Design of a Prestressed-Concrete Pressure Vessel with Refractory Concrete for Use in Primary and Secondary Containment of LMFBR Plants

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SUMMARY

Presented is preliminary information on an on-going study of possible use of refractory concrete to improve the performance of the prestressed concrete reactor vessel under high temperature exposure during a hypothetical core-disruptive accident in a liquid-metal fast breeder reactor (LMFBR). A design in which a normal prestressed concrete reactor vessel is covered on the internal (hot) side by a layer of refractory concrete is analyzed. The refractory concrete is considered to be assembled from fired blocks and protected by a liner. An alternative design in which a primary steel vessel separated by a gas gap is deleted and hot molten sodium is in contact with the liner of the refractory concrete layer is also investigated. Several rather advantageous features transpire from these investigations; however, the results are still preliminary.

1. Introduction

A potential problem in the use of reinforced concrete for any structure in an LMFBR plant, whether it is for primary or secondary containment or equipment cells, is the deterioration of the performance of concrete at high temperatures and a possible chemical attack by molten sodium. The chemical reaction of sodium with concrete is of particular concern as it leads to the release of large quantities of hydrogen that may pose a threat to the reactor containment, and causes serious physical damage to the concrete structure.

This paper gives preliminary information of an on-going study of a possible use of refractory concrete, the purpose of which would be two-fold: (1) to reduce the detrimental elevated temperature effects on the main concrete structure, and (2) to avoid a highly deleterious chemical reaction of molten sodium with concrete, particularly with the water contained in concrete. This concept, which seems to be sufficiently promising, could be applied not only to the primary and secondary containment structures but also to any structural concrete which might be exposed to molten sodium.

The idea to use a hot liner and hot concrete under the liner is not new and has been studied by Német and co-workers in Austria [1]. A similar idea for using refractory concrete and hot liners of a prestressed concrete pressure vessel for a coal gasifier was recently proposed by Oland, Greenstreet, and Callahan in the United States [2]. These studies encouraged the authors to initiate this investigation described in this paper.

2. Statement of Problem

The advantages of the refractory concretes compared to normal concretes at high temperatures are well known. They consist in a substantially smaller loss of strength and elastic stiffness due to heating, as well as a substantially smaller increase in creep. Furthermore, the refractory concretes offer the possibility of a castable material that is totally free of water, provided that the material is fired at elevated temperature. In normal concrete complete loss of water results in a total loss of strength. This difference in behavior between normal and refractory concretes is due to the formation of ceramic bond in the latter. The absence of water in a fired refractory concrete will hopefully cause a substantially reduced reaction with molten sodium, thus eliminating or at least greatly reducing during the period of an accident the penetration of sodium into concrete, the inherent gas evolution and potential disintegration of the structure.

Consequently, an examination of using refractory concrete in reactor vessels, containments, or cells for LMFBRs appears to be useful. Refractory concrete would preserve advantages of a concrete vessel, compared to a steel vessel, consisting of an enormous energy absorption capability, ductility and strength reserve, simultaneous radiation shielding, etc. (Bažant, Nuclear Technology, 1977). With this motivation, a study was initiated with the following objectives: (1) to examine suitable designs of a primary vessel or secondary containment with a refractory concrete; and (2) to evaluate such designs from the viewpoint of deformation and strength, response to heating, etc.

A careful study of the physical and mechanical properties of refractory concretes under reactor accident conditions as well as in service conditions is also required. These investigations have recently been initiated under a joint program between Northwestern University and Portland Cement Association (sponsored by EPRI, Palo Alto).

3. Description of Possible Design

3.1 Background Information

While normal concrete loses all strength around 900°C to 1000°C, refractory concretes can carry loads at temperatures up to 1800°C. With regard to the possible contact of hot molten sodium with a layer of refractory concrete, the refractory concrete layer must be deprived of all water by firing it over 1000°C. The absence of water in this layer may be expected to essentially eliminate or at least greatly mitigate the deleterious chemical reaction with sodium during the period of an accident. Moreover, the absence of water would obviously eliminate the high stresses that may be caused by steam pressure in the pores of normal concrete. Furthermore, since the thermal expansion coefficient of fired refractory concrete is considerably less than that of normal concrete, thermal stresses and thermal expansion would be also reduced. If the design of such a refractory concrete layer can be effected at a resonable cost, it would be invaluable to all types of structures for LMFBRs. The usefulness of such a design would not be limited to energetic core-disruptive accidents, but may also provide adequate protection against spillages of hot sodium.

In what follows we describe the concept for the reactor vessel. It applies equally well to secondary containment and equipment cells.

3.2 Design Alternatives

It seems to be neither necessary nor reasonable to use refractory concrete for the entire structure. Rather, it appears appropriate to use a layer of refractory concrete on the inside of a prestressed concrete reactor vessel (PCRV) cast of normal concrete.

Various design alternatives, all using an intact interior layer of refractory concrete about 30 to 40 cm thick, are considered. First we study designs in which the refractory concrete layer is protected on the interior side by a steel liner, as is usual with normal concrete vessels. To facilitate protection of the normal concrete from very high temperatures, an intermediate layer of insulating light-weight refractory concrete is contemplated. This layer is separated from the normal concrete by a relatively thin steel membrane. The buried steel membrane also serves as an added protection against possible leakage of gas or sodium from the reactor cavity, as well as a barrier against migration of water from normal concrete into the refractory concrete layer.

Behind the refractory concrete, separated by a thin steel membrane, there is a thick wall of ordinary concrete, essentially the same as (although somewhat thinner than) the PCRV designs recently proposed for LMFBRs, reinforced and prestressed as usual. An example of one cross section that is currently under study is shown in Fig. 1.

The purpose of the layer of insulating concrete is to reduce the flow of heat into normal concrete in case of a hypothetical core-disruptive accident. Such an insulating layer would serve the same purpose whether or not a refractory layer is used in front of it. Since the insulating layer impedes the removal of heat, it is appropriate to install cooling ducts at the interface between the normal and insulating refractory concrete. Again, this would be necessary whether or not a refractory concrete layer is used. In case of a cooling duct system failure, the normal concrete behind the separating steel membrane would also get heated to high temperatures; this would not normally lead to a complete failure of the PCRV, but it still remains to be determined what would be the effect on the PCRV of such an over heating. This problem exists even when no refractory concrete is used.

Two possible arrangements of the primary coolant boundary made of steel are being considered:

(1) A conventional arrangement (design alternative A at left of Fig. 1), in which the primary coolant boundary is formed by the usual primary steel vessel separated by a gas gap from the secondary vessel--the PCRV with the refractory concrete layer. In this case, the refractory layer on the interior face of the vessel is provided with a conventional steel liner, the same as in the existing design of a PCRV for LMFBR [3,4,5].

(2) An unconventional arrangement in which the primary steel vessel is deleted and the primary coolant boundary for the hot molten sodium is formed by the liner of the PCRV attached to the refractory concrete layer. This novel arrangement has some disadvantages, but it also possesses some attractive advantages. The arrangement provides a much stronger primary vessel, which is essentially earthquake proof due to increased rigidity and strength of the PCRV. Deletion of the primary steel vessel should reduce capital costs. Furthermore, since the innermost steel liner would always be under compressive internal in-plane forces (during operational as well as accidental conditions), the concern about possible fracture of the liner would be greatly reduced compared to the conventional independent primary steel vessel. The liner in this design alternative must be somewhat thicker than in the first one. See the design alternative B at right of Fig. 1.

For either design alternative, the liner is anchored by steel studs running through the refractory concrete layer as well as through the secondary steel membrane separating the insulating refractory concrete from the normal concrete of the PCRV. The conduction of heat through the steel studs into the normal concrete still remains to be evaluated, but does not seem to pose a great problem.

In the design alternative B, which does away with the primary steel vessel, the steel liner is subjected during normal service conditions to compressive thermal forces, since it is installed in a cool state and then heated from the start of operation of the reactor. Calculations indicate that the liner will be subjected to compressive strain several times exceeding the yield limit. Thus, the whole liner would be under plastic compression forces. Obviously, very closely spaced studs would have to be provided, to limit deflection due to buckling of the liner. Assuming that the steel of the liner in a plastic state and at high temperature has an essentially zero tangential elastic modulus in the plastic state, buckling of the liner cannot be prevented no matter how closely the studs are spaced. It seems, however, acceptable to allow some buckling, provided that the maximum deflection of the liner from the refractory concrete is small. Various calculations have shown that the maximum separation of the liner between the anchoring studs would amount to about 3% of the spacing of the studs. At the apex of the buckle between the studs, the steel of the liner would be under plastic tension while the opposite side of the liner would be under plastic compression. The resultant of the normal stresses within any cross-section of the liner would remain compressive; which is more favorable with regard to fracture propagation than the case of tension, which exists in independent steel vessels. Although the concept of a plasticized compressed and bucked steel liner under operating conditions is very unconventional, it deserves a closer look, particalarly since there will be very few loading and unloading cycles during the life of the plant (the primary coolant is always at a fairly high temperature).

As for the refractory concrete, it appears most effective from the viewpoint of construction technology to build the refractory concrete layer from precast blocks that would be fired before their assembly. The alternative would be to cast a monolithic refractory concrete layer, cover it with high temperature insulation, provide hot gas circulating system and fire this whole monolithic large structure, either simultaneously or in sequence, to a temperature exceeding 1000°C. The firing of such a large structure would probably be costly and difficult. More importantly, it would render more difficult the subsequent construction of the liner within the fired refractory shell (since the steel liner cannot be exposed to firing temperatures).

For the joints between the refractory blocks, it seems preferable to consider a dry joint, i.e., the blocks would be placed next to each other without any cementing material. The refractory blocks would be provided with indentations to serve as shear keys between the blocks. The blocks would be reinforced in three directions with a heat resistant steel, but reinforcement that would cross the joints between the blocks appears to be undesirable as well as unnecessary. The blocks would be provided with holes through which the anchors of the liner would subsequently be installed and injected with refractory cement after all blocks and anchors are in position. The amount of water that could be released from the small volume of injected cement would be small and probably acceptable.

As for the type of the refractory concrete, a high-alumina cement with crushed fire brick (or chamotte) seems to be a suitable choice. Alternatively, one may consider chrome aggregate, because of its lesser deformability, particularly lesser creep, at high temperatures. The question of the choice of the type of refractory concrete for use in LMFBR applications is being investigated under a joint program at Northwestern University and Portland Cement Association, sponsored by EPRI.

As another unconventional alternative, a study of the use of a ceramic refractory rather than steel for the primary coolant boundary has been also initiated. This would eliminate the difficulties with buckling of the steel liner, due to the relatively high thermal expansion coefficient of steel. No castable, no refractory concrete can probably be used as the primary coolant boundary because its porosity is greatly increased by the loss of water due to firing, making the material no doubt susceptible to chemical attack by molten sodium over long time periods. However, it may be possible to use as the primary coolant boundary a layer of dense fire bricks which have negligible porosity. There is much experience with such brick linings in chemical industry. The bricks would be probably dry-jointed, and each of them individually anchored by steel anchors (studs) into the underlying concrete. Directly under the bricks one should probably use again a monolithic layer of refractory concrete (high-alumina concrete). The layer of refractory concrete with the brick lining should be fired, which would have to be done on the site. The firing would be possible because this layer has no liner.

3.3 Discussion of Proposed Designs

Some concern may arise over the use of insulating refractory concrete in the reactor vessel since it may inhibit the transfer of heat energy from the primary system to the containment which is required under certain accident conditions. It should be noted that the use of refractory concrete for primary vessel as such does not contribute to keeping the heat within the building in case of an accident. It would be only the use of an insulating layer behind the normal refractory concrete, which would inhibit the flow of the heat out into the reactor containment building. The question of heat removal is thus independent of the question of the use of refractory concrete. The heat would need to be removed from the PCR and rejected into the building either by active cooling systems or possibly by use of passive heat pipes.

For the same reasons as mentioned above, the use of a fired refractory layer might be advantageous for the building containment structure, giving it the capability of resisting extremely high temperatures in case of an accident. It may also be expected to render benign a possible contact with sodium. The design of the containment with the refractory concrete layer is rather similar to that of the primary vessel (PCRV). The main differences are a thinner steel liner on the interior face, a thinner steel membrane separating the refractory and normal concrete, and a much thinner exterior layer of normal concrete representing the load carrying structure of the containment shell. Also, the post-tensioning of the structure does not appear to be hampered by the design features studied. If it is necessary (under accident condition) to transfer heat fairly rapidly through the containment building then the use of an insulating layer of concrete will, of course, impede such heat transfer. On the other hand, the insulating layer prevents the temperatures of normal concrete from rising too high, and the overall design may be capable of meeting these severe accident conditions.

The reaction of fired refractory concrete with liquid sodium will have to be determined experimentally. The authors expect that the reaction is much more feeble than it is for normal portland cement concretes and that a significant reaction is obtained only after a very long exposure time.

The coefficient of thermal expansion of fired and refactory concrete is about 2 to 4 times smaller than that of steel, while that of normal concrete used in the PCRV is also somewhat smaller than for steel. This indicates that, since the liner as well as the steel membrane will be attached in a cold state, the subsequent heating will produce in the liner and the membrane compressive internal forces. Further compression is produced in them by the shortening of the PCRV due to creep under prestress load as well as by shrinkage of concrete. Consequently, the steel liner and the embedded steel membrane would be under permanent compressive forces, possibly with the exception of some local effects near openings, or tensions produced by dynamic accident loads and liner buckling. This contrasts with the present situation in the conventional independent primary steel vessel, in which the whole thickness of the steel wall is under permanent hoop tension and, if suspended, also under vertical tension. With regard to fracture considerations, tensile internal forces are undesirable. Compressive stresses cannot result in fracture propagation.

It should be noted that the overall thickness of the primary coolant vessel as well as that of the containment structure appears to be roughly the same as the thickness in previous designs for which no refractory concrete was considered.

4. Preliminary Analytical Results

A transient analysis involving the ICECO and DYNAPCON codes was performed on an analytical model shown in Fig. 1. [11]. The energy source was considered as 2720 MW-s, which is considerably greater than the energy source used in conventional LMFBR designs. The results indicate that the proposed design is sufficiently strong to resist even this excessive loading: the tendons remain elastic after the excursion, and cracking of concrete is not very extensive.

5. Conclusions

If the sodium vessel, containment, or equipment cells of an LMFBR need to be designed to withstand high temperature exposures and provide good resistance to the chemical attack by molten sodium, then the use of refractory concrete may have certain distinct advantages. The fact that refractory concrete, in contrast to normal concrete, can be deprived of all water without reducing its strength and stiffness to zero, is beneficial in case of contact with hot molten sodium, at least as far as the evolution of hydrogen is concerned. However, the effect of the penetration of sodium into the refactory concrete (due to the porosity increase caused by firing) must be investigated. Preliminary analysis indicates that the design of a concrete structure, in which the refractory concrete is used as a layer on the internal (hot) face of the structure, is an attractive possibility.

It must be emphasized that this is a report on a study still in progress and that the present conclusions are preliminary. The design is certainly highly unconventional and many more questions will have to be answered, including the use of steel liners in a plastic stress state not now permitted by U.S. codes. Further materials research of mechanical behavior of refractory concrete under the expected exposure will need to be carried out.

6. Acknowledgements

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7. References

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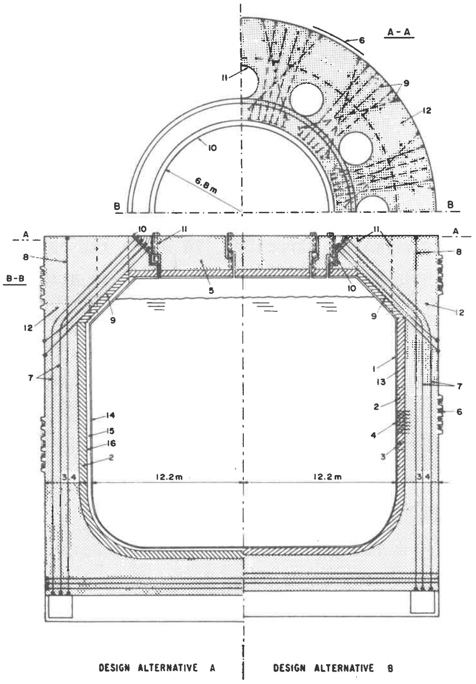
LEGEND:

1- STEEL LINER
2- REFRACTORY CONCRETE BLOCKS
3- JOINTS BETWEEN BLOCKS
4- ANCHORING STEEL STUDS
5- ROTATING PLUG
6- STEEL CLAD CHANNELS
7,8,9- PRESTRESSING TENDONS
10- STEEL RING
11- OPENINGS
12- CONCRETE PCRV
13- STEEL MEMBRANE
14- PRIMARY STEEL VESSEL
15- GAS GAP
16- STEEL LINER



1. Schematic Vertical and Horizontal Cross-Sections of a Possible PCRV Design with a Refractory Concrete Layer.