper.

2.2. Presentation of the CFV core concept

The version of the core investigated for ASTRID severe accident studies presented here is the CFV-v3 (core including mitigation devices, DCS-M-TT) Table 2, Figs. 2 and 3. This core has been designed in order to increase the time before boiling in case of ULOF transients and also to reduce the severity of a primary power excursion in case of severe accidents. For a classical core featured by a large positive sodium voiding effect, the sodium boiling transient resulting from a ULOF, would certainly lead to a large reactivity insertion that would cause a core power excursion (Papin, 2012). The low void worth effect of the CFV core results mainly from the presence of a sodium plenum above the fissile zones (Sciora et al., 2011) combined to the presence of a fertile plate in the inner core (Fig. 2). The height of the outer fissile zone enables the void reactivity effect to be decreased due to neutron leak enhancement. A previous comparison between a CFV core concept and a homogeneous core showed the better natural behaviour of the CFV concept before sodium boiling onset in case of ULOF (Chenaud et al., 2013). The shroud of all the core sub-assemblies (SAs) represented on Fig. 3 consists in steel hexagonal tubes (HT).

The integration of DCS-M-TTs is presented on Fig. 4 as well as the relocation process expected in these tubes. On the right hand side of Fig. 4, the local analysis of fuel and steel relocation in a DCS-M-TT is performed with SIMMER III (this code is presented by Kondo et al. (2000)). In the SIMMER illustration view of Fig. 4, the fuel and the steel of the neighboring molten SAs (left side of the view) is relocated in the DCS-M-TT (center of the view) that has been drained before due to FCI.

3. Objective of severe accident studies during the conceptual stage

The purpose of severe accident studies is to demonstrate that the associated radiological releases are acceptable and that, following any type of accident, the reactor can go back to a safe state. In order to satisfy this general objective of limiting the releases, the aim is to maintain the integrity of the 2nd barrier (main primary vessel) and the leaktightness of the 3rd barrier (safety vessel: additional shell around the main primary vessel), and thus to reduce the possibilities of occurrence of severe energetic accidents that may affect these barriers. In practice, two temporal phases of the accident scenario can be distinguished, during which the confinement must be preserved:

- the short-term phase in which it is necessary to control the generation of mechanical energy which could result from the accident

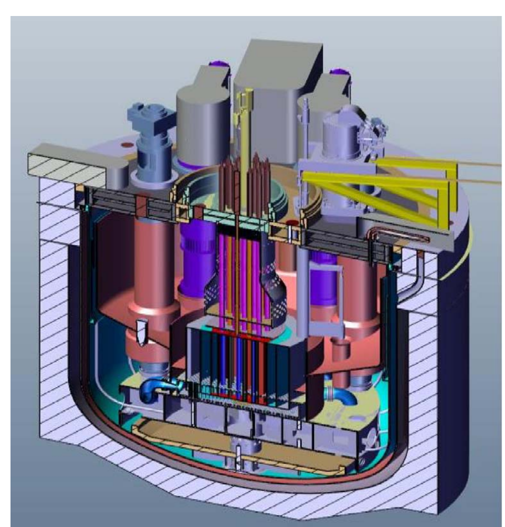

Fig. 1. Primary system arrangement for ASTRID.