DESIGN OF PRIMARY CONTAINMENT FOR LOOP AND POOL ARRANGEMENTS OF LMFBRs

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SUMMARY

1. *Introduction.* LMFBR-prototypes have different technical concepts for the primary system: France and the U.K. are constructing pool-type reactors, USA and DEBENELUX have selected loop-type reactors. Obviously, the relation between the technical concept and the possibilities to limit the consequences of a hypothetical whole core accident is a widely discussed question.

2. *Pressure loading and response of radial and axial structures.* Three modes of loading phenomena are considered:

1) the transient pressures due to expansion of the vapourised fuel
2) the transient pressures given by a coherent sodium fuel interaction
3) the "equilibrium" pressure given by transfering the excess heat in the fuel to an amount of sodium which produces the highest possible quasi steady-state pressure in the system.

The structural response of pool and loop system is studied in respect to the salient modes 2 and 3.

3. *Load transfer.* The axial forces during the accident have to be transferred via the plug and via the core support to the reactor vessel support. The technical solutions depend on the primary system concept.

4. *Engineered safeguards.* The given structures can be supplemented by special devices to protect cover and vessel against excessive loads. In a first approximation, such safeguards are independent of the technical concept.

The post accident heat removal is accomplished for commercial plants preferably by in-vessel solutions. The expenditure for in-vessel solutions depends more on singularities of a given design than on the particular design concept.

5. *Containment aspects.* The intermediate (primary/secondary sodium) heat exchanger is a critical component of the containment system. The coupling between the source of the accident and the intermediate heat exchanger is different in both systems.

6. *Conclusions.* Pool and loop systems are both adequate in limiting the consequences of an unprevented nuclear excursion of a reasonable size. Advantages and disadvantages are well-balanced for both systems.

1. Introduction

This comparison between pool and loop arrangements of the primary system limits itself to aspects of whole core accidents and is made at a relatively early stage of LMFBR development. Significant differences in approaches between various countries and projects can be identified. International exchanges are now getting underway but there is still a considerable way to go to achieve common judgements in the safety field and common design criteria to accomodate accidents. This paper should therefore be regarded as a preliminary attempt in this area and it should not be expected that final conclusions can be achieved.

The LMFBR prototypes employ different technical concepts for the primary system: UK and France are constructing pool type reactors, USA, DEBENELUX and Japan have selected loop-type reactors. The USSR is constructing both types (see Figure 1).

The essential differences between the primary containments of the two systems are the larger tank and roof of the pool and the external piping and IHX's of the loop designs. So far as developmental aspects are concerned it has to be realized that PFR and SNR-3oo are prototypes on very different timescales designed against requirements of different licensing bodies. It may be expected that commercial designs will show a closer convergence because of technical exchanges and collaboration.

The initiating event of a whole core accident is postulated to be loss of power to all pumps or a positive reactivity ramp. The reactor protection system is assumed to fail so that the reactor goes prompt critical. The nuclear energy release is terminated by the Dopplereffect and the disruption of the core due to a pressure build-up in fuel and coolant. Where fuel and sodium remain separated fuel vapour would be the main source of the explosion. A part of the hot fuel may be mixed with the coolant giving rise to a sodium vapour explosion.

2. Primary containment functions

The functions of the primary containment require to be specified both for normal operation and accident conditions. In the context of this presentation two dominant requirements are identified.

1) The loss of coolant from the primary system must be prevented. The containment of the primary sodium volumes in a large simple tank without penetrations which is subjected to relatively low temperature and irradiation levels and surrounded by a close fitting leak jacket is a major safety feature of the pool arrangement. The loop concept is more sensitive to a rupture of the primary containment, but effective safeguards can be provided: an elevated primary system, cavities around the lower parts of reactor tank, pumps and IHX's and a reliable pump shut down are the solutions selected for the SNR-3oo.

2) To accomodate a whole core accident within the primary system, two requirements must be satisfied:
   - the primary containment must withstand the pressures due to any fuel and sodium vapour generation
   - any debris of fuel released must be deposited and cooled safely inside the primary boundary.

3. Initiating faults and accidents processes considered

Typical initiating faults which are considered for a nuclear excursion are: failure of the reactor shut down system after loss of power to all pumps or following a reactivity disturbance; a large gas bubble passing into the core; expulsion of a control rod out of the core; melt down of a core after a loss of coolant. The relevance of these initiating faults to the design requirements of the primary containment is somewhat different in the United Kingdom and in Germany.

In both approaches the distribution of thermal energy in the core fuel mass after the excursion forms a common starting point for the analysis of the loading phenomena. Three modes of loading phenomena are considered:

1) The transient pressures due to expansion of the vapourised fuel bubble.
2) The transient pressures given by a coherent sodium fuel-interaction.
3) The "equilibrium" pressure given by transfering the excess heat in the fuel to an amount of sodium which produces the highest possible quasi steady-state pressure in the system.

In general for the severity of excursions which have to be considered the loading in the first mode is weaker than in the second and third. Thus, the salient modes are two and three but the first must not be exchanged from consideration. As discussed in chapter 4, the pool system has so far received most attention to accomodate loads in the third mode, while the loop system has been designed for the second mode.

4. Studies on Structural Response

4.1 Components to be considered

The main primary system boundaries to contain pressure in the pool design are the leak jacket and reactor roof structure. The interspace between the leak jacket and primary vessel provides an additional relief volume to the reactor cover gas blanket. The transient pressures arising from mode 2 are limited in the SNR by an internal pressure barrier, consisting of the shield tank, the dip plate attached to the top plug and the grid plate with its support from the tank bottom. This internal pressure barrier is perforated. The loading on the outer barrier, i.e. the reactor tank and its plug, arises through load transfer from the inner to the outer barrier by the supports and by the coolant. In both concepts the refuelling plug is achored to the surrounding structure. The smaller weight of the SNR top plug is hold down by strain bolts. The primary to secondary system interface formed by the IHX's would in both cases be loaded by pressure waves through the primary coolant. The loading of seals in the demountable penetrations of the primary system corresponds to the reactor cover gas pressure.

4.2 Structural Response

Simplified models are used to discuss the structural response to loading modes 2 and 3.

In the case of the equilibrium pressure loadings the reactor cover gas volume acts as expansion volume for both designs. The additional volume between the primary vessel and leak jacket may also be invoked which is larger in case of the pool design. Although considerable increase in vessel thickness could be incorporated in a loop design without excessive increases in material volume or costs simple geometrical considerations give values which override fabrication possibilities. The equilibrium pressure concept is considered as over-pessimistic and by loop designers the transient pressure mode 2 is applied. Pressures which develop slowly to override the design limits of the vessel and plug of a loop system could be accommodated by additional relief measures as indicated in Chapter 7.

The transient loads in mode 2 have been investigated with a simplified regional model using an energy source of 15o MWsec of mechanical work for a 3oo MWe power plant and assuming linearity between excursion energy and power.

The driving function for excursion loadings was defined considering a coherent sodium-fuel interaction. The results show a pressure distribution which decreases with the radius. The effectiveness of the radial inner pressure barrier is given by the strength of this structure. Masses without strength are of minor importance. The forces on the plug are reduced by a dip plate. The influence of the mass of the plug itself is not dominant for the energy release levels considered. A detailed presentation of the results derived for characteristic prototype and commercial plant dimensions are given in the full paper.

The load on the primary to secondary sodium interface in the IHX's is mainly controlled by

1) the pressure pulse propagated along the path of the normal coolant flow (pool and loop)
2) the direct pressure exerted from the core region through the surrounding structure to the IHX's (pool only).

In a pool design damping of the pressure pulse in case 1 is provided by energy diffusion due to large changes of flow cross-section. The coolant pipes of the loop system give damping of the pressure pulse by plastic deformation of the pipe material. It is indicated, that in both concepts sufficient reduction of the pressure amplitude will occur so that the containment boundary remains intact without providing additional safeguards

Direct pressure exerted from the core region and loading the IHX must be considered in the pool design. The full paper discusses model tests carried out for PFR.

4.3 Experimental studies

For a number of years experimental studies have been made in the UK on the containment of core explosions in pool reactors principally using RDX/TNT charges in models typically of 1/16th scale. Work of a more fundamental nature on simple tank configurations has also been undertaken. These studies have given reactor designers an appreciation of behaviour in the explosion containment context. The work is being continued for large commercial reactors and includes tests on simplified reactor models to validate calculational methods. A special low density high explosive charge has been developed to give an improved representation of explosive fuel vapourisation.

U.K. work on effects of an MFCI (Molten Fuel Coolant Interaction) is aimed at fundamental studies of the processes to provide data for containment loading calculations. In this work the charge characteristics and experimental approach have been chosen to be representative of the whole core accident situation.

Within the SNR-consortium BN conducts together with Euratom Ispra a vessel explosion program consisting of 1/12 scaled tests and 1/6 scaled tests. In all tests a slow burning powder simulates the nuclear excursion. The 1/12 tests were performed first in rigid and then in deformable vessels with and without the inner pressure barrier to allow the separation of different physical effects. These experiments revealed as their major result the adequate function of the internal pressure barrier of the SNR. The validitation of the theoretical models is just underway. The final complex 1/6 test is scheduled for autumn this year and will help to analyse and demonstrate the excursion containment in a mock-up close to the real reactor vessel.

5. Special component engineering aspects

5.1 Inner pressure barrier

The integrity of the primary system in the loop design can be maintained for the whole core accidents considered, if in addition to the tank wall as the main boundary a perforated inner pressure barrier is included. For idealized conditions this may be considered as a vessel, which does not transfer forces to the surrounding structure. For the required access to the core for fuel handling either the top of this inner enclosure must be removable together with the main top plug, or the head of the inner enclosure must be rotatable with the main plug and requires slots and other penetrations. The first solution would require a hot cell refuelling scheme and is not used for any of the large prototypes under construction. In the second solution the required stiffness of the top of the inner enclosure can be provided only by connecting the upper plate by strong supports to the main top plug, since only such a combined system is able to withstand the forces. A further consequence of this is that the forces cannot be reacted internally but the load transferred from the upper plate via the supports to the top plug and its hold-down. From here the forces are transmitted through the vessel wall to the support ring in the base and back to the inner pressure barrier.

5.2 Roof and Plug

There are no principal differences in considerations of refuelling plug design for both pool and loop-system. They can be designed for the required loads and can be connected with suitable hold-down systems to the adjacent structures. The roof is a particular feature of the pool design and has to accept loads from the plug and withstand the internal gas pressure as well. It can be shown that the roof structure and the connection between roof and vessel can be designed to withstand the required loading excursions. In contrast to the smaller diameter of a loop reactor, the force transfer from the relatively large roof to the surrounding structure is a separate engineering problem.

6. Engineered safeguards for post accident situations

6.1 Internal core catcher

After a whole core accident it must be assumed that part of the fuel is able to move. It is likely be dispersed as fine solid particles in the sodium. To ensure containment of the activity inside the primary containment this debris must be safely deposited and cooled.

A fuel layer of some centimeters thick is thermodynamically stable on a steel plate immersed in sodium, if the heat can be removed from the coolant. There are strong arguments, that a considerable amount of molten fuel can be deposited and cooled in the lower core and tank structures. Pool and loop systems can both claim this benefit, but evidence for larger quantities is difficult to establish. At the present stage of development protection of the primary containment under the assumption that a major part of the core is molten requires that additional provisions - the internal core catcher - should be incorporated. A device of limited capacity was designed for PFR at a late stage. In the current CFR-programme provisions for increased capability are being investigated including arrays of members which would retain debris while allowing coolant to convect between them.

Such an internal core catcher can be installed in pool and loop reactors. The expenditure depends more on singularities of a given design than on the particular design concept.

6.2 Decay heat removal

The decay heat which is transferred to the primary coolant must be dissipated to a secondary coolant system. Separate from the main heat transfer systems PFR and SNR-3oo have additional emergency coolers which are immersed in the primary sodium of the tank. The design aspects of these coolers are more favourable for a pool system - there is more space and primary sodium heat capacity available. As far as the reliability of function during post accident heat removal is concerned, for both systems considerations for coolers which will withstand accidents loads are similar.

7. Developments in primary containment features

For the pool as well as for the loop concept the designs used in the present comparison are not the only possible ones. In design of the large commercial reactors possible modifications which would improve their behaviour in whole core accidents are being given major attention.

At the present time detailed design work is under way on pool schemes which utilise a prestressed concrete outer vessel similiar to those employed for gas-cooled reactors. This would allow accomodation of the required design basis excursion with a more economic solution. The adoption of the concept for the loop would probably involve difficulties but it should be possible in principle to provide support of the inner pressure barrier with such a design or even replace it.

In the case of slowly developing high gas pressures (chapter 4.2) additional spaces for gas expansion could be provided in a loop system. Referring to the SNR 3oo design, e.g. the volume in the pit above the top plug which is filled with inert gas during reactor operations could be connected to the tank. These connections must be designed in such a way that they will open only after exceeding a certain pressure inside the tank.

8. Additional containment barrier provisions for whole core accidents

From the safety as well as from an economic standpoint the primary goal should be to accomodate a whole core accident within the primary containment. Provision of an inner containment barrier close to the primary containment barrier reduces the leakage requirements on the primary containment. A low pressure reactor building with an atmosphere vented through a filtersystem to a stack after the accident would be adequate for pool and loop systems.

In SNR 3oo it has been required to provide a back-up containment concept to cater for primary containment failure. To achieve this, the inner containment consisting of the reactor cell, the plug pit, the primary cells and a pressure relief room are designed to accomodate the accident after a gross failure of the reactor tank. An external core catcher - which is filled with sodium after the accident - is installed on the floor of the reactor cell and an internal natural circulation of the atmosphere in the inner containment is arranged to dissipate the decay heat to the large concrete masses of the inner containment walls. The outer containment system accepts the leakages from the inner containment. It is surrounded by a leaktight steel shell and would be operated after the accident as a reventing system. Thus, zero release conditions can be maintained for weeks until the outer containment has reached its design pressure and exventing through filters and the stack is initiated. It must be realized that a such a back-up containment system would probably be an unacceptable economic burden for a large commercial power plant. From this point of view, a comparison between pool and loop systems seems to be an irrelevant question. Nevertheless, the capability of a loop-type power plant to accept a limited sodium vapour release by utilising the larger space arrangements around the reactor seems worth stating to show a basic flexibility for accomodating a whole core accident.

9. Discussion and conclusions

For the accomodation of a whole core accident pool and loop systems each have specific advantages and disadvantages. With respect to the pessimistic equilibrium pressure approach, the pool system offers the advantage of large internal gas volumes to relieve the sodium vapour pressure. The high transient pressures of a coherent sodium-fuel interaction can be attenuated by an inner pressure barrier. From a design standpoint, this inner pressure barrier system may be better realized in a loop system. The containment demands on seals and primary to secondary coolant interface are similar for both systems. The simple shaped and compact primary containment boundary gives confidence for a pool system. The more sensitive boundary in a loop system may be compensated by accomodating sodium vapour outside the primary system. The cooling of molten fuel debris offers the same problems and possibilities in both systems.

The conclusions of this preliminary comparison is that although they have different features either a pool or a loop scheme may be designed for satisfactory containment of whole core accidents.

PRIMARY SYSTEM OF POOL AND LOOP CONCEPTS