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SAFETY CRITERIA FOR THE FUTURE LMFBR's IN FRANCE AND MAIN SAFETY ISSUES FOR THE RAPIDE 1500 PROJEC

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SAFETY CRITERIA FOR THE FUTURE LMFBR's IN FRANCE
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ABSTRACT

The main safety criteria for future LMFBR in France and the related issues for the RAPIDE 1500 project are presented and discussed. The evolutions with respect to SUPER-PHENIX options and requirements are emphasized, in particular for the concerns of the prevention of core melt accidents, fuel damage limits and related required performances of the protection system, since one main option is not to consider whole core melt accidents in the containment design. One shall also point out the advantages of some mitigating features which were nevertheless added in the containment design, although without any explicit consideration for core melt accidents.

INTRODUCTION

In september 1983, the head of SCSIN (Central Service for the Safety of Nuclear Installations) adressed to the general manager of EDF (Electricité de France) a directive (1) concerning the LMFBRs following SUPER-PHENIX, i.e. more precisely the RAPIDE 1500 project. This decision results from : 1) preliminary discussions which started in 1975, 2) then followed in 1977 and 1979 by the issue by IPSN (Institute for Protection and Nuclear Safety) of two drafts of safety criteria, 3) in 1980 by the issue of safety options of the RAPIDE 1500 project by EDF, 4) and finally by two assessments by the Permanent Group in charge of nuclear reactors in 1980-81 and 1983, during which further discussions occured between EDF and the licensing authorities.

The SCSIN directive specifies the safety criteria to be applied, examines each option with respect to the concerned criteria and indicates in some cases the additional necessary conditions to be fulfilled. In this paper, the general approach which was retained by the licensing authorities will be presented first, then the main issues of the SCSIN decision and their rational will be discussed, in particular on the matters concerning core melt accidents where an appreciable evolution occured with respect to the approach taken for SUPER-PHENIX, and finally the matter of emergency plans related to beyond design basis accident will be briefly discussed in connection to the present situation for SUPER-PHENIX.

MAIN DESIGN FEATURES - GENERAL SAFETY APPROACH

For the RAPIDE 1500 project, the main options and the general safety approach are in continuity with those which were retained for PHENIX and SUPER-PHENIX reactors.

With respect to SUPER-PHENIX, the main modifications in the design options (2) are the suppression of the dome in the primary containment design, the replacement of the water cooling of the reactor closure head by an air cooling, on the four secondary sodium loops the suppression of the sodium-air heat exchangers which has been compensated by an increase in the cooling capacity of the four emergency sodium loops, the replacement of the external spent fuel storage by an in-pile storage, and the use of seismic pads in order to reduce the earthquakes loads on the reactor.

The general safety approach is the "defence in depth", as it was applied to PWR or LMFBR's power plants now in operation or construction in France (3, 4, 5). The approach includes the usual three levels : 1) reliable plant operation and prevention of accidents during normal operation, 2) protection against both anticipated and unlikely faults, in order to prevent the propagation into serious accidents, 3) mitigation of the consequences of hypothetical accidents. These three levels mostly concern the design basis for which, in order to fix the safety margins or the necessary degrees of redundancy and diversification, a design guideline of less than 10^{-7} per year and reactor for the probability of an accident with unacceptable consequences is used (3), the expression "unacceptable consequences" meaning that out of site dispositions are necessary. The design basis which are so defined and include the accommodation of design basis accidents are then completed by studies of very low probability accidents leading to unacceptable consequences, in order to obtain, when this is possible by emergency operating instructions or reasonably achievable by constructive dispositions, an additional reduction of the residual risk, either by further prevention of these accidents or by mitigation of their consequences.

For each safety related system or main component, the SCSIN directive details the condition to be fulfilled, with emphasis on the first level concerning prevention, for which attention is put on the need to take provisions for in-service inspection and improve the related methods. Reference (1) also provides lists of design basis plant operating conditions (i.e. 1st to 4th category conditions), external events and beyond design basis accidents, to be considered, the conditions of application of the single failure criteria and of combination with the loss of external a.c. power, and a further list of events which are to be classified after complementary studies.

Since the general design approach is essentially in continuity with the approach which was retained for SUPER-PHENIX (5) and is developped in another paper in the conference with details on the present status of conditions analysis done by the applicant (6), this paper will deal mostly with the main safety issues, which are the approach with respect to core disruptive accidents, designs of the decay heat removal system and the containment. For SUPER-PHENIX, although whole core melt accident were not strictly considered as design basis accidents (7), the containment is designed with this respect in order to withstand a mechanical release of 300 MJ and the long term consequences of core melt (11). For the RAPIDE 1500 project, as the applicant took the option of not considering whole core melt accident in the containment design (8), a qualitative method of analysis was used, in order to assess in view of the current practice, which was applied to PWR, the applicant justification for an approach alternative to the SUPER-PHENIX one, and to identify all the conditions which should be fulfilled in such an approach. This method which is called the lines of defence approach was already outlined at the Lyon Conference (4) and will be presented here after, with its connection with the general approach.

LINES OF DEFENCE APPROACH

The analysis which is used in the lines of defence approach is identical to the line of assurance analysis which was first proposed by J.L. Griffith (9) and also preconised by P. Tanguy (10). It consists essentially to identify the various defences which are available in order to avoid core melting or further to reduce the consequences of such core melting.

In the lines of defence approach, one further uses a qualitative quantification of the quality of each line of defence by making a distinction between strong line of defence and medium line of defence.

A strong line of defence corresponds either to :

- the components or systems which are used in normal operation or anticipated transients and whose failure will lead to an hypothetical accident classified in 3rd or 4th category ; straightforward exemple of such a first strong line of defence are : the main vessel, the normal decay heat system,

- the safeguard components or systems, which are designed with respect to the conditions imposed by hypothetical accidents ; exemple of these second lines of defence are the guard vessel the emergency decay heat system.

In the usual scheme which is shown on Figure 1, the two first lines of defence belong to the design basis of the reactor, the objective being to limit radiological consequence below the limit of 4th category accidents, which may be qualitatively defined as radiological releases for which no significant out of site disposition should be necessary (2) ; they are designed and fabricated with the highest standards, taking into account conservative margins. Redundancy, diversity and geographical separation must be introduced in the design of all the concerned systems or components, in order to achieve a high degree of reliability coherent with the general probabilistic objective, and to cope with common failure modes which may impede the required independence of the lines of defence.

A medium line of defence essentially corresponds to what is called an additionnal beyond design feature, the objective being an additionnal reduction of the residual risk either by a further prevention of severe accidents or by mitigation of their consequences.

The additional dispositions are part of the internal emergency plan (see below) ; they are not necessarily designed, realized and qualified with the same conservatism than the design features.

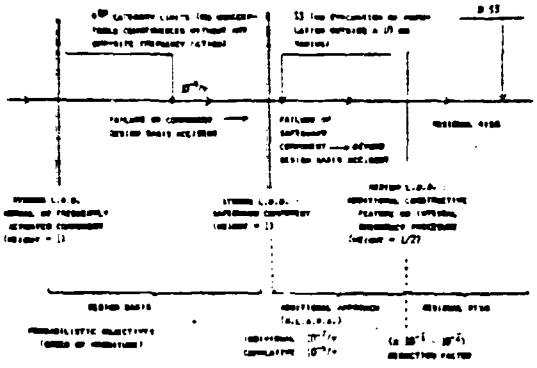

FIG. 1 "LINES OF DEFENCE" APPROACH : ASSOCIATED CRITERIA

The preceding scheme shown on figure 1 must be adapted to each particular risk, in particular when dealing with low probability abnormal transient which can be identified to the failure of a medium line, or design basis external events which can be virtually identified as the failure of a strong line of defence.

By weighting for 1 each strong line of defence and 1/2 each medium line, the general criterion for the RAPIDE 1500 which was settled down (4), is to identify with respect of each particular risk a total number of lines with a weight of at least 2 1/2 ; Figure 1 summarized the overall lines of defence approach, which is clearly a qualitative risk assessment method.

As was shown in a comparison of PWR's and LMFBR's in operation or construction in France (5), the preceding criterion is generally fulfilled by SUPER-PHENIX 1. In the criterion which has been settled down for future LMFBR's, the essential evolution which must be emphazised is that when assessing a risk reducing feature, no qualitative difference is made between reducing the probability of occurrence of an accident or mitigating its consequences.

This had the important output that the licensing authority accepted not to impose mitigation of the consequences core melt accidents as an a priori for containment design. The consequence of such an approach is the need for very strict requirements for the prevention of core melt accidents. These requirements will be discussed now.

PREVENTION OF CORE MELT ACCIDENTS

The question of prevention of core melt accidents is directly linked to the key issues concerning the fuel damage limits in abnormal plant operating conditions and the subsequent needed performances of the protection system. These two issues will first be discussed in a general way and then further detailed for the plant operating conditions affecting primarily the core, which are the transient of power and loss of flow accidents. The discussion of core melt accident initiators will then be completed by dealing with local fault accommodation, cooling of the core by natural circulation and failures of internals.

Fuel damage limits

From the general requirements which have been settled down by licensing authorities for each category of plant operating condition, for the concern of prevention of whole core accidents, one can focus on the 4^{th} category accident requirement which is that, after shut down by the protection system, the fuel should be still in place in a coolable state. However this requirement is not directly applicable to the protection system, since one must rather settle down the requirements until shut down ; for this, the rational may be presented as follows :

1) Until shut down numerous clad failures must be avoided, since the fission gas ejection might introduce positive reactivity and so lead to CDA by the well known close loop of feed backs "rupture → increase of power → additionnal ruptures". So for an approach reduced to prevention, one should conservatively fix a first set of limits, for which clad rupture would be excluded by purely deterministic argument. These limits (noted as condition I here after) must be based on sufficient theoretical and experimental analysis and include conservative margins. One must be awared of the fact that this first condition is very difficult to be fulfilled, since in principle it must be based on sufficient experiments on irradiated fuel for all types of cladding introduced in the reactor, including new types.

2) Straight forward probabilistic arguments show that condition I cannot be considered as an absolute guaranty for the maintenance of the integrity of some 10^{+5} pins submitted to an abnormal thermal transient ; such a guaranty would indeed require to demonstrate that the conditional probability of failure of each pin during the transient is less than 10^{-10} for anticipated transient and 10^{-3} to 10^{-5} for faulted operating condition, which is clearly impossible to show both because of the experimental difficulties which have been emphazised and physical reasons since, in view of such low figures, it is impossible to exclude the occurence of remaining fabrication defects leading to some clad failures. The second requirement, quoted as condition II hereafter, is then to show that in any subassembly a failure occuring before shut down will not propagate to the other pins with : a) large release of gases leading to the subassembly voiding or, b) fuel or clad melting such that the concerned subassemblies would not be cooled after shut down.

The fuel damage limits should then satisfy conditions I and II.

These general considerations will now

be detailed for two main transients of interest which are the inadvertant rod withdrawal and the rupture of the inlet pipe to the core diagrid.

Inadvertent control rod withdrawal

Inadvertent control rod withdrawal are presently classified as anticipated occurrences (2^{nd} category event). Current available data and analysis show that the maximum hot spot clad temperature may rise up to 800°C without clad failure, which fulfills condition I. The same analysis shows that condition I should be also satisfied if up to a certain limit the central volume of the pin melts. Now satisfaction of condition II needs to answer the question of what happens to a subassembly, where most of the pin have a fraction X of molten fuel, when one of these pins fails.

From the extensive work which has been done on possible consequences of clad failures in normal operating condition and has shown that there is then no fast propagation of clad failures, one can answer that condition II is fulfilled when both the maximum clad temperature is less than 800°C and X = 0. To satisfy this last requirement, which is to avoid any fuel melting in inadvertent rod withdrawal transient, improving the design of the protection system is very likely feasible. Nevertheless, a good knowledge of the behaviours of fresh and irradiated fuels during steady state and slow transient is required, and efforts should be continued in that area to improve the estimation of the fuel temperatures.

To search up to what fraction X condition II may be fulfilled is of course an alternative approach which might relax somewhat requirements on the protection system ; it does not seem to be really worthwile in view of the experimental difficulties.

Double ended rupture of the inlet pipe from the primary pump to the diagrid

The guillotine rupture of the inlet pipe from the primary pump to the core diagrid is classified as a 4^{th} category accident. In the SUPER-PHENIX case, the final flow is about 40 % of nominal flow and maximum sodium temperature remains below the boiling temperature. Fuel does not reach its melting point. Concerning the requirements to fulfill conditions I and II, analysis which was done for SUPER-PHENIX has shown the need for improving knowledge on the following points : 1) temperature dependant rupture stress limits of the clad, in particular with respect to the possibility of failures near the mid-plane, 2) consequences of the different possible types of clad failure, with respect to possibility of fast propagation to the other pins and subassembly voiding by ejection of fission gases. On these items, experiments on irradiated fuel are foreseen in CABRI and SCARABEE. If these experiments show that there is a risk of fast propagation of pin failure, the protection system of the RAPIDE 1500 project will need a fast response to the loss of in core flow, a condition which is presently not satisfied for SUPER-PHENIX in the case of this type of accident.

General requirements for the protection system

The requirements of the detection part of the protection system are directly correlated to the fuel service limits and have been discussed on the points which are still open issues. Concerning the redundancy and the diversification, the general requirement is to satisfy the lines of defence approach taking into account the category of the initiating event and the possibility of manual shut down in the case of slow transients.

For that purpose, the present options are :

- two completely separated main systems, each of which satisfying the single failure criterion and achieving safe shut down by actuating rigid and articulated rods ; these two systems will be both actuated in case of transient or anticipated transient like trip of power ; for class 3 or 4 accident a case by case analysis is required,
- a complementary device independent from the two main logics actuating directly the articulated rods in the case of loss of external electrical power ; in case of failure of automatic shut down, manual shut down should be sufficient with respect to other frequent transients.

Local fault accommodation

The basic approach which was retained with respect to subassembly accident is : 1) to avoid local fault by preventive dispositions concerning design and fabrication, design of the plant to avoid loose parts, operation of the fuel with no direct contact between sodium and pellets, 2) detection of flow anomalies by thermocouples and of open clad ruptures by delay neutrons detection in order to avoid blocage and subassembly melting, 3) demonstration that the complete melting of one subassembly will not propagate further than six subassemblies and design of an internal core catcher, with respect to the melting of seven subassemblies.

Each of these three steps corresponds to a line of defence according to basic approach already shown on figure 1. Extensive studies are in progress to demonstrate that each line will be fulfilled, in particular in pile experiments in SCARABEE concerning mainly the third line of defence.

Cooling by natural convection

With the present options which have been taken for the electrical sources of the RAPIDE 1500 project, cooling of the core by natural convection of the primary sodium in case of loss of all a.c. power is required. Start-up tests in SUPER-PHENIX will help to confirm that it is possible to achieve this requirement which has been demonstrated on PHENIX at 4 MW and more completely on FFTF and PFR, the key point being the onset of the sodium flow in all parts of the core just after the electrical black-out. In any case, start up tests will also be necessary on the RAPIDE 1500 to verify that cooling by natural convection is achieved and so to confirm that the present options concerning the redundancy of electrical sources and primary pump coastdown inertia were adequate.

Risk of failure of internals

Extensive analysis of the risk of failure of internals is asked to the applicant who has proposed, both for the core support structure and the other internals, the following approach : 1) prevention of defects by careful fabrication and control, 2) calculation of the evolution of undetected defects during the over-all operation and demonstration that submitted to seismic loads these defects cannot be critical, 3) design of the internal in such a way that either critical cracks or geometrical defects will not cause a catastrophic failure by fast fracture or buckling which could impede the core support, the forced convection by the primary pumps or the decay heat removal by the heat exchangers.

This approach has been accepted by the licensing authorities, with the further condition that methods for in-service inspection of internals should be improved.

A special attention must be paid to the risk of failure of several pump-diagrid connections caused by earthquakes which may constitute a common mode. Should this risk appear not to be negligible, the early shutdown of the reactor during the earthquake should provide sufficient defence against it ; however the coolability of the core in the shutdown state will have to be demonstrated.

DECAY HEAT REMOVAL

For the decay heat removal system which is shown on figure 2, the options and engagements which have been taken by the applicant and which are quoted as acceptable in the SCSIN directive are the following :

1) Residual heat removal by feed water is normal plant unit operationnal configuration. Arrangement are also made to cool down the reactor using the steam generators for a period of about a quarter of an hour in the event of the loss of off site power supply.

2) Four additionnal sodium loops independant from intermediate sodium loops and from each other are provided to remove decay heat for all abnormal design plant conditions including superposition of loss of external power and application of the single failure criteria. Each sodium loop has a heat exchanger immersed in the primary sodium and connected to an external sodium-air heat exchanger.

3) The validity of the options must be confirmed or adapted on the basis of the results of a reliability analysis making due allowance for risks of common modes.

Concerning this last requirement, one must point out that the question of diversification in design, construction and plant operation procedure will be a key issue, for the evaluation of common failure risks.

The status of the on-going studies related to the decay heat removal systems is presented by the applicant in another paper in this conference. This status has not been assessed by the authorities.

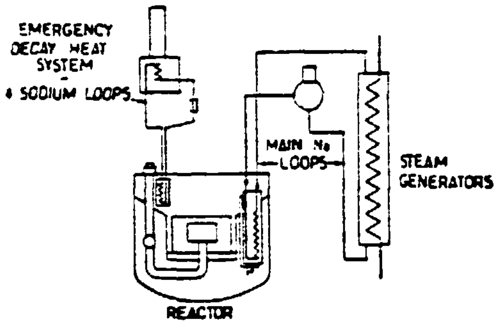

FIG. 2 DECAY HEAT REMOVAL SYSTEM

CONTAINMENT

Containment design

The containment arrangement which is schematized on figure 3 includes the main vessel, the reactor closure head, the safety vessel and the reactor building.

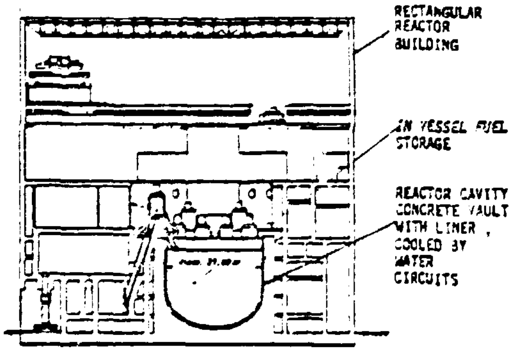

FIG. 3 CONTAINMENT SYSTEM

The safety vessel prevents a main vessel leak from impairing core cooling ; its integrity must be preserved when full of sodium and nominal temperature, during a seismic aftershock with an acceleration level half of the safe shutdown earthquake.

According to the lines of defence criteria, loss under realistically defined conditions of main and safety vessels leaktightness must be considered. This has lead to an extensive R & D program on sodium concrete reactions, which is still in progress.

The secondary containment corresponds to the reactor building which is leak controlled and maintained at subatmospheric pressure, exhaust air is monitored before release to the stack and treated when required. The required performances of the ventilation and filtration in accidental conditions are still matters of discussion : the conclusion will depend both on the results of the analysis of accidents concerning the fuel integrity and on the possibilities of detection and localisation of leakages in the cover gas primary containment.

Sodium fires

The applicant strategy for sodium fire accommodation and related experimental and theoretical development is presented in another paper in this conference (12). It is presently recognized that improvements are necessary on : design of the insulation in order to increase the leak detection capability, characterisation of maximum possible sodium leaks in connection with detection capability, development of large scale experiments and well qualified codes to estimate the consequences of spray and pool combined fires. To cope with the eventual difficulties of such a design approach which has to deal with numerous possible configurations and different failure causes, provisions should be added in the containment design in order to accommodate beyond design sodium fires (e.g. by completing the safety valves with blowing up pannels) and to assure decay heat removal in such events.

Additionnal features

Although the approach which is adopted by the applicant is to deal with core melt accidents only by preventive features, there is an agreement on two additionnal features which are included in the containment design, although without any explicit consideration of core melt accidents :

1. The essential characteristics of the SUPER-PHENIX core catcher design will be kept (11), taking so full profit of the available space under the core support, which means that this device will have an effective retention capacity of molten fuel corresponding to a large fraction of the core.

2. Concerning the reactor closure head, it will be designed to withstand a static internal overpressure of 3 atmospheres, and further, without major modification in the main design options, in particular keeping the air cooling option, improvements in its resistance to dynamic loadings must be searched ; then, the maximum loadings, that can be so withstood by the reactor head structure, will have to be considered to design the support of the reactor head structure and to check the long term integrity of the containment.

One may further point out, that the cooling circuit of the reactor pit which, once the safety vessel is full of sodium, can withdraw about 24 MW could play a significant role in case of a complete failure of the decay heat removal system.

If necessary, these additionnal features will be considered, when assessing the results of the studies concerning the prevention of core melt accident or the reliability of the decay heat removal system, especially with respect to the question of common mode failures.

EMERGENCY PLANS

As stated before, the beyond design basis accidents are generally taken into account to establish out of site emergency plans. Concerning constructive dispositions on the plant and the internal emergency plans, the objective is (see figure 1) to reduce the radioactive consequences of such accident to a source term corresponding to a feasible off-site emergency plan (3), which means that no evacuations should be necessary outside a 10 km radius.

The beyond design basis accident which have been identified so far are : 1) failure to scram in slow transient, requiring manual shut down, 2) melting of one subassembly, with possible propagation to six other subassemblies, 3) loss of leaktightness of the main and guard vessels, 4) sodium water reaction in steam generator larger than the reaction corresponding to the guillotine rupture of one tube, 5) large sodium fire on the reactor slab.

From the preceding discussion of key issues, it appears that the beyond design basis approach must remain sufficiently flexible in order to accommodate difficulties in on going studies. The progress made in establishing similar procedures for SUPER-PHENIX will also help to develop a coherent set of procedures for the RAPIDE 1500 project.

CONCLUSION

The general approach which was used for the RAPIDE 1500 project has been proven to be well appropriate to reach an agreement between utility and licensing authorities. It should be also adequate to accommodate eventual difficulties concerning the basic options or to benefit of the progress made in the safety assessments of the other LMFBRs in operation or in construction.

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