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DRIED HOT CONCRETE VESSEL FOR NUCLEAR REACTORS: PROPOSAL OF A NEW DESIGN CONCEPT

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The paper discusses special features of the concept of a dried hot prestressed concrete reactor vessel for pool-type liquid-metal cooled fast breeder reactors. In particular, the potentially advantageous feature of removing evaporable water from concrete when it is being kept hot is discussed along with its technological implications.

1. Statement of problem and practical needs

So far, utilization of prestressed concrete reactor vessels (PCRV) has been limited to gas cooled reactors [1–4] for which the PCRV offers important advantages in resisting failure by internal static pressures [5]. Although there were some early suggestions [6] for PCRV utilization and more recently a British concept of LMFBR with a PCRV has emerged, no serious effort has been made so far to adapt the PCRV for liquid-metal cooled fast breeder reactors (LMFBR's). The start in this direction was slow, due to the fact that LMFBR's operate at practically atmospheric pressures and thus do not seem to present a need for a strong pressure confinement as offered by the PCRV's.

Recently, there appears to be a revived interest in PCRV's for the LMFBR. For this, there are several reasons: Firstly, the 1200–1300 MW commercial LMFBR's currently visualized will have to be provided with primary containment for hypothetical core disruptive accidents, which is in excess of current design practice, although future reactor physics research might eventually reduce these hypothetical releases. Secondly, the large loop-type and pool-type LMFBR's will require reactor cavity covers of large diameters. The load that is applied on these covers by the hypothetical accidents is particularly severe, consisting of a slug impact of a large liquid sodium mass moving upward. It appears that the PCRV can serve these purposes well, provided that it is properly designed. Thus, the application of the PCRV to the LMFBR consists chiefly in utilizing the PCRV's capability to resist the loads resulting from hypothetical core disruptive accidents. These dynamic loads are: (1) an early shock wave, (2) a subsequent liquid sodium momentum (slug impact) upon the top slab, and (3) a relatively slowly expanding gas bubble.

Extension of the dynamic analytical techniques for hypothetical core disruption accidents to PCRV's is the subject of a parallel study [7]. At the same time, however, certain problems which are particular to concrete as a material will have to be resolved. One problem which is not sufficiently understood at present is the response of massive concrete walls to sudden high-temperature exposure. In the case of LMFBR's, a second, even more serious problem, is the chemical attack of hot sodium (up to 883°C or 1621°F) on the concrete wall in the case of the liner being ruptured in an accident.

Therefore, it is desirable and prudent to take design measures which would minimize these effects. One measure, which would reduce the thermal stresses due to thermal dilatation and achieve partial relaxation of thermal stresses in the microstructure, is to keep the concrete vessel hot (above 100°C or 212°F). This measure, which is not allowed by the current code [4] because of the lack of information on the behavior of hot concrete, has two advantages: Firstly, in case of an accident, the magnitude of temperature rise during the accident would be less than that for a standard-type vessel kept cool (below 70°C or 158°F). Secondly, the concrete has passed the boiling point of water already before the accident. This means that the concrete of the vessel is already conditioned and tested for high temperatures, and that the response to the passing of boiling point, a most severe loading stage, does not add to the uncertainty in predicting the response to the hypothetical accident. An additional advantage which is gained by this approach is the possibility of removing the insulation layer on the interior side of the steel liner because the liner is designed to be hot. This makes direct inspection of the liner at any time feasible, which is not true of current PCRV's in which the liner is covered by permanent insulation. The foregoing design measures have been recently adopted for the Austrian high temperature reactor project [8,9].

It is the aim of this paper to show that another, potentially advantageous, feature of the hot reactor vessel is the possibility of removing evaporable water from the concrete when the concrete is kept hot. If this could be done without cracking the concrete, the strength would not be impaired and it might even be slightly increased. More importantly, the thermal dilatations would become more predictable, the relaxation of localized accident-induced internal stresses in concrete due to creep would be much more significant, and, above all, the danger of explosive spalling would be greatly reduced.

The designers of the Austrian PCRV with a hot liner did not make any use of drying, undoubtedly because the wall of the vessel is too thick to allow a sufficiently rapid loss of moisture. However, it will be shown that the concrete vessel can be dried and kept permanently deprived of evaporable water if one takes advantage of the hot condition of concrete. To accomplish this, it is proposed that regularly spaced ducts through which hot dry air can be circulated are provided within the concrete. Based on the known rates of drying under 100°C (212°F) it may seem that the spacing of the ducts would have to be unacceptably small. E.g., at 25°C (77°F) and spacing of about 15 cm (6 inches) it would take at least 20 years to dry concrete between the ducts. However, the rates of moisture diffusion through concrete enormously increase when 100°C (212°F) is surpassed [10], which has been recently learned from tests at Northwestern University. As will be shown here, it is possible to dry the concrete wall within about 8 days, using ducts spaced as much as 30 cm (1 foot) apart. Nevertheless, it would not be possible to dry the concrete wall completely without providing drying ducts within the concrete wall.

In the case of a primary containment concrete vessel for LMFBR, the drying of concrete brings about a most important, further advantage in the diminished reactivity of concrete with sodium [11].

2. Description of the proposed cross section of the primary containment concrete vessel

The concrete reactor vessel is considered to be prestressed rather than just reinforced, which offers certain advantages in failure behavior; see ref. [5]. The proposed cross section of the vessel is shown in fig. 1, and that of the wall in fig. 2. The mass of standard concrete of the vessel (about 3.0 m or 10 feet thick) is covered by a 30 cm (12 inch) layer of insulating lightweight concrete, which in turn is covered by a 6.4 mm (1/4 inch) steel liner. Design of a proper anchorage of the liner to avoid buckling under compressive thermal stress as well as stress due to high temperature creep will undoubtedly be an important consideration. Nevertheless, it is clear that designing the liner for a temperature rise from 120°C to about 550°C would be easier than designing for a rise from 70°C to 550°C, which would be the case of an accident in a standard concrete vessel with cool concrete.

The liner can be anchored by long transverse bars welded on the liner (rather than by the usual short studs). These bars are preferably extended through the whole thickness of the vessel (fig. 3). In this form the bars also assure integrity of the insulating concrete

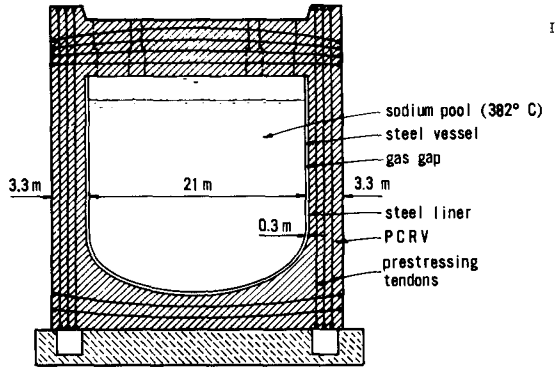

Fig. 1. Simplified sketch of vertical cross section of the concrete primary containment vessel (PCRV).

with the standard concrete, and at the same time they serve as transverse reinforcement of the vessel wall. These bars will further provide additional resistance to explosive spalling of the wall in case of a sudden heat shock reaching the liner in a nuclear accident. Because of the concreting procedure which would indoubtedly require placing the insulating concrete prior to the standard concrete, a formwork would have to be provided on the outside of the insulating concrete layer. The standard concrete would be subsequently cast against the insulating concrete serving as formwork. It would be rather unwieldy for construction if the long transverse bars were let to protrude through the holes drilled through the formwork for the insulating concrete. Therefore, each bar may have a splice joint (weld, or a threaded sleeve) near the formwork. On the interior face, the liner, assembled first, may serve as the formwork of the insulating concrete layer, as usual. Even though the insulating concrete has a Young's modulus of only 0.1 to 0.2 of that of standard concrete, it would still be stiff enough to hold the liner laterally in place. In fact the lateral support of the liner is ensured by the transverse bars welded upon the liner, and buckling of the liner to the side of the air gap is always more likely than buckling into the insulating concrete. Because of the great length of transverse anchoring bars, no stud-type heads are needed at the end and standard hooks should suffice.

A question may arise as to whether a second, buried liner should not be provided between the insulating concrete and the standard (structural) concrete, as in the Austrian vessel design (fig. 1 of ref. [8]), with an injected mortar layer filling the gap between the insulating concrete and the later erected second liner. It is believed, however, that such a second liner would be unnecessary and, breaking the continuity of concrete, perhaps even detrimental to the integrity of the vessel.

The liner is not covered by any insulation, which renders direct inspection of the liner feasible. The temperature of the liner would thus nearly attain the temperature of the sodium pool (382°C or 720°F). Over

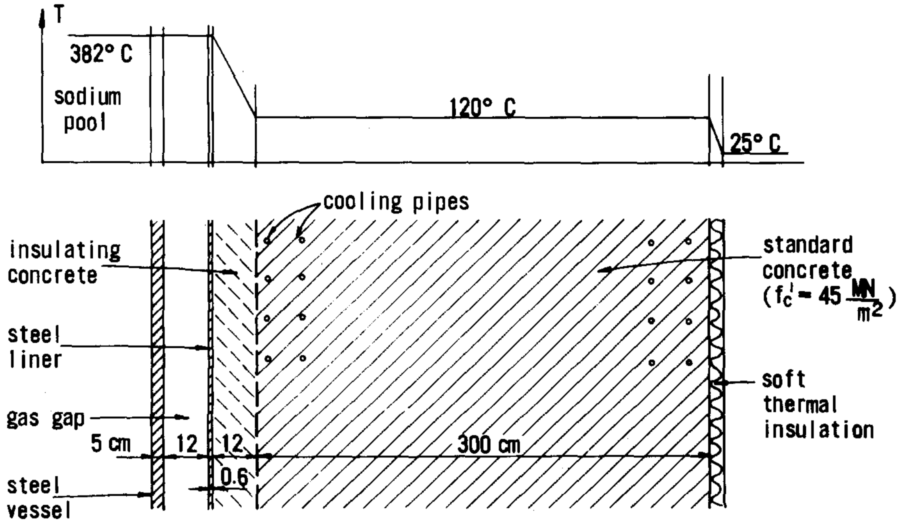

Fig. 2. Cross section of wall of the primary containment vessel (PCRV) and operating temperature profile.

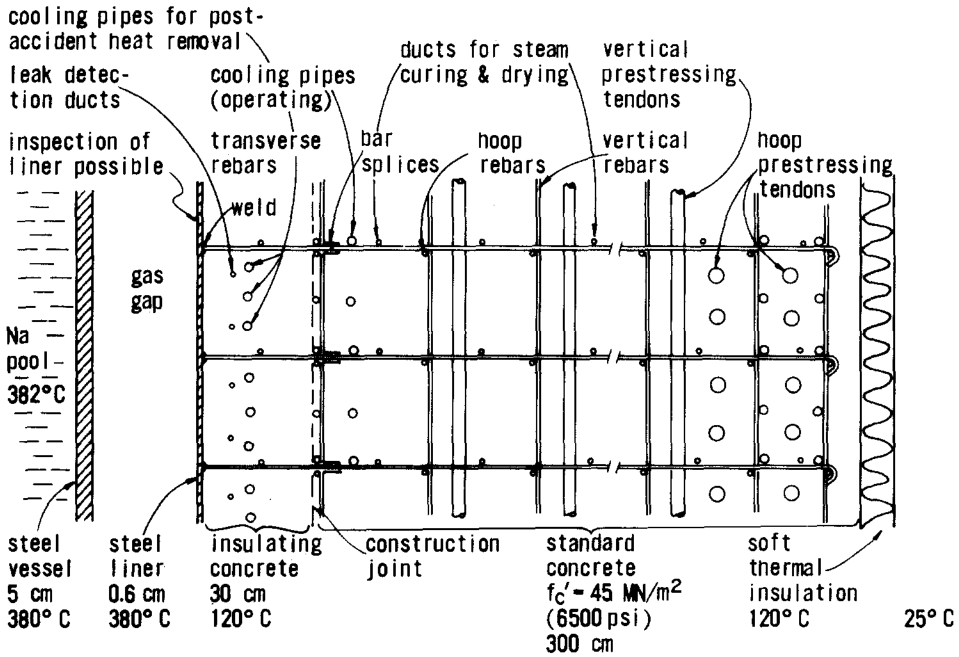

Fig. 3. Reinforcement, ducts and pipes within the cross section of wall of the primary containment vessel.

the thickness of the 30 cm (12 inch) insulating concrete layer, temperature would drop to 120°F), the steady-state temperature of the standard concrete. This temperature would be kept almost uniform throughout the thickness of standard concrete (about 3.0 m or 10 feet). For this purpose, adequate buried cooling tubes must be provided at the interface with insulating concrete. On the external face, the standard concrete would have to be covered by thermal insulation (of the soft, fibrous type), and it will have to be heated by recirculating the cooling gas (air, or CO_2, He) through the ducts which will be located near the external face under the liner.

Direct detection of a possible leak of the liner may be accomplished monitoring possible penetration of the atmosphere behind the liner into leak detection ducts which will be located within the insulating concrete, several inches under the liner.

The reasons for using a layer of insulating rather than ordinary concrete under the liner are as follows:

(1) Insulating concrete will greatly reduce the demand for cooling of the vessel (about 10-times).

(2) Insulating concrete is a porous, lightweight-aggregate concrete which is known to have a much weaker tendency to spall in fire exposure (see [12], p. 531). It also shows a smaller loss of strength on heating and a lower thermal expansion than does the ordinary concrete.

(3) Insulating concrete is more deformable, and thus, in case of an accident, thermal stresses would undergo stronger relaxation due to creep. However, pre-drying would reduce the relaxation capability to some extent.

A possible disadvantage of insulating concrete might be that it would inhibit post-accident heat removal. This problem could be solved by placing, strictly for the purpose of an accident, additional cooling ducts close to the liner. If post-accident heat removal is the main concern, the insulating concrete should perhaps be replaced by standard concrete. On the other hand, insulating concrete can be allowed to heat to a higher temperature than the structural concrete.

The purpose of keeping the standard concrete continuously at uniform temperature of 120°C (248°F) during the operation of the plant (and, if possible, even during shut-downs) consists in the following.

1) The response of concrete would be made more predictable. The response of dried concrete is known reasonably well from fire testing, where

dimensions of specimens are usually so small that moisture is lost at the beginning of the fire test. The response of concrete which is prevented to lose moisture during heating is not known at present sufficiently well.

2) Dry condition of concrete would be ensured, thus increasing strength and making thermal dilatations more predictable (and smaller as compared with wet concrete at constant water content).

3) The thermal strain on heating in an accident would be greatly reduced, which is achieved by eliminating the large thermal strain between 25°C (77°F) and 120°C (248°F) as well as the drying shrinkage. These would otherwise occur during the accident in a rather non-uniform distribution throughout the wall.

4) The possibility of a build-up of large steam pressure in the pores of concrete if concrete is heated well above 120°C (248°F) in the event of an accident would be greatly reduced. (However, some steam will always be generated, even from an initially dry concrete, due to dehydration of silicates above 120°C.) Reduction of pore pressures should alleviate the danger of bulging of heated liner and of explosive spalling of a layer of concrete under the liner. (Whether concrete walls protected by a steel liner can exhibit explosive spalling has not been investigated, but according to the theory of explosive spalling (cf. ref. [11]) it appears that susceptibility to it should be higher because a liner allows a larger pore pressure build-up in the concrete wall.)

5) The reactivity of concrete with liquid hot sodium would be diminished. This would largely suppress the highly exothermal, rapid reaction $2\,Na + H_2O \rightarrow Na_2 + H_2$. The reactions $6\,Na + Fe_2O \rightarrow 2\,Fe + 3\,Na_2O$, $2\,Na + FeO \rightarrow Fe + Na_2O$, and $Na_2O + SiO_2 \rightarrow Na_2SiO_3$ [10,13], which are also rather rapid and exothermal, would not be eliminated, but evolution of hydrogen would be suppressed, which is very desirable from the safety point of view.

6) The elevated temperature of concrete could be utilized to achieve accelerated curing of concrete, as well as development of higher strength; see next section.

7) Creep of concrete at high temperatures is significant even for short load durations [10]. In the accident situation, creep would be undoubtedly diminished by the absence of moisture. This may be both useful, by reducing deformations, and detrimental, by diminishing the relaxation of thermal stress in concrete.

The surface of concrete should not be allowed to cool below 100°C because concrete would then begin reabsorbing moisture from the environment (although cooling for brief periods would probably be of little consequence).

Drying of concrete reduces its neutron absorption capability. However, this is of no consequence because, due to strength requirements, the thickness of the concrete wall would in any case have to be greater than is needed for radiation shielding.

The relaxation of prestressing tendons at 120°C (248°F), as compared with the 25°C to 40°C range, is significantly higher. Nevertheless, as has been demonstrated by tests for the Austrian project [8], the relaxation values are still acceptable; they are 14% rather than 3% for an initial stress of 0.6 of the strength of wires, and 23% rather than 7% for 0.7 of the strength of wires. These prestress losses might eventually be reduced by retensioning of the tendons after heating, taking proper account of allowable strain. Another drawback is the increased creep of concrete at high temperature. This would also increase the prestress loss, and further it would induce higher compression stress in the steel liner [1], which would have to be properly analyzed and taken into account in design. These drawbacks have already been handled in the Austrian project [6,13].

3. Drying of concrete walls by means of ducts

To dry the concrete wall and heat it uniformly to 120°C (248°F), it will be necessary to provide regularly spaced ducts within the wall of standard concrete; see figs. 2–4. A square array of side $2l$ may be considered. It is necessary to demonstrate that it is possible to dry up the wall within a reasonable time span.

As a rough approximation, the process of drying of concrete may be described by a linear diffusion equation,

$$\partial w/\partial t = C\nabla^2 w \,, \tag{1}$$

in which w = evaporable water content per unit volume of concrete, t = time, ∇^2 = Laplacian operator, C = moisture diffusivity in concrete. At room temperature, C is extremely small and rises only modestly with

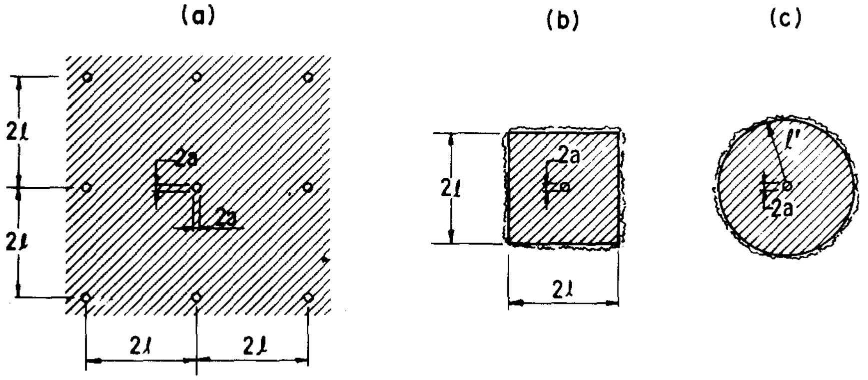

Fig. 4. Array of drying ducts in an infinite solid (a); equivalent problem (b); and simplified problem (c).

increasing temperature. However, as has been confirmed by recent tests at Northwestern University, C increases by orders of magnitude as 100°C (212°F) is surpassed.

To estimate the drying time, eq. (1) has to be solved for an infinite region with a rectangular array of holes; see fig. 4a. Due to symmetries, this is equivalent to a square region with an insulated boundary (grad $w = 0$) and prescribed $w = 0$ on the boundary of a circle of diameter $2a$ located within the center of the square of side $2l$; see fig. 4b. The initial condition at $t = 0$ is $w = w_0$ for all points of the domain, w_0 being the saturation value of w. In Carslaw and Jaeger's book [14], the solution of this problem is not indicated. It would be possible to obtain it, but for the present purposes an adequate estimate can be made by replacing the square domain with a circular domain (fig. 4c) of equal area, which should give a mean estimate, or with a circumscribed and an inscribed circle, which would give the upper bound and the lower bound on the drying times. Solution of this case can be easily obtained as an infinite series of Bessel functions by the method described in [14]. Up to the time t_1, when the drying front spreading from the hole reaches the boundary of the circle, the solution must be identical to that for an infinite solid with a hole, having $w = 0$ and $w = w_0$ at infinity. This case allows an even simpler estimate of the drying time. The solution to this case is given by fig. 41 on p. 337 of [14].

Consider that the drying ducts are spaced at $2l = 30$ cm (12 inches) and their diameter is $2a = 13$ mm (0.5 inches). For the boundary of the inscribed circle, $x/a \approx 24$, x being the radius coordinate. The solution in [14] is plotted in terms of $^{10}\log(x/a)$. Reading the ordinate for $^{10}\log 24$ as 1.34, one obtains $Ct_1/a^2 \approx 40$, in which t_1 is the time for the drying front to reach the boundary of the inscribed circle of diameter $2l = 30$ cm (12 inches). Hence, $t_1 \approx 40\, a^2/C = (40/24^2) \times l^2/C = 0.069\, l^2/C$. This may be compared with the drying time of a long solid cylinder of radius l, exposed at the surface. According to the solution also plotted in [14], the drying front, spreading from the surface inward, reaches the axis of the cylinder within the time $t_0 = 0.035\, l^2/C$. Thus, $t_1 \approx 2t_0$ i.e., drying of the wall by means of ducts spaced at distances $2l$ is about half as fast as the drying of a solid cylinder of diameter $2l$. It has been observed by tests at Northwestern University that complete drying of a 6-inch diameter cylinder at 120°C (248°F) of a representative concrete takes about 1 day. Thus, drying of a 30 cm (12 inch) diameter cylinder would take about 4 days, and so the drying time of the wall is finally estimated as $t_d \approx 2 \times 4 = 8$ days.

Similarly, one can estimate that for ducts of 25 mm (1 inch) diameter spaced also at 30 cm (12 inch) distances, the drying time would be about 6.5 days, and for ducts of 6 mm (0.25 inches) diameter spaced at 30 cm (12 inch) distances, the drying time would be about 10 days. (For $a \to 0$, one obtains, of course $t_d \to \infty$.) Since circulation in a duct of 6 mm (0.25 inch) diameter may be too slow, ducts of diameter $2a = 13$ mm (0.5 inch) are probably a reasonable choice.

If no drying ducts were provided, drying of the wall of 3 m (10 feet) thickness, insulated by the steel liner on one side would be impossible as it would take about 7 years at 120°C (248°F). Besides, the gradients of stress due to thermal dilatation and shrinkage could lead to large cracks.

To allow uninhibited moisture transmission into the ducts, the wall of the duct cannot be made, of course, of a simple steel tube. The duct wall can be formed by plain concrete, which could be achieved, e.g., by collapsible inflated tube forms as used on British PCRV's. Alternatively, perforated or porous tubes could be considered for forming the walls of the ducts.

4. Procedure of curing, heating, and drying

The procedure of curing, heating and drying may consist of the following two phases.

I. The drying ducts, which have to be within the concrete anyway, may be used to further advantage in the curing of concrete. Namely, by first circulating through the ducts steam (moist air) of temperature about 80°C (176°F), a low-pressure, low-temperature steam curing (cf., e.g., [8]) can be easily accomplished. This type of curing yields essentially the same type of concrete as does room temperature curing; but the strength development is about 10-times faster. Thus, after approximately 2 months of steam curing, a 2-year strength value can be attained. Temperature would be raised to 80°C (176°F) gradually, over a period of several days, to assure an almost uniform temperature distribution at all times and eliminate the chance of creating long cracks in concrete due to thermal stress. For the same reason, the surface of concrete would have to be thermally insulated from the beginning.

As an alternative one might consider high-temperature steam curing (autoclaving, beyond 100°C or 212°F) [12]. However, this curing requires large pressure, and it would probably be undesirable to expose the wall to pressure from within rather than from outside, because tensile cracks could be produced. This curing yields concrete of a different microstructure, with a much smaller internal surface area, and a somewhat different chemical composition.

II. The circulation of moist air 80°C (176°F) warm would then be replaced by the circulation of hot dry air (or some other gas, such as CO_2 or He), whose temperature would gradually be (over a period of a few days) raised to 120°C (248°F). After about 8 days, this will achieve complete drying of the concrete wall. The concrete will exhibit considerable shrinkage, but because of close spacing of ducts the shrinkage cracks should remain small and densely spaced. Anyhow, proper shrinkage reinforcement must be provided. Even more effective in preventing shrinkage cracks would be a prestress of the vessel if it were applied before drying. To achieve more uniform drying and greatly reduce shrinkage stresses, the temperature could be raised to 120° (248°F).over a period of one month.

5. Conclusion

The new concept of a dried hot prestressed concrete primary containment vessel appears to be technically feasible and is distinguished by attractive safety features. The concept deserves detailed study.

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Appendix I

Why prestressed concrete rather than steel primary containment

The safety advantages of prestressed concrete reactor vessels as compared to steel vessels have been analyzed in general in ref. [5]. They include the absence of failure propagation characteristics (as in brittle fracture of steel); more favorable load-deflection diagram, the property of closing of cracks on unloading after an overload; greater capability of energy absorption (as compared with a steel vessel exhibiting brittle failure); and better resistance to earthquake, external missiles, blasts and tidal waves (in detail, see [5]).

Furthermore, with a concrete rather than steel guard vessel, one makes double use of the concrete wall which has to be provided anyway for neutron absorption. Various advantages of using concrete for the primary containment vessel have been pointed out.

Since the primary containment vessel of a pool-type sodium-cooled breeder reactor is not exposed to any significant internal pressure during normal operation, it might seem that no prestress is necessary. However, in spite of this fact, prestress is needed for the following reasons.

1) Without prestress, the cracks created in the vessel by internal pressure during an accident would not close after the internal pressure disappears, because of the well-known irreversibility of concrete stress-strain curves as well as load-deflection diagrams of concrete structures.

2) Prestress is beneficial in preserving integrity of concrete by eliminating shrinkage cracks and thermal cracks.

3) Prestress would reduce the opening of cracks in case of an accident.

4) Prestressing is probably also economical, due to the highly reduced weight of steel reinforcement needed.