

CONCRETE FOR RADIATION SHIELDING--IN PERSPECTIVE

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A historical outline of the use of concrete for radiation shielding is presented with particular emphasis on the Hanford operations in the state of Washington.

Keywords: aggregates; barite; boron; concretes; ferrophosphorus; ferrosilicon; heavyweight aggregates; heavyweight concretes; high temperature; history; limonite; magnetite; metal scrap; mortars (material); nuclear reactors; radiation shielding; preplaced aggregate concrete; serpentine; shotcrete.

THE FIRST HANFORD REACTORS WERE BUILT ABOUT 25 YEARS AGO. REACTOR SHIELDING CONSISTED OF ALTERNATING LAYERS OF STEEL PLATE AND SHEETS OF MASONITE. THE STEEL PROVIDED DENSITY; WHEREAS, THE MASONITE (A COMPRESSED WOOD PRODUCT) SUPPLIED THE HYDROGEN REQUIRED FOR ATTENUATING HIGH-ENERGY NEUTRONS. THE REACTOR SHIELDS WEIGHED ABOUT 265 LB PER CU FT AND PERFORMED WELL. HOWEVER, THEY WERE EXPENSIVE TO CONSTRUCT AND COULD NOT BE OPERATED AT VERY HIGH TEMPERATURES. FOR THESE REASONS, CONCRETE WAS USED TO CONSTRUCT THE BIOLOGICAL SHIELDS FOR THE SECOND GENERATION OF HANFORD REACTORS. THE PROBLEMS THAT WE ENCOUNTERED WHILE DESIGNING AND CONSTRUCTING THESE SHIELDS ARE PROBABLY SIMILAR TO THOSE FACED BY MANY OF YOU; FOR EXAMPLE:

- 1) WHERE CAN HEAVY AGGREGATES BE OBTAINED AND HOW TO USE THEM, AND
- 2) WHAT ARE THE PHYSICAL AND SHIELDING PROPERTIES OF THE RESULTING CONCRETE?

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SOMETIME PRIOR TO 1950, ENGINEERS AT THE OAK RIDGE NATIONAL LABORATORY DEVELOPED TWO TYPES OF SHIELDING CONCRETE, ONE MADE WITH STEEL PUNCHINGS AND LIMONITE AGGREGATES AND THE OTHER WITH BARITE. THE LATTER MATERIAL WAS OBTAINED FROM SWEETWATER, TENN., AND HAD A SPECIFIC GRAVITY OF AROUND 4.2. THE LIMONITE CAME FROM THE JAMES MINE IN MICHIGAN. IN ORDER TO LOCATE SOURCES OF SHIELDING AGGREGATE CLOSER TO HANFORD, WE MADE A NUMBER OF SURVEYS. OVER 200 SAMPLES OF HEAVY AGGREGATE AND SERPENTINE WERE OBTAINED AND TESTED TO DETERMINE THEIR SUITABILITY FOR MAKING CONCRETE. THE SAMPLES INCLUDED VARIOUS TYPES OF IRON ORE, BARITE, GALENA AND FERROPHOSPHOROUS. THE INVESTIGATION INDICATED THAT THERE WERE A NUMBER OF WESTERN VENDORS WHO COULD SUPPLY SHIELDING AGGREGATES OF EXCELLENT QUALITY. HOWEVER, THE BARITE IN THE WESTERN PART OF THE UNITED STATES WAS NOT AS HEAVY, OR AS STRONG, AS THAT FROM SWEETWATER, TENN. WHEREAS, MAGNETITE WITH A SPECIFIC GRAVITY GREATER THAN 4.5 WAS QUITE PLENTIFUL AND LESS EXPENSIVE. FOR THESE REASONS WE BEGAN TO USE MAGNETITE AND OTHER IRON-BEARING AGGREGATES TO PRODUCE HIGH-DENSITY CONCRETE. OUR FIRST MAGNETITE CONCRETE SHIELD WAS BUILT IN 1951. THE MAGNETITE HAD A SPECIFIC GRAVITY OF AROUND 4.2, SO THAT THE CONCRETE WEIGHED ONLY 220 LB PER CU FT. HOWEVER, WE WERE PLEASED WITH THIS WALL, AS IT WEIGHED AS MUCH PER CU FT AS THE BARITE CONCRETE PRODUCED AT OAK RIDGE.

SHIELDING CONCRETE FOR THE INLET AND OUTLET SHIELD OF THE K-REACTORS HAD TO HAVE A CHEMICAL COMPOSITION SIMILAR TO THAT OF THE OLD STEEL AND MASONITE SHIELDS. THE REQUIRED DENSITY AND COMPOSITION COULD BE OBTAINED BY USING A MIXTURE OF STEEL PUNCHINGS AND LIMONITE, SIMILAR TO THAT USED IN THE CONSTRUCTION OF THE BROOKHAVEN REACTOR. IF USED TO CONSTRUCT THE K-REACTOR SHIELDS, IT WOULD HAVE TO BE PLACED BETWEEN AND AROUND NUMEROUS, CLOSELY SPACED TUBE SLEEVES, REINFORCING BARS, AND OTHER EMBEDMENTS. HOWEVER, IT WAS DOUBTFUL IF THIS TYPE OF CONCRETE, WHICH WEIGHED 265 LB PER CU FT, COULD BE PLACED SUCCESSFULLY UNDER SUCH DIFFICULT CONDITIONS BY MEANS OF THE CONVENTIONAL METHOD. FOR EXAMPLE, IF THE

CONCRETE WAS TOO STIFF WHEN PLACED IN THE FORMS, VOIDS MIGHT RESULT. IF TOO WET, THE STEEL SLUGS WOULD LIKELY SEGREGATE FROM THE LIMONITE MORTAR. THUS, WE DECIDED TO USE THE PRE-PLACED AGGREGATE METHOD FOR PLACING SHIELDING CONCRETE IN THE BIOLOGICAL SHIELDS OF THE NUCLEAR REACTORS BEING BUILT AT HANFORD IN THE 1950s. (THE PRE-PLACED AGGREGATE METHOD IS CURRENTLY REFERRED TO AS THE PA METHOD.) QUALITY CONTROL PROCEDURES WERE DEVELOPED TO ASSURE THAT THE PA CONCRETE, MADE WITH SPECIAL SHIELDING AGGREGATES, WOULD HAVE THE REQUIRED UNIFORMITY, DENSITY AND COMPOSITION, AND THAT IT COMPLETELY FILLED THE FORMS. THE DECISION TO USE CONCRETE TO CONSTRUCT REACTOR SHIELDS WAS JUSTIFIED BY 1) ITS SUPERIOR STRUCTURAL STRENGTH, 2) ITS SHIELDING EFFECTIVENESS, ESPECIALLY AT HIGH TEMPERATURES, AND 3) THE LOWER COST OF CONSTRUCTION. A SAVINGS OF OVER 11 MILLION DOLLARS WERE REALIZED BY USING HIGH-DENSITY CONCRETE TO CONSTRUCT THE BIOLOGICAL SHIELDS FOR THE TWO K-REACTORS INSTEAD OF STEEL AND MASONITE.

THE PRE-PLACED AGGREGATE (PA) METHOD PROVED VERY EFFECTIVE FOR PLACING HIGH-DENSITY CONCRETE IN SHIELDING STRUCTURES WHEN CONDITIONS WERE DIFFICULT AND THE FORMS RESTRICTED. THIS WAS ESPECIALLY TRUE WHEN THE PRE-PLACED AGGREGATES CONSISTED OF TWO OR MORE TYPES OF AGGREGATE, SUCH AS STEEL PUNCHINGS AND LIMONITE. THE LIMONITE, USED AS COARSE AGGREGATE, HAD TO BE STRONG AND RELATIVELY FREE OF FINE DUST. IN ADDITION, LIMONITE USED IN REACTOR SHIELDS HAD TO BE DENSE AND HIGH IN HYDRATED WATER. THIS REQUIRED A SPECIAL TYPE OF ORE. OUR INVESTIGATION OF AGGREGATE SOURCES LOCATED ONLY THREE VENDORS WHO COULD SUPPLY THIS QUALITY OF MATERIAL, ONE OF WHICH WAS IN PRODUCTION AT THE TIME. LIMONITE-GOETHITE ORE WAS EVENTUALLY PROCURED FROM A MINE LOCATED NEAR MONTELLO, NEVADA, AND WAS USED TO CONSTRUCT SHIELDS FOR THE TWO K-REACTORS. THIS MATERIAL WAS VERY TOUGH AND HAD A HIGH WATER CONTENT; HOWEVER, THE MINE WAS DEPLETED OF HIGH-DENSITY ORE BEFORE THE PURCHASE ORDER WAS COMPLETED. A SMALL AMOUNT OF LIMONITE WAS SUBSEQUENTLY OBTAINED FROM THE JAMES MINE TO COMPLETE THE JOB.

AT THE PRESENT TIME, I DON'T KNOW WHERE TO OBTAIN LIMONITE AGGREGATES HAVING THE PREMIUM SHIELDING QUALITIES OF THE TWO TYPES USED TO CONSTRUCT THE K-REACTOR SHIELDS. THE JAMES MINE, I AM TOLD, IS FILLED WITH SEEPAGE WATER; WHEREAS, THE THIRD SOURCE MENTIONED ABOVE IS NOT IN PRODUCTION. IF I HAD TO HAVE SOME LIMONITE AGGREGATES FOR SHIELD CONSTRUCTION IN THE NEAR FUTURE, I WOULD PROBABLY HAVE TO FACE THE SAME PROBLEMS TO OBTAIN THEM AS I DID EARLIER. THIS IS ONE PROBLEM AREA THAT HAS NOT CHANGED OVER THE YEARS. IF ANYTHING, IT IS WORSE, AS I DON'T HAVE THE JAMES MINE TO BACK ME UP.

ALTHOUGH THE PRE-PLACED AGGREGATE, OR PA, METHOD WAS USED TO CONSTRUCT A NUMBER OF REACTOR SHIELDS AT HANFORD, OTHER METHODS WERE INVESTIGATED AND USED WHEN FEASIBLE. AS A MATTER OF FACT, THE BULK OF THE CONCRETE USED TO CONSTRUCT RADIATION SHIELDING STRUCTURES HAD A NORMAL WEIGHT OF 150 LB PER CU FT AND WAS PLACED BY CONVENTIONAL METHODS. ON THE OTHER HAND, THERE WERE TIMES WHEN SPECIAL METHODS WERE UTILIZED FOR PLACING HIGH-DENSITY CONCRETE. FOR EXAMPLE, AFTER CONSTRUCTION WAS UNDER WAY FOR A FUEL-PROCESSING PLANT, CERTAIN EQUIPMENT WAS CHANGED. THIS MODIFICATION REQUIRED MORE GAMMA SHIELDING IN A PARTICULAR BARRIER WALL. IT WAS TOO LATE TO DOUBLE THE THICKNESS OF THE WALL, SO PLANS WERE MADE TO INCREASE ITS DENSITY. ALSO, THERE WAS NOT ENOUGH TIME TO PROCURE STEEL PUNCHINGS OR FERROPHOSPHOROUS. FORTUNATELY, THE AEC HAD ON HAND SEVERAL THOUSAND TONS OF STEEL SLUGS, TWO TO FOUR INCHES IN DIMENSION. THIS MATERIAL HAD BEEN EXCESSED OFFSITE AND OBTAINED FOR SHIPPING COSTS. BECAUSE OF SIZE RESTRICTIONS, IT COULD NOT BE USED IN REACTOR CONSTRUCTION. NECESSITY IS OFTEN THE MOTHER OF INVENTION: THUS, THE "PUDDLING" METHOD WAS CONCEIVED. THE LARGE CHUNKS OF STEEL WERE SUBSEQUENTLY USED TO CONSTRUCT THIS BARRIER WALL. THE "PUDDLED" CONCRETE WEIGHED OVER 310 LB PER CU FT.

ANOTHER INNOVATION IN SHIELD CONSTRUCTION WAS THE USE OF SHOTCRETE TO CONSTRUCT THE WALLS OF A LARGE HOT CELL IN 1959. TESTS INDICATED THAT HIGH-DENSITY

CONCRETE COULD BE PLACED EFFECTIVELY IN VERTICAL SHIELDING WALLS. UNIT WEIGHTS OF 235, 280, 287, AND 325 LB PER CU FT WERE OBTAINED WITH THE FOLLOWING SANDS: MAGNETITE, FERROPHOSPHOROUS, A MIXTURE OF STEEL SHOT AND MAGNETITE, AND FINE STEEL SHOT, RESPECTIVELY. WE WERE REALLY INTERESTED IN USING MAGNETITE SAND, AS THIS MATERIAL WAS AVAILABLE IN QUANTITY ON SEVERAL BEACHES OF THE LOWER COLUMBIA RIVER. EVEN WITH THIS RELATIVELY INEXPENSIVE SOURCE OF MAGNETITE, IT WAS NECESSARY TO RECLAIM AND WASH THE REBOUND SAND. OTHERWISE, THE SHOTCRETE METHOD WOULD NOT HAVE BEEN COMPETITIVE WITH MORE CONVENTIONAL METHODS FOR PLACING MAGNETITE CONCRETE.

TWENTY YEARS AGO, LITTLE WAS KNOWN ABOUT THE PROPERTIES OF HEAVY AGGREGATES AND VARIOUS TYPES OF SHIELDING CONCRETE. TO OBTAIN DATA REQUIRED FOR SHIELD DESIGN, AN EXTENSIVE TEST PROGRAM WAS INITIATED IN 1948 AND CONTINUED UNTIL ABOUT 1965. THIS PROGRAM WAS FUNCTIONAL IN NATURE RATHER THAN INVOLVING FUNDAMENTAL RESEARCH. TIME WAS LIMITED FOR A GIVEN SERIES OF TESTS. DESIGN AND CONSTRUCTION SCHEDULES HAD TO BE MET. THUS, ONLY THOSE TESTS REQUIRED TO DEMONSTRATE THE ADEQUACY OF A PARTICULAR TYPE, OR TYPES, OF SHIELDING CONCRETE WERE PERFORMED.

ALTHOUGH HANFORD HAS AN EXCELLENT CONCRETE CONTROL LABORATORY, IT DOES NOT HAVE FACILITIES FOR PERFORMING GENERAL RESEARCH ON CONCRETE PROPERTIES. FOR THIS REASON, CONTRACTS WERE ESTABLISHED WITH OTHER LABORATORIES. WE SUPPLIED THEM WITH SHIELDING AGGREGATES, DESIGN MIXES, AND TEST PROCEDURES. FOUR TYPES OF SHIELDING CONCRETE AND ONE STRUCTURAL CONCRETE WERE TESTED AT THE UNIVERSITY OF WASHINGTON DURING 1952. FROM 1953 TO 1965, OUR TESTS WERE PERFORMED BY THE CORPS OF ENGINEERS AT THE NORTH PACIFIC DIVISION LABORATORY LOCATED IN TROUTDALE, OREGON. DURING THE LATTER PROGRAM, 11 TYPES OF SHIELDING CONCRETE WERE INVESTIGATED, INCLUDING 5 KINDS OF PA CONCRETE. OVER 40 TYPES OF MORTAR WERE ALSO TESTED. THE FOLLOWING TYPES OF AGGREGATE WERE USED IN THE DEVELOP-

MENT PROGRAMS: STEEL SLUGS, IRON SHOT, FERROPHOSPHOROUS, LIMONITE, GOETHITE, HYDROUS-IRON ORE, MAGNETITE, ILMENITE, BARITE, SERPENTINE, AND CONVENTIONAL SAND AND GRAVEL. BESIDES THE USUAL CONCRETE TESTS, PHYSICAL PROPERTIES WERE DETERMINED ON AIR-COOLED SPECIMENS THAT HAD BEEN PREVIOUSLY HEATED AT ELEVATED TEMPERATURES UP TO 350 C.

RADIATION SHIELDING PROPERTIES OF SEVERAL TYPES OF CONCRETE WERE DETERMINED BY PLACING CONCRETE SLABS IN TEST WELLS LOCATED IN AN OPERATING HANFORD REACTOR. AN ARRAY OF NEUTRON DETECTORS AND EQUIPMENT FOR MEASURING GAMMA RADIATIONS WERE PLACED BETWEEN THE VARIOUS ATTENUATION SLABS. ATTENUATION MEASUREMENTS WERE MADE ON THE FOLLOWING TYPES OF CONCRETE: IRON-LIMONITE, IRON SERPENTINE, MAGNETITE-LIMONITE, MAGNETITE, FERROPHOSPHOROUS, BARITE, AND CONVENTIONAL. DATA DESCRIBING THE RESULTS OF THE HANFORD ATTENUATION TESTS ARE SUMMARIZED IN THE ENGINEERING COMPENDIUM ON RADIATION SHIELDING, BEING PUBLISHED BY SPRINGER-VERLAG.

WE WERE SUCCESSFUL IN DEVELOPING VARIOUS TYPES OF HIGH-DENSITY AND IN USING THEM TO CONSTRUCT BIOLOGICAL SHIELDS. HOWEVER, WE WERE NOT SO SUCCESSFUL IN OUR ATTEMPT TO DEVELOP A CONCRETE THERMAL SHIELD. (A THERMAL SHIELD, WHILE EXPOSED TO HIGH TEMPERATURES, ALSO RECEIVES INTENSE LEVELS OF GAMMA RADIATION AND NEUTRON FLUX.) PHYSICAL AND THERMAL PROPERTIES WERE DETERMINED FOR A NUMBER OF REFRACTORY MORTARS MADE WITH BORON ADDITIVES AND ONE OF THE FOLLOWING AGGREGATES: STEEL SHOT, FERROPHOSPHOROUS, FERROSILICON, TABULAR ALUMINA, ALUMINUM PELLETS, OR SILICON CARBIDE. THE AGGREGATES WERE SELECTED BECAUSE OF THEIR STABILITY AT HIGH TEMPERATURES AND THEIR HIGH THERMAL CONDUCTIVITY. MOST OF THE MORTARS HAD ADEQUATE STRENGTH AT ELEVATED TEMPERATURES; HOWEVER, THEIR THERMAL CONDUCTIVITY DROPPED APPRECIABLY WHEN HEATED. WORK WAS DISCONTINUED AFTER IT WAS DECIDED TO USE BORON STEEL PLATE, AND NOT CONCRETE MORTAR, FOR FABRICATING THERMAL SHIELDS AT THE N-REACTOR.

AT ONE TIME IT WAS NOT KNOWN IF SATISFACTORY SERPENTINE AGGREGATES COULD BE OBTAINED FOR USE IN PA CONCRETE. THEY WOULD HAVE TO BE STRONG, AS WELL AS FREE OF ASBESTOS FIBER. FOR THIS REASON, TESTS WERE PERFORMED TO DETERMINE IF HYDROUS AGGREGATES COULD BE MANUFACTURED BY CRUSHING HARDENED MORTAR MADE WITH PORTLAND CEMENT AND WATER. THE CONCEPT SHOWED PROMISE; HOWEVER, THE PROGRAM WAS STOPPED AFTER SUITABLE SERPENTINE AGGREGATES HAD BEEN LOCATED. ADDITIONAL RESEARCH MIGHT HAVE DEMONSTRATED THE FEASIBILITY OF THE TWO CONCEPTS DESCRIBED ABOVE. HOWEVER, THERE IS STILL AN ECONOMIC INCENTIVE TO DEVELOP A TYPE OF CONCRETE OR MORTAR WHICH COULD BE USED TO CONSTRUCT THERMAL SHIELDS, AS CAST IRON AND BORON STEEL SHIELDS ARE VERY EXPENSIVE.

MUCH HAS BEEN ACCOMPLISHED DURING THE PAST 25 YEARS AT HANFORD, AS WELL AS AT OTHER REACTOR SITES. WE KNOW BY EXPERIENCE THAT SPECIAL AND HIGH-DENSITY CONCRETES CAN BE FORMULATED AND PLACED SUCCESSFULLY BY A NUMBER OF METHODS. IN RETROSPECT, I BELIEVE THAT ANY SUCCESS THAT WE HAVE HAD AT HANFORD WITH RADIATION SHIELDING CONCRETE WAS DIRECTLY RELATED TO THE QUALITY OF AGGREGATES THAT WE WERE ABLE TO OBTAIN FOR SHIELD CONSTRUCTION. THE EFFORT EXPENDED IN LOCATING AND OBTAINING THESE PREMIUM AGGREGATES WAS JUSTIFIED IN MANY WAYS. IT ALSO HELPED US AVOID CERTAIN PROBLEMS THAT HAVE BEEN EXPERIENCED AT OTHER REACTOR SITES. FOR EXAMPLE, ALL OF OUR CONCRETE MIXES HARDENED NORMALLY, INCLUDING THOSE MADE WITH FERROPHOSPHOROUS. GAS GENERATION HAS NOT BEEN TROUBLE-SOME. AGGREGATES USED IN SHIELD CONSTRUCTION WERE NOT CHEMICALLY REACTIVE WITH PORTLAND CEMENT, INCLUDING SOME WHICH CONTAINED PYRITE. MINIMUM CONCRETE DENSITIES WERE OBTAINED WITHOUT DIFFICULTY. NO SIGNIFICANT VOIDS WERE LEFT IN THE CONCRETE SHIELDS. OUR QUALITY CONTROL MEASURES, SPECIFICATIONS AND THE EXPERTISE OF OUR CONSTRUCTION PERSONNEL ALSO CONTRIBUTED TO THE SUCCESSFUL COMPLETION OF THE WORK.

CONSIDERABLE INFORMATION IS PRESENTLY AVAILABLE ON THE PROPERTIES OF SHIELDING CONCRETE. IN ADDITION, STANDARDS FOR HEAVY AGGREGATES AND FOR CONSTRUCTING CONCRETE RADIATION SHIELDS ARE AVAILABLE. THUS, THE ENGINEER CAN PROCEED WITH MORE ASSURANCE THAT HIS SHIELD DESIGN WILL FUNCTION PROPERLY, THAN HE COULD A NUMBER OF YEARS AGO. HOWEVER, HE STILL NEEDS ADDITIONAL INFORMATION ON ITEMS SUCH AS: 1) THE EFFECT OF GAMMA RADIATION AND NEUTRON FLUX ON CONCRETE PROPERTIES, 2) THE EFFECT OF HIGH TEMPERATURES, 3) CREEP, 4) THERMAL PROPERTIES, 5) WATER MIGRATION, AND 6) THE BEST TYPE OF AGGREGATE FOR A PARTICULAR SHIELD DESIGN. TESTING IS COMPLICATED BECAUSE OF THE WIDE VARIETY OF AGGREGATES AND CONCRETE THAT ARE BEING USED TO CONSTRUCT RADIATION SHIELDS, AND BECAUSE EACH TYPE MAY BE EXPOSED TO ELEVATED TEMPERATURES AND DIFFERENT ENVIRONMENTS.

REFERENCE TO THE PRINTED PROGRAM FOR THIS SEMINAR, INDICATES THAT A NUMBER OF THE DELEGATES ARE CONCERNED WITH THE ABOVE PROBLEMS. I, FOR ONE, AM LOOKING FORWARD TO HEARING THEIR REPORTS AND OF LEARNING ABOUT RECENT ADVANCES IN THE USE OF CONCRETE FOR NUCLEAR REACTORS.

Discussion by Bryant Mather

Dr. Davis, in all three of his papers on shielding concrete, makes reference to ferrophosphorus-aggregate concrete. He stated⁽¹⁾ "All of our concrete mixes hardened normally, including those made with ferrophosphorus. Gas generation has not been troublesome." In the appendix to his second paper⁽²⁾ it is reported that permeability tests could not be made on ferrophosphorus-aggregate concrete because gas was generated in the specimens and prevented movement of water through them. Ferrophosphorus is mentioned in the third paper⁽³⁾ as a material that can be used with serpentine in shielding concrete. I should like to call attention to problems that have been encountered by others who have used ferrophosphorus as aggregate. ASTM Designation: C 638-69T⁽⁴⁾ states that ferrophosphorus "may radically affect setting time of concrete, and will result in the generation of flammable and possibly toxic gases which can develop high pressures if confined." Clendenning, Kellam, and MacInnis⁽⁵⁾ have described the experience of Ontario Hydro as related to evolution of hydrogen gas. They mention minor explosions of hot-cell windows traceable to the use of ferrophosphorus concrete. They abandoned the use of ferrophosphorus after

- (1) "Concrete for Radiation Shielding - in Perspective" (Session 1)
- (2) "N-Reactor Shielding" (Session 12).
- (3) "Iron-Serpentine Concrete" (Session 13).
- (4) 1969 Book of ASTM Standards, Part 10.
- (5) Journal, American Concrete Institute, Proc., Vol. 65, December 1968, pp 1021-1028.

the problem of gas evolution developed and completed the work using metallic iron. The U. S. Atomic Energy Commission reported⁽⁶⁾ a high-pressure gas release in a 6-in. diameter shield plug in the wall of a radioactive materials laboratory hot cell. The plug, which was steel-encased, 3-ft long, and 200 lb in weight was found on the floor in the operations area into which it had jetted out of the cell wall after internal pressure had ripped open the circumferential weld on the inner end plate. Subsequent inspection revealed convex ends on most of the 1/4-in. steel plate ends of the other plugs. About 90 of the 100 plugs were found to have internal pressure. The plugs contained ferrophosphorus-aggregate concrete. Unpublished data from the Tennessee Valley Authority and from Mr. R. S. Barneyback, Jr., Director of Research, Kaiser Sand and Gravel, Oakland, California, report ferrophosphorus-aggregate concretes that evolved acetylene gas, that failed to develop set in 30-days time after mixing, that evolved hydrogen gas, and that manifested serious spontaneous spalling and cracking beginning several months after placement. Since the explanation for these various forms of undesirable behavior is as yet not adequately known, I conclude that it is prudent not to use ferrophosphorus as aggregate in shielding concrete since there is no procedure that I know of to insure that future experience will be satisfactory--as was that reported by Dr. Davis.

(6) USAEC "Serious Accidents, No. 295," 9 December 1968.

I am aware of each of the cases cited by Mr. Mather in which difficulties have been experienced when using ferrophosphorous in concrete. I am also a member of the ASTM committee responsible for C 638-69T. Thus, I helped prepare the statement in this standard which is intended to warn the potential user that certain difficulties may be experienced when using ferrophosphorous aggregate. However, ferrophosphorous has been used successfully to produce shielding concrete at a number of nuclear plants. Apparently some sources of ferrophosphorous are satisfactory; whereas, others are not.

In my first Berlin paper, "Concrete for Radiation Shielding -- In Perspective," I indicated that we had expended a great deal of effort in locating premium quality, shielding aggregates and in proving that they would be satisfactory. In this way, we were apparently able to avoid some of the difficulties experienced by others. In the case of ferrophosphorous, we rejected a number of sources for one reason or another. Ferrophosphorous is a byproduct obtained during the manufacture of phosphorous and fertilizers. Some vendors make no effort to control the final quality of the byproduct; whereas, the vendor which supplied us with ferrophosphorous aggregates, made a special effort to produce a chemically stable product that could be used in concrete.

Additional research is needed to explain the various forms of undesirable behavior that have been experienced with some types of ferrophosphorous and not with others. Until complete information is available, the shield designer should proceed with caution, and make sure that a particular type of ferrophosphorous is satisfactory prior to using it to construct concrete radiation shields. Proper care should be used to prevent pressure build-up in shielding plugs, for example, by providing an adequate number of vents. I know of one case where a small amount of a flammable gas was produced in a concrete made with limonite and magnetite aggregates. In this case, the gas evolved as the concrete hardened but had no deleterious effects. Thus, the production of flammable gas is not limited to ferrophosphorous concrete alone.

BRYANT MATHER'S COMMENTS ON FERROPHOSPHOROUS CONCRETE

By Robert E. Wilde

POWER REACTOR DEVELOPMENT AND PRESTRESSED CONCRETE
REACTOR PRESSURE VESSELS

By I. DAVIDSON* and T. A. JAEGER**

The advantages of prestressed concrete reactor vessels especially in comparison with steel pressure vessels are discussed. The natural economic trend toward large unit sizes of power reactors favors concrete pressure vessel due to possible vessel dimensions in combination with internal pressures, freedom of shape, and increased safety.

Keywords: gas-cooled reactors; heat exchangers; nuclear power plants; nuclear reactor containment; nuclear reactors; pressure vessels; prestressed concrete; safety; water-cooled reactors.

For several years, there has been a marked trend to large unit sizes of nuclear power plants. The driving motivation for ever larger unit sizes comes from the fact that, with increased capacities, capital costs and operating costs per MW of electric power installed are reduced more rapidly with nuclear plants than with conventional plants.

With gas-cooled and water-cooled reactors, the natural economic trend to very large unit sizes of power reactors is opposed by technological difficulties inherent in steel pressure vessel construction. The advent and rapid development of prestressed concrete reactor pressure vessels offers several great advantages:

1. The possibility of attaining vessel dimensions in combination with internal pressures, which are not feasible when using steel;
2. Considerable freedom in the realization of any vessel shape known to be advantageous in a structural and functional sense; and

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3. Increased safety, due to the peculiar structural characteristics of prestressed concrete designs and, further due to the possibility of arranging boilers and ducts within the pressure vessel itself.

The prestressed concrete pressure vessel concept, therefore, offers a significant step forward in performance, safety and economy of gas-cooled and water-cooled power reactors. For the gas-cooled power reactor development line, there is no alternative to prestressed concrete reactor pressure vessels. For the water-cooled reactor development lines--namely the pressurized water systems and the boiling water systems--reductions in the construction time and, possibly, reductions in the capital costs of nuclear power plants may be expected. With the water-cooled power reactor systems, the most important item is the good safety characteristic of prestressed concrete construction.

New advances in nuclear power have for many years been expected to arise almost solely in the area of nuclear physics and reactor core design; but by introducing the prestressed concrete pressure vessel concept, civil engineers have made a great contribution to the economy and safety of nuclear power stations.

It is clear that an optimum result in the technological development, as well as in specific design solutions, for prestressed concrete pressure vessels for gas-cooled or water-cooled power reactor systems can be achieved only if the reactor vessel is not considered as just a civil engineering structure. Such a result can be achieved only when the prestressed concrete reactor pressure vessel is considered as a unit incorporated into the power reactor system, with interrelated functional, safety and economic connections. Only close collaboration of the specialists participating in power reactor development can produce true technological and economical success.

Let us recall the main steps in the development of the gas-cooled power reactor line and illustrate the associated steps in the layout of the prestressed concrete reactor pressure vessels.

Table 1 shows the development of the layout of gas-cooled thermal power reactors with a steam-turbine circuit. The steps of the development of the reactor system of gas-cooled power reactors are assembled in Table 2.

The development line runs towards higher and higher gas temperatures. Starting from reactors with metallic fuel in metallic cladding, the development proceeded to reactors utilizing ceramic fuel in metallic cladding, and further to reactors with purely ceramic core composition. The development is in the direction of further increase of the core power density, and correspondingly in the direction of an increase of the cooling gas pressure.

With the temperatures and pressures which are achievable now, another important step in the development of the gas-cooled power reactor system is the step from the indirect heat exchanger and steam turbine circuit to the direct cycle gas turbine circuit.

The technological progress of a reactor type aimed at reducing power generating costs is mainly achieved along three avenues; namely:

1. By better utilization of the nuclear fuel,
2. By achievement of higher thermodynamic efficiencies,
3. By improvements in the reactor system layout towards greater simplicity.

An overall impression of how dramatically the change from the steel pressure vessel concept affected the layout of nuclear power plants within the same generation of gas-cooled power reactors follows.

Figure 1 shows a perspective cut-off view of the complicated layout of the Sizewell nuclear power station which uses steel pressure vessels and consequently external heat exchangers. In comparison, *Figure 2* shows a corresponding view of the Oldbury nuclear power station which utilizes prestressed concrete reactor pressure vessels with incorporation of the whole primary circuit. This illustrates the second step in the development of the prestressed concrete reactor pressure vessel concept--the first step simply consisted of the utilization of a prestressed concrete vessel structure instead of a steel vessel structure. *Figure 3* shows a vertical section of the EDF-3 reactor pressure vessel.

The next step in the development was the so-called integrated design concept, as shown by *Figure 4*. The adoption of the integrated design concept in the case of gas-cooled reactors, where boilers and blowers, and eventually the charge machine, are also enclosed within the pressure vessel extends the potential for superior safety of prestressed concrete vessel structure to the whole primary system.

The absence of pressurized ducting and separate boiler shells eliminates the difficult technical problem of connections for relative expansions and at large structural discontinuities which represent the most vulnerable areas in a non integrated design. With an integrated design, gross failure producing large openings in the pressure circuit is not a credible accident.

An alternative to the radial arrangement of the incorporated heat exchangers is their vertical arrangement, shown schematically in *Figure 5*.

There is, however, a rather severe drawback to the integrated design concept of the Mark I gas-cooled power reactors, namely the difficult maintenance and repair problems posed by the irreplaceable installation of very large heat exchangers. But this drawback has been resolved in the course of gas-cooled reactor development which led to a drastic reduction of the required heat exchanger surface area.

When the cooling gas outlet temperature was increased from about 400°C with the Magnox type reactors to about 670°C with the advanced gas-cooled reactor type, the required heat exchanger surface area was reduced to a quarter. On the next development level, with the high-temperature gas-cooled reactors, the required heat exchanger surface areas are reduced to one-tenth of those required with the Magnox type reactors. This is indicated in the last column of Table 2.

These reductions of the required heat exchanger surface areas facilitated the development of shop fabricated cylindrical heat exchanger units of rather small diameter with replaceable installation in the prestressed concrete pressure vessel. This technological development is of considerable importance for the improvement of plant availability and contributes to extend the working life of gas-cooled nuclear power plants.

However, the structural problem created by the required large openings in the top or bottom slab of a prestressed concrete pressure vessel are rather severe. An alternative design, deviating from the single vault concept, shows the way out of these structural difficulties. In this so-called pod boiler concept, shown schematically in *Figure 6*, the prestressed concrete pressure vessel encloses only the reactor core.

The boilers, instead of being located within the cylindrical vault, are accommodated in vertical holes within the pressure vessel wall and are connected by ducts to the central reactor vault. *Figure 7* shows an advanced design of this type with the gas passing downward through the core.

As reactor development proceeds, it is certain that higher gas outlet temperatures will become achievable. A reactor type using coated particle fuel has the potential of reaching very high gas temperatures. However, the conventional indirect steam cycle cannot benefit greatly by the achievement of gas temperatures beyond 850°C, either thermodynamically or economically.

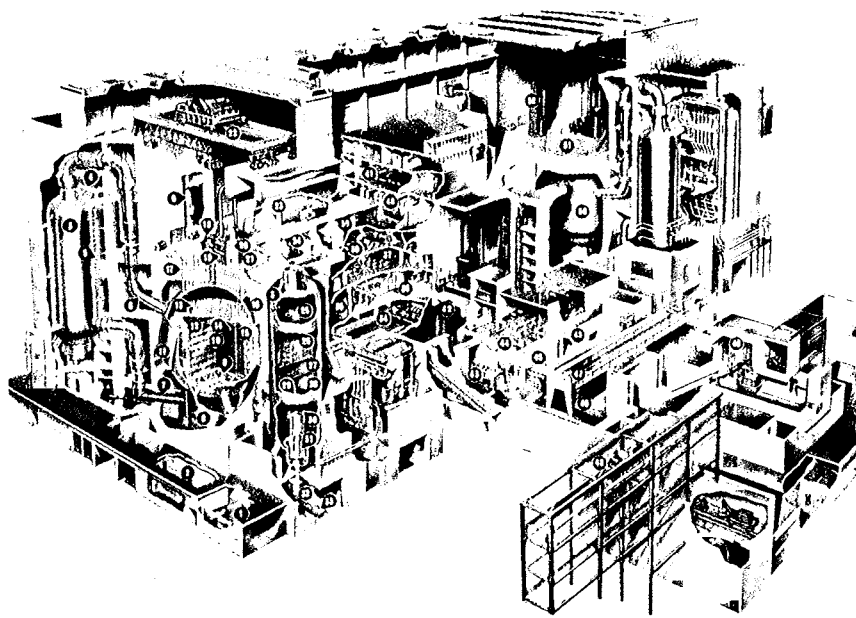
On the other hand, a closed gas turbine cycle requires a high temperature to be competitive and it takes advantage of the possible increases in outlet gas temperatures. Any increase in gas outlet temperature is associated with an improvement in thermodynamic efficiency and a saving in capital cost.

A design example is shown in *Figure 8*. In this design, the whole of the turbo-machinery and the heat exchange equipment is contained within pods in the cylindrical wall of the prestressed concrete pressure vessel and the power gas-turbine is installed within a horizontal pod in the vessel bottom. In recent years, at least a dozen different conceptual designs requiring different piercing of the pressure vessel have been described in the literature. Much work remains to be done in the study of thermodynamic cycles, in component development and in reactor plant layout to determine the optimum design of closed-cycle helium gas-turbine power plants. The suitable choice of the thermodynamic cycle and of the

equipment is a complex optimization problem which is coupled with the overall layout of reactor, turbo-group and prestressed concrete pressure vessel.

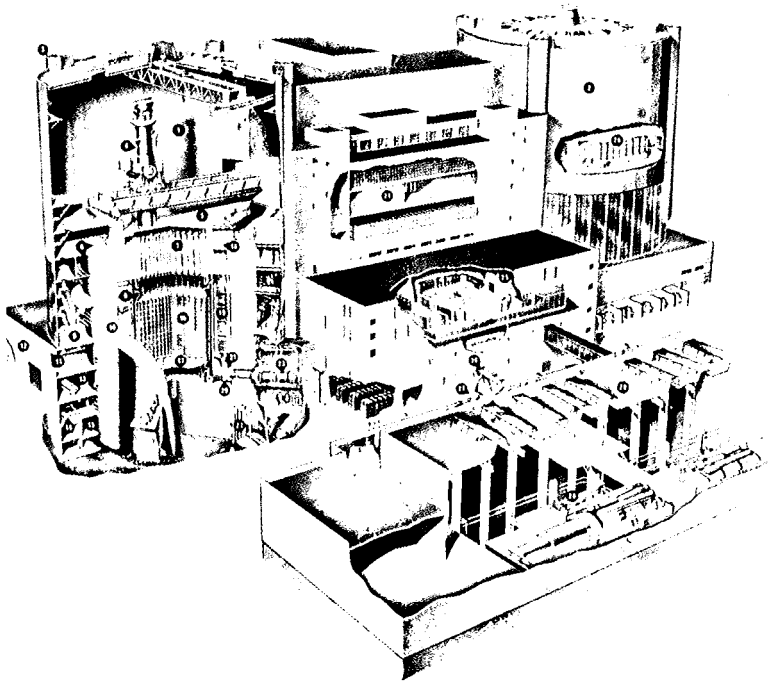
The ultimate step in the development of the gas-cooled power reactor family is the gas-cooled fast reactor with direct cycle helium turbine circuit. Such a reactor type holds promise of a very high breeding potential. The gas pressure required for such a system lies within the range of 50 to 120 atm, but the required reactor core volume is relatively small.

Relatively small reactor cores and high cooling medium pressures are also the characteristics of water-cooled power reactors. Boiling water power reactors operate at pressures about 70 atm, and pressurized water reactors operate at pressures about 150 atm. In this field, steel pressure vessel technology has been escalated dramatically to comply with the requirements of large capacity reactor units. But safety aspects and large dimensioning possibilities, as well as certain flexibility of construction schedules, may also profitably introduce the prestressed concrete pressure vessel concept into water-cooled power reactor technology.



- | | |
|--|---|
| 1 Gas circulator instrument and control room | 29 Mixed low temp. HP and LP economizer |
| 2 Gas circulator instrument room | 30 Hot gas deflector plates |
| 3 Boiler | 31 Gas circulator |
| 4 HP steam drum | 32 Main circulator motor |
| 5 LP steam drum | 33 Auxiliary circulator motor |
| 6 Gas outlet ducts | 34 Standby diesel generator sets |
| 7 Gas inlet ducts | 35 Main fuel store |
| 8 Pressure vessel support skirt | 36 CO ₂ ancillary equipment room |
| 9 Moderator support grid | 37 Reactor safety circuit motor generator sets |
| 10 Graphite moderator | 38 Shield cooling fans |
| 11 Cooling air cowl | 39 Burst cartridge detection equipment room |
| 12 Charge pans | 40 Sub-fuel store |
| 13 Control rod guide tubes | 41 Ventilation plant |
| 14 Control rod | 42 Conveyor for irradiated fuel elements |
| 15 Fuel elements | 43 Fuel element segregating tray in pond reception bay |
| 16 Pressure vessel Number 1 | 44 Fuel element tonging equipment |
| 17 Pressure vessel standpipes | 45 Pond fuel element reception bays |
| 18 Pile cap service trolley | 46 Fuel element storage skips |
| 19 Fuelling machine | 47 Cooling pond crane |
| 20 Fuelling machine magazine | 48 Gantry for irradiated fuel transport flask conveyance |
| 21 Number 1 reactor pile cap | 49 Pneumatic skip lifting equipment with skip in position |
| 22 Pile cap crane | 50 Pressure vessel Number 2 |
| 23 Central control room | 51 Number 2 reactor pile cap |
| 24 Fuel preparation rooms | 52 Reactor servicing machine |
| 25 Mixed HP and LP superheater | |
| 26 HP boiler banks | |
| 27 High temperature HP economizer | |
| 28 LP boiler | |

Fig. 1. Perspective cut-off view of Sizewell-A nuclear power station



- | | |
|--|---|
| 1 Number 1 reactor | 16 Core |
| 2 Number 2 reactor | 17 Core support structure |
| 3 Relief valve outlets | 18 Boiler access slot |
| 4 Charge/discharge machine and gantry | 19 Boilers |
| 5 Operating floor | 20 Gas circulator |
| 6 Upper stressing gallery | 21 Circulator outlet duct |
| 7 Charge and control standpipes | 22 Steam and feed pipes to turbine hall |
| 8 Boiler shield wall | 23 Gas circulator drive and auxiliaries |
| 9 Boiler annexe | 24 Central control and charge block |
| 10 Concrete vessel | 25 Main control room |
| 11 Flux measuring room | 26 Burst cartridge detection room |
| 12 Circulator house | 27 Reserve feed water tanks and H/L deaerator |
| 13 Pressure vessel liner coolant coolers | 28 Feed heating plant |
| 14 Pressure vessel liner coolant pumps | 29 Turbine house |
| 15 Lower cable stressing gallery | 30 6-ton crane |

Fig. 2. Perspective cut-off view of Oldbury-A Nuclear Power Station

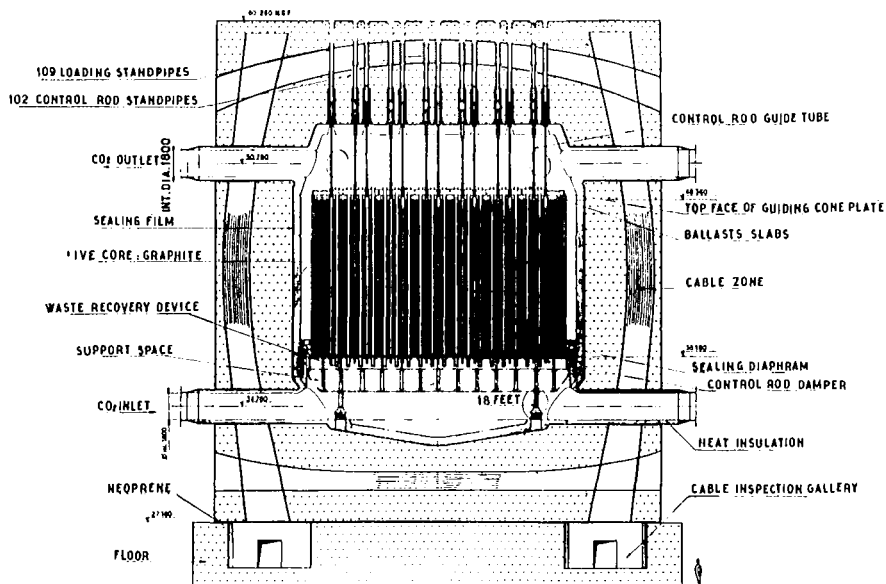


Fig. 3. Vertical section of the EDF-II prestressed concrete reactor pressure vessel

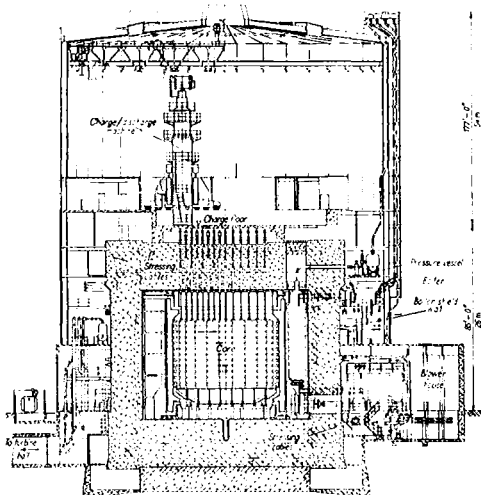


Fig. 4. Vertical section of the Oldbury prestressed concrete reactor pressure vessel

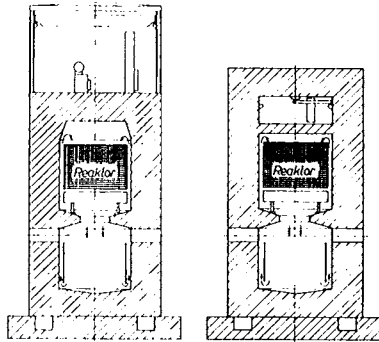


Fig. 5. Schematic sketches of vertical arrangement of reactor and heat exchanges in prestressed concrete reactor pressure vessels

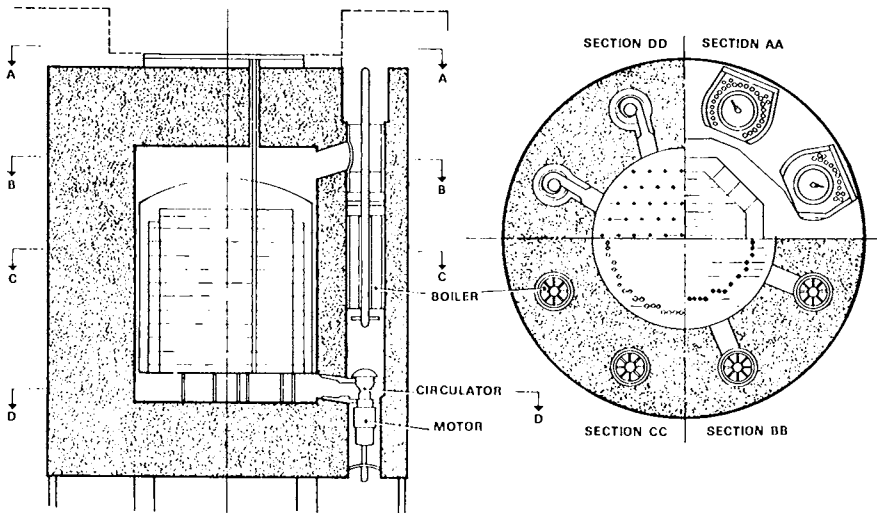


Fig. 6. Diagram of prestressed concrete reactor pressure vessel with pod boiler arrangement

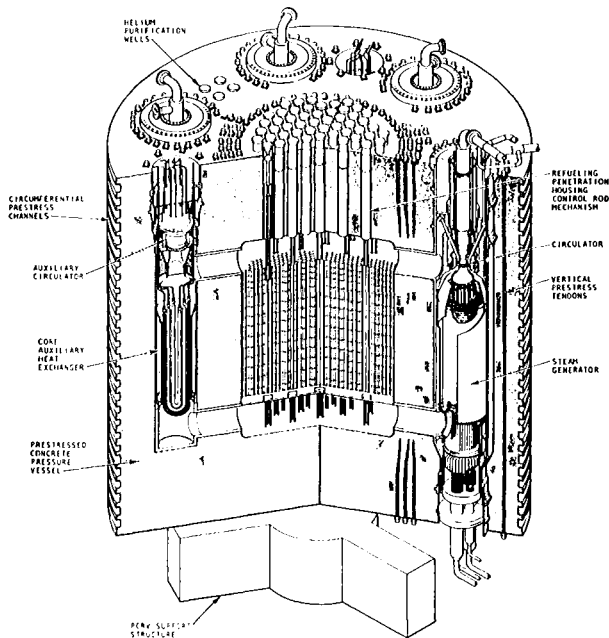


Fig. 7. Arrangement of high-temperature gas-cooled power reactor with downward gas flow

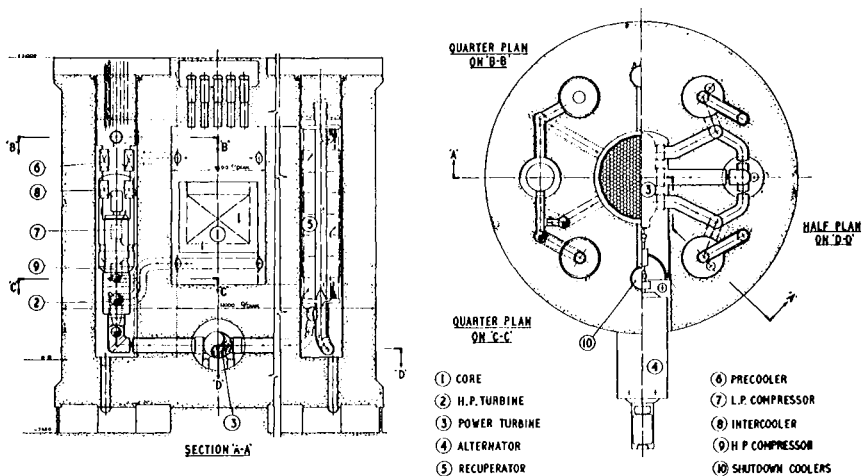


Fig. 8. General arrangement of high-temperature gas-cooled power reactor with gas turbine

Table 1

Reactor Generation	Prototype: Calder Hall 1956	1. Generation of commercial reactors (Magnox)	2. Generation: Advanced gas-cooled reactors 1970	3. Generation: High-temperature gas-cooled reactors
Moderator	graphite	graphite	graphite	graphite, later: C/BeO
Coolant	CO ₂	CO ₂	CO ₂	He
Fuel	natural uranium	natural uranium	enriched UO ₂	enriched UO ₂
Cladding	Magnox	Magnox	stainless steel	graphite
Pressure vessel	steel	steel; later: prestressed concrete	prestressed concrete	prestressed concrete

Table 2

Generation	Reactor	Start of operation	Unit capacity [MWe]	Thermal efficiency %	Average core power density [MW(th)/m ³]	Gas outlet temperat. [°C]	max. coolant pressure [kp/cm ²]	relative required heat exchanger surface
0	Calder Hall	1956	34	19	0,8	336	8	> 100
1	Bradwell Dungeness A	1962 1965	150 275	28 33	0,8 0,8	390 410	14 25	100
2	Dungeness B	1971	600	41,5	2,6	675	31	25
3a	THTR	1974	308	40	6,0	850	40	10
3b	THTR	after 1976	1000	40	7,0	850	50	
4	THTR (GT)	?	1000	42	8,0	950	52	-
5	GCFR	?	1000	42	240 ^{*)}	1000	> 52	-

^{*)} Average value for core and blanket:
54 MW(th)/m³

CONCRETE CONTAINMENT: A 1970 ASSESSMENT

By M. BENDER* and G. D. WHITMAN*

The use of concrete structures, both conventionally reinforced and prestressed, for containment has become the prevalent structural approach for large nuclear power applications. The engineering practices followed for these structures generally conform to the recommendations of ACI 318, "Building Code Requirements for Reinforced Concrete," with appropriate modifications to cover the special nature of membrane shells lined with steel or plastic. Much attention has been addressed to the matter of shear resistance of cracked membranes, an inherent characteristic of conventionally reinforced containment shells. The inelastic behavior of prestressed concrete is the matter of greatest interest for prestressed concrete containment structures. The effects of high stress and temperature accelerated creep are both pertinent factors. Because of the wide use of concrete containment structures in the growing nuclear power industry, the need for parallel growth in the technological understanding of these structures is self-evident as a part of the industry obligation to guarantee adequate provision for public safety.

Keywords: economics; high temperature; linings; nuclear power plants; nuclear reactor containment; nuclear reactors; pressure vessels; prestressed concrete; radiation shielding; reinforced concrete; safety; shells (structural forms); stresses; structural design; thermal stresses.

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The current trend in power reactor containment favors reinforced and prestressed concrete structures. Most pressurized-water reactor systems rated above 400 Mw(e) have been contained in concrete structures, but until recently, most of the boiling-water reactor systems have been contained in steel structures. However, even these latter systems now have proponents for concrete containment. Since containment is such an important safety consideration in nuclear applications, a reexamination of the essential features related to concrete containment may help point out the motivation for this trend as well as the areas of concrete containment technology that must be strengthened in response to it.

If the thickness of a steel shell necessary to meet containment load conditions is great enough to require stress relief of welded joints, the complications, while not unmanageable, are a major impediment to the orderly construction of a nuclear power plant. For this reason, many power plant designers strongly favor concrete containment. But, even when stress relief of welded joints is not required, there are other considerations that encourage the use of concrete containment structures.

First, the geometry of a concrete containment structure can be varied more easily than that of a steel containment structure, permitting greater flexibility in the orientation of equipment within the structure.

Second, the concrete shell can provide the foundation and support for internal structures, whereas this support must be separately engineered when steel shells are used.

Third, the containment penetrations can be solidly anchored in the concrete structure, reducing the need for separate thrust anchors and

eliminating the uncertainties associated with bellows which protect steel shells from pipe reactions introduced by fluid force and thermal expansion.

Last, the concrete containment has substantial resistance to accident-generated projectiles that must be considered in the engineering of a containment structure.

There are, of course, some counter-values in the use of steel containment shells, the most pertinent being the highly ductile nature of conventional low-carbon steel that reduces concern for stress concentrations. Another is the engineering simplicity inherent in the homogeneous steel structure when compared with the composite of steel, concrete, and supplemental liners characteristic of concrete containment structures.

The criteria for selection between conventional reinforced concrete and prestressed concrete containment structures is still somewhat nebulous. There are some qualitative factors favoring each approach, but the judgments tend to be subjective and the important features of each are not well suited to a quantitative comparison. In favor of prestressed concrete structures, it has previously been stated¹ that

1. structural action under postulated accident conditions can be verified prior to any ultimate demand upon the structure;
2. the lifetime behavior of the structure can be monitored for structural deterioration and corrected before utility is lost;
3. predetermined crack patterns under working loads can be established and cracking can therefore be used as evidence of deterioration;
4. with unbonded steel tendons, the potential for regular testing and maintenance of the principal load carrying steel elements can be provided for the life of the structure; and
5. the primary load carrying steel is continuously accepting load conditions very close to the ultimate design loads so that an accident can be a minor transition in the structural lifetime of the vessel.

This generally boils down to the contention that with prestressed concrete structures, the state of readiness under accident conditions is readily ascertainable.

Values associated with conventional reinforced concrete are long experience with mild-steel embedments and great flexibility in the use

of the steel to resist structural forces. Both reinforced concrete and prestressed concrete installations have redundant structural elements that eliminate dependence on perfect quality in every steel component. Without question, both types of structure have a place in nuclear applications. Circumstances as well as economics will determine the appropriate application. What is intended here is the presentation of a perspective view of concrete containment that will enable those concerned with developing the technology to see the relative place of the technological developments to be discussed at this conference in the overall containment problem.

Important Properties of Containment

The following definition of containment is provided in the preliminary draft of the ACI Committee 349 "Criteria for Concrete Containment".

"... nuclear containment is defined as the functional capability of a system to control and limit the spread of radioisotopes in the event that these radioisotopes are released from the primary nuclear system."

To satisfy this function, the containment structure needs the capability of assured leakage control under accident conditions, adequate strength to withstand the adversities of nature in combination with possible nuclear accidents, and the assurance of protection of these properties against deterioration over the lifetime of the nuclear plant.

The ability to verify the capability of the containment with respect to these properties and the possibility of correcting deficiencies which can develop during construction or operational lifetime are central considerations in the public acceptance of nuclear installations. Consequently, most of the engineering treatment of concrete containment is focused on providing these properties. There is no absolute scale by which they can be judged, and they must be closely correlated with the specific nuclear system being engineered. Containment adequacy is determined by a composite evaluation of the system effecting the containment in conjunction with the nuclear system being contained. The

latter encompasses such a broad territory that the correlations cannot be treated in more than a superficial manner in these discussions.

The containment function for gas-cooled reactor systems is often combined with the pressure containing system for the primary coolant, while the containment for pressurized-water and boiling-water reactor systems is engineered separately from the primary coolant systems. Typical concrete containment structures for water-cooled reactor systems are illustrated in Figs. 1 and 2. However, in some applications even gas-cooled reactor systems have separate containment systems. Examples of this are the EL-4 in France, the AGR and Dragon reactors in the United Kingdom, and the Peach Bottom reactor in the United States. Large-scale versions of the HTGR type of reactor in the United States may have separate containment in spite of the fact that this function is combined with the primary coolant pressure containing system in the Fort St. Vrain reactor. Further clarification of containment rationale is available in the literature.² In this assessment, we will attempt to point up considerations that have evolved in the engineering of known nuclear installations under preestablished circumstances. We caution against applying any fixed viewpoints derived from this discussion without full understanding of the context.

Safety Considerations of Containment

The concept of containment was devised to satisfy public safety needs. Most of what has been determined with respect to the adequacy of containment is in the context of public safety. Everyone recognizes that there will be very infrequent and hopefully no circumstances when a reactor containment will have to be used for this essential purpose, but if this need should arise, capability must be the engineering basis for the containment. So the first question that must be answered is whether the containment is able to withstand the accident conditions associated with an unlikely event.

Within the context of water-cooled reactors, this is usually treated as a circumstance under which the primary coolant system has ruptured and

permitted a large release of steam that caused an increase in the containment pressure and a coincident increase in the temperature of the fluid adjacent to the containment structure. A substantial amount of contained radioactivity that would be harmful if released is assumed to be mixed with the containment fluid.

Under the conditions of such an unlikely event, the pressure retaining capability of the containment is generally more easily understood than other considerations. Pressure tests will usually verify the pressure retention capability, and we are accustomed to this type of strength verification. The thermal response feature is less easily understood since it is a time dependent characteristic that involves the combination of accident transient factors in the nuclear system with the thermal characteristics of the structure. The adversities of nature must be considered on somewhat philosophical grounds since we cannot know absolutely whether there will be an earthquake, a tornado, or a tsunami during the lifetime of a containment structure. But in spite of this, we may have to reckon with such circumstances as the triggering cause of a nuclear accident. These considerations provide the basis for the design criteria that must be satisfied. The technological developments with respect to containment are largely directed toward verifying that the criteria can be satisfied.

The determination of whether the criteria are satisfied is an engineering problem. It can be subdivided into four engineering categories. The first is fixing a suitable design basis that correlates the design practice with the design conditions of interest for public safety purposes. Of prime interest is a method for proportioning the concrete and steel in a geometrical orientation that meets functional requirements by providing adequate strength and leakage control capability. We must consider the fact that strength is not necessarily a criterion of leakage control. Consequently, any structural considerations that have an effect on leakage characteristics must be accounted for. This generally leads to design techniques which combine the strength capability of steel-reinforced concrete with the leak-sealing characteristics of a membrane seal. Thus, the composite capability of the two separate functions of pressure retention and leakage control have to be consolidated in this design basis.

The second engineering category has to do with the construction technique. Material control, craftsmanship, and site characteristics need to be integrated and correlated with the design requirements if the intent of the design is to be satisfied. Containment structures are usually massive and the construction process itself can introduce special structural problems that require at the very minimum a high degree of care during construction. Hence, engineering adequacy must account for construction methods and these require definition.

The third engineering category involves proof of capability through testing. Here again, both design and construction have to be effected in such a way that proof of performance capability can be demonstrated.

The fourth engineering category involves demonstrating that the design conditions will not be exceeded during the lifetime of the structure. This means that there has to be some definition of the operational controls of which the most important are temperature, chemical environment, and mechanical loading. Each of these factors must be controlled over the life of the finished structure if the adequacy of the containment for public safety is to be assured.

Determination that a containment structure has been adequately designed, constructed, and tested, and that its operational controls have been properly defined may verify the initial capability of the structure to meet its design intent. But we must also have a basis for knowing whether a state of readiness is established and that it can be maintained throughout the lifetime of the structure. One of the more troublesome considerations is the matter of whether the test used to verify initial capability has total meaning in terms of the containment function. We are dealing with structural lifetimes of about 30 years in which failure mechanisms involving long-term degradation of engineering properties are major uncertainties. Consequently, we are very interested in gauging the state of readiness of these structures. Are we all right for the moment only to be in trouble later, or is the structure such that time will not affect its capability? We want to know the symptoms that indicate potential trouble. What gives us comfort that we have adequate design margins? What is the mechanism of failure and are the consequences themselves limited and within the boundaries of our safety criteria?

Generally, we are looking for structures that have an inherent capability for ameliorating engineering flaws and for structures that will show signs of trouble in time to permit correction of the deficiency before the capability is lost. And finally, we are looking for structures that minimize our dependence on human action. There is never 100% certainty of devising a structural design that guarantees a state of readiness, but designs that provide the greatest assurance that a state of readiness exists are the ones most nearly suited to the purpose.

Current Practices

Nuclear power plant containment is the only type of containment that has been critically examined from a structural standpoint even though there are many other applications of nuclear containment that need to be understood. These include the containment systems for fuel reprocessing plants, nuclear waste disposal, high-level radiation sources, and even for thermonuclear machinery. Nevertheless, we are presently familiar with practices related only to nuclear power plants, so only the containment structures for these plants will be covered in this discussion of current practices.

Containment structures for nuclear power plants are intended to retain radioactivity under dynamic circumstances involving the concurrent natural phenomena that may impose serious external loads on such structures in conjunction with a serious failure in the nuclear system that may result in pressure and temperature rises, substantial energy release, and a significant amount of radioactivity in gaseous and particulate form within the containment enclosure. The containment structures that limit the consequences of such events to the norms for public safety are for the most part reinforced concrete structures of three types. These are the conventional reinforced structure, the fully prestressed concrete structure, and the partially prestressed concrete structure.

The use of the conventional reinforced concrete structure is typified by the recent Connecticut Yankee³ installation. The use of the fully prestressed structure is exemplified in the EL-4⁴ and the Palisades⁵

installations, and the use of the partially prestressed structure is exemplified by the Robert E. Ginna⁶ and the H. B. Robinson⁷ containment structures. The characteristics of these three types of containment structure are compared in Table 1 with respect to the important structural features. There is no purpose to be gained by a detailed discussion of the designs except to point out some special structural characteristics that are pertinent.

The first of these is that conventional reinforced concrete structures subjected to membrane tension loads are necessarily cracked through the concrete membrane, and the ability to withstand shear loads through the cracked section is an important consideration. The dowel action of the reinforcing steel provides one type of shear resisting capability, and the aggregate interface engagement at the crack provides a second. The shear resistance of these two factors is only partially defined. In some cases, the liner itself may provide a third type of shear resistance. Some work carried out at Cornell University⁸ has indicated that the shear strength of the aggregate interface has substantial value if the width of the crack is limited. Design study has shown⁹ that the effectiveness of the dowel action of the reinforcing steel is a function of the steel bearing force on the surrounding concrete at the cracked section. A quantitative basis substantiated by experiment for determining the shear resistance in a membrane crack for a reinforced concrete shell that combines these three structural actions is not yet available.

Prestressed concrete is credited with having no membrane cracks, so shear load resistance can be determined from the composite action of the entire ferro-concrete section. The principal reservation in this type of approach is related to the possible loss of prestress through creep and shrinkage with particular reference to elevated temperatures within the structure. Both the time-dependent relaxation of steel and the inelastic movement of the concrete are pertinent to this matter. Thus far, most designers are thought to have been very conservative in considering the loss of prestress. However, the structures are evaluated as though they were large, homogeneous thin shells with idealized behavior, and no localized effects that might result from material flaws or deterioration of prestressing steel are accounted for in the design.

The approach to assessing inelastic movement is undocumented except that allowances suggested in the ACI Standard 318, "Building Code Requirements for Reinforced Concrete," are provided in prestress relaxation allowances. However, containment structures are designed to operate at temperatures up to 120°F (49°C) and are therefore subject to temperature accelerated concrete creep at concrete compressive stress levels of 2000 to 3000 psi. Concrete compressive stress levels in some designs have been limited to a design value of 0.3 times the cylinder strength for axial compression and 0.6 times the cylinder strength for axial compression plus flexure. With commonly used cylinder strengths of 5000 psi, this represents a stress range of 1500 to 3000 psi under steady-state loads with attendant stress-induced inelastic movement. While elevated temperatures may not appear in regions coincident with high stress levels, the techniques by which combined elastic and inelastic strains in containment structures are assessed are not documented. This leaves the whole matter of inelastic strain effects open to question. Methods of strain analysis specifically related to the application that account for inelastic as well as elastic response would be helpful in this instance.

Geometrical Arrangement

A number of design arrangements have been used in concrete structures for containment in nuclear power plants. All of them are basically vertical axisymmetric structures with flat-slab bases and domed ends. A combined cone frustum and cylinder with a domed top has been proposed as the geometrical arrangement for the reinforced concrete structure containing the Shoreham boiling-water reactor system of the Long Island Power and Light Company.¹⁰ Other commonly used geometrical arrangements are basically cylindrical in shape. The form of the dome ranges from the hemispherical shape used in the EL-4 and the R. E. Ginna structures to the shallow spherical segment used in the Palisades plant.

These geometrical variations are largely adapted to fit the equipment orientation within the containment while coping with internal pressure requirements. Clearly, the flat dome provides a large volume fraction of

useful space for equipment installation, but the thickness of the dome will be greater for the shallow shape. The conical shape seems to be of value mainly for boiling-water reactor installations because of the need for a large pressure-suppression pool space at the bottom of the containment. Low pressure encourages a trend toward reinforced concrete structures, while high pressure encourages a trend toward prestressed concrete structures. The rationale here is probably associated with the fact that shielding requirements establish a minimum thickness that every containment structure must provide, putting a limit on the incentive to reduce shell thickness through the use of prestressing techniques. Thus, in low-pressure containment systems, the structural requirements often are not the controlling requirements fixing the thickness of the concrete.

The variety of base connections currently used include the EL-4 Freyssinet hinge, a unique elastomer hinge applied in the R. E. Ginna installation, and the rigid connection exemplified in the Palisades plant. The basis for selection of various base connections is largely a matter of design judgment, but it is becoming increasingly evident that the shear resistance attainable with a rigid connection makes this type of connection attractive for sites where seismic shear is a controlling design load.

Openings

The design of large openings has been a debatable point for several years. The principal matter of concern is matching the stiffness of the perimeter of the opening with that of the vessel shell. In the United States, the general practice now seems to involve the use of an embedded steel ring at the hole perimeter supplemented with radial and circumferential steel reinforcing extending from the edge of the opening into the body of the shell. The primary steel in the shell is routed around the opening. This approach seems to be adequate regardless of whether the vessel is reinforced conventionally or prestressed. Placement of the reinforcing steel is premised on sequential but controlled cracking at the perimeter of the opening that causes the over-stiffened perimeter

to adjust its stiffness modulus to match that of the adjoining shell region. The sequence of loading is pertinent in this design approach, and the behavior of the opening may vary, depending on whether or not the vessel is prestressed.

The treatment of the openings in the EL-4 is uniquely interesting because of the exceptionally large fraction of the shell region taken up by the openings. The designers found it desirable to provide a heavy prestressed concrete stiffening ring above and below the openings that were in turn tied together by vertical prestressing in the spaces between openings. The vessel as a whole was prestressed. The opening reinforcement arrangement rigidized the section of the vessel carrying the openings so that vessel compatibility problems were shifted to the areas above and below the reinforcing rings.

While there are no published reports to provide quantitative information about the structural behavior of large openings in containment installations, there has been no indication that any of the openings showed signs of distress during proof testing. However, consideration should be given to the fact that the initial deformation of the opening perimeter will probably be outward rotation of the rigid ring, causing compression in the outer face of the shell and cracking at the hidden surfaces. Consequently, exterior examination of the shell may not be meaningful unless the compressive stress in the outer face is so severe that early spalling occurs.

Reinforcement Techniques

Where applicable, the recommendations of ACI Standard 318 with respect to the proportioning of steel and concrete have generally been followed in the placement of steel in concrete containment structures. Since shell structures are not covered by ACI 318, the reinforcement methods for shell membranes have followed the precedent set for circular concrete water tanks where the reinforcement is positioned as though it was acting at the midplane of the shell. In conventional reinforced concrete shells, the steel is permitted to carry the tensile load only by membrane

cracking of the concrete. Hence, the steel distribution has to be arranged to control the crack distribution in the shell. Large steel reinforcing bars (Nos. 14 and 18) have been successfully used without difficulty.

Only post-tensioned prestressing systems have been used in concrete containment structures, and many stressing arrangements of this type have been applied. The multi-wire BBRV tendon system and Stressteel high-strength bar system have been used in vertically prestressed installations, and the BBRV and the Freyssinet tendon anchorage systems have been used in a rectangular grid array in fully prestressed structures. Mechanically anchored helically placed tendons have been used in one application.

The most common arrangement of dome prestressing is a triangular grid pattern of tendons anchored into a ring beam at the perimeter of the dome. Other schemes can also be used. The principal problems involved in dome prestressing are associated with the complex anchorage arrangement¹¹ caused by the need to overlap the dome and cylinder tendons at the point of connection between these two structural elements.

All prestressed concrete containment structures have been supplemented with mild-steel reinforcement to provide flexural strength at discontinuities and to provide shear resistance at the base for seismic or other natural forces. In addition, the common practice of reinforcing anchorage zones with mild steel has been followed universally.

Thermal strain has also been controlled in most cases through the use of mild-steel reinforcement. Thermal gradients up to 150°F can be anticipated when the exterior of the structure is exposed to low ambient temperatures concurrent with interior temperatures approaching 120°F. Reinforcing steel at the inner and outer faces of the structure can limit cracking from thermal strain cycling, but this structural action has to be combined with that from the steel provided to resist membrane forces. No data are available that indicate the manner in which the reinforcing steel accepts the load from these two separate strain effects. No difficulties have been reported with the approach used for the installations in service thus far, but experience with concrete reactor vessels suggests caution in appraising the composite structural behavior.

Containment Liners

The possibilities for lining containment structures are several. The type of lining prevalent in the United States is a thin steel membrane (1/4 to 1/2 in. thick) intermittently attached to the concrete shell by steel studs, brackets, channels, or other shapes embedded in the concrete after having been welded to the shell. A plastic paint has been used as a liner in several prestressed concrete structures. Apparently, both types of liners provided adequate capability for their particular applications, but there is considerable uncertainty about plastic liners for long-term containment service where leak-tightness requirements are as rigorous as those specified for power reactor installations in the United States.

The engineering of steel liners for containment structures is derived from steel pressure vessel practices. The fabrication methods, inspection practices, and material requirements generally follow the requirements of Section III, Nuclear Vessels, of the ASME Boiler and Pressure Vessel Code. However, the liner is not a free-standing structure capable of resisting the internal pressure, and the shell evaluation methods commonly used to determine the structural adequacy of pressure vessels are not applicable. The composite load resistance of the liner and the adjoining concrete shell has been the engineering basis. This composite load resistance has been determined by considering the biaxially stressed liner as a series of buckled plates fixed and restrained by their attachments to the concrete.¹² Hence, much engineering attention is devoted to the adequacy and reliability of these attachments.

The principal engineering criterion is that stress-strain effects of the various loadings caused by pressure, concrete inelastic action, thermal expansion, or mechanical loads of attached structures (piping, tanks, supports, material handling equipment supports) shall not be sufficiently severe to cause leakage through failure of the liner. Limit design methods have proved useful in this engineering approach. The basis of this approach is to show that elastic buckling occurs before the yield stress limits of the steel membrane are exceeded as a result of primary loads and to control the frequency of such

yielding within conservative fatigue limits for secondary loads. Anchors are arranged so that shear failure of an attachment reduces the buckling stress and relieves the forces on adjacent anchors. Of course, cyclic strains are of interest, but these are caused primarily by thermal expansion or attachment forces and can be evaluated by superposition of fatigue analysis techniques in the same manner in which secondary loadings for pressure vessels are treated.

Perhaps it is unwise to attempt to define the engineering approaches used for plastic linings. Obviously, the chemical bond between the lining and the concrete provides the strength to hold the lining in place, and cracks or other flaws on the internal surface of the concrete will determine the structural resistance. Temperature effects are very difficult to evaluate, and lifetime deterioration is a common uncertainty in such linings. The seals around penetrations where thermal expansion and mechanical movement cause severe localized straining of the plastic are regions that are suspect. Mechanical abrasion during operation that could easily damage the plastic surface also introduces uncertainty. But the adequacy of the lining is determined by the stringency of the leak-tightness requirements. Consequently, if the reactor system will permit some tolerance of leakage uncertainty in the containment without jeopardizing safety limits, the plastic liner approach can be adequate for the application.

Construction Methods

Practices that are comparable to those used for any important concrete structure are followed in the construction of containment shells. As in concrete reactor vessel practice, the liner provides the inner form for the concrete. Since the liner is thin and flimsy, dimensional stability must be provided by internal shoring. Slip forming was used for the EL-4 and Gentilly vessels,¹³ but conventional wood or metal forms that can be worked around random penetrations normally placed throughout the containment shell have been used for other containment structures.

The most troublesome aspect of containment shell construction has proved to be the placement of concrete in the regions where a high

concentration of reinforcing steel is necessary. This, of course, slows the placement rate and requires special attention to vibration techniques to assure the absence of voids.

The post-tensioning methods used for prestressed concrete containment structures have been similar to those used in concrete reactor vessels with the principal attention directed toward sequencing the tensioning operation to assure that loads are properly balanced during tensioning.

Operational Controls

All containment installations require provision for periodic testing of their leakage control capability. Pressure testing at regular intervals during the life of the structure is the most common practice. Arrangements have been made in some installations to avoid critical points of potential leakage by providing pressurized buffer systems that can be monitored continuously. These also assure a positive pressure against out-leakage from the shell in the event of an accident. This buffering technique provides insurance against out leakage but interferes with the ability to separate sources of leakage that are acceptable from those which require correction. This ability to identify leakage points that require correction is an important reliability consideration in the containment concept. While there is universal recognition that the most probable sources of leakage in containment structures are likely to be associated with penetrations and access openings, the need to affirm the leak-tightness of the entire structure continually during its lifetime cannot be ignored.

Aside from leakage monitoring, the only useful control for conventional reinforced concrete structures is visual observation of the crack behavior over the operational lifetime of the structure. Consequently, a map of the initial significant cracks in the structure is important in determining whether time is causing deterioration to set in. It is particularly useful to examine the crack distribution under pressure test conditions since that is the only time when the load resisting capability of the structure can be even partially evaluated.

Some additional operational controls of interest are introduced in prestressed concrete structures. Loss of prestress caused by corrosion of tendons and inelastic movement of the concrete and tendon steel are important factors that deserve attention. Because deterioration is readily discernible in a prestressed concrete structure, its reliability is enhanced over that of an installation whose degree of deterioration cannot be determined. However, attainment of this reliability calls for positive action to periodically examine those conditions which would indicate whether deterioration has occurred. There is a tendency among structural designers, perhaps stemming from aesthetic influences, to lean toward designs in which flaws and deterioration cannot be detected by inspection, but it is well known that the emphasis in all nuclear installations is on maximum inspectability to assure reliability. There is no reason why containment structures should be an exception to this precept.

Economic Considerations

Appraisal of containment economics is a complicated problem. The lowest cost containment structure may not be the most economic one. Reliability of containment may have no direct relationship to the ultimate power cost, but it may make the difference between the acceptance and rejection of a particular power plant site. Consequently, we cannot discuss containment economics solely in terms of lowest construction costs. We can suggest some factors in the economic evaluation that deserve consideration when engineering containment concepts.

The most obvious is minimizing materials costs. From this standpoint, the efficient use of reinforcing steel would favor prestressed concrete. However, this type of evaluation cannot be meaningful if the requirements for supplemental reinforcing steel are not considered. So much supplemental steel is provided in some designs to control thermal stresses and to resist shear forces that it alone can almost resist the ultimate design load. Under such circumstances, thermal cracking permitted by reinforced-concrete design practice could negate the structural demand on the supplemental reinforcing steel provided by design

and permit it to carry much of the primary load. Thus far, no containment design defines the approach to considering this load-sharing capability in prestressed concrete, so the potential cost effects are difficult to evaluate.

A strong incentive to minimize concrete thickness always arises from the straightforward determination of costs on the basis of cubic volume. However, this often fails to account for construction premiums associated with tightly controlled steel placement tolerances and restrictions on concrete placement efficiency in overly compact arrangements or overly equipped installations. Much of the premium in construction costs has resulted from failure to recognize the difficulties in construction operations caused by tightly packed reinforcement. If the placement of steel is an important consideration, the lapsed time and efficiency factors should be included in the cost estimate when minimizing concrete wall thicknesses.

The Westinghouse Ice Condenser Containment scheme¹⁴ for pressurized-water reactors has led to a substantial reduction in containment pressure levels, permitting the use of a separate steel pressure shell surrounded by a thick, non-pressure retaining concrete shield. The concrete structural problems associated with such installations are not fully defined but are most likely to be interactions with penetrations and foundations of minor economic significance. Hence, the concrete structure is probably not a controlling economic factor in this special containment concept.

The ability to use relatively low wage-rate crafts with high productivity has always been an economic advantage in concrete construction. However, craftsmanship requirements for containment installations are well above those normally acceptable in ordinary concrete installations. The concrete quality requirements are stringent, and high-strength mixtures with their inherent workability difficulties are commonly used. Steel arrangements are complicated and involve unusual geometrical orientations that require full understanding of the layout.

The heavy steel bars used for reinforcement sometimes require special equipment for forming and handling. Thermit welding techniques for splicing reinforcing bar call for special training in the splicing

methods and special controls over the splicing environment. Prestressing steel has special corrosion control problems that require attention from factory shipment to final service application. The liner is a precision fabricated assembly where quality welds involve careful fitting of large steel sheets. Anchorages for both liners and prestressing steel are highly stressed and must be installed with care in placement and attention to joining techniques. Fitup between the steel liner and concrete shell is important in the strain control design approach which depends on composite structural action. Material control with respect to chemical composition of steel, cleanliness of components, and environmental conditions for fabrication all require special attention. The sequence of erection is often intimately related to the power plant construction schedule so careful planning is a prerequisite to efficient operation.

While not unique to containment, these factors are a complicating influence on construction because of their sheer number. This tends to increase the importance of craftsmanship at least as it pertains to understanding the work requirements. Consequently, the work involves a tightly controlled sequence of operations that is unsuited to massive use of craftsmen unless elaborate supervision is provided.

Inspection and testing are special categories of work in the construction program. Most construction problems have arisen from failure to control dimensions or failure to follow the placement of steel and concrete closely. In many cases, design drawings do not adequately show the three-dimensional problems of assembly, so the inspector has to have a thorough understanding of the design intent and be able to control it in the field through continual discussion with the structural designers. Proof testing takes various forms but usually includes provision for measuring overall deformation and strains in critical elements. Liners are usually radiographed, and some welded seams are leak tested during assembly. These operations call for special preparation in the construction operation that can have an important effect on costs.

Probably the most important factor in containment economics is the provision of containment construction and installation that minimizes its effect as the rate-controlling step in power plant completion. This requires attention to the conditions to be established for equipment

installation. Designs which allow maximum flexibility in subsequent construction work and provide the greatest latitude for adjustment to allow for construction contingencies have great economic attraction. Often, it is worth a substantial cost premium to establish conditions that minimize interference with other power plant construction work so that it can proceed concurrently with the containment construction.

In the same vein, containment designs that interfere least with power plant operation over long-term use have great economic values. A containment design that requires frequent shutdown of the power plant for pressure and leak testing will be costly in terms of plant availability. Designs that have great potential for deterioration and require frequent inspection under difficult access limitations introduce operational requirements that are frequently unacceptable to power plant owners. Consequently, containment designs that reduce the future operational burdens on the power plant owner have important economic value even though the initial cost may be relatively high.

Current Technological Uncertainties

The controls over engineering and performance characteristics of the types of containment structures currently accepted for power reactor installation in the United States fully assure the containment adequacy required for public safety. This is possible only because of very conservative engineering practices combined with a rigorous test and surveillance program for the structures. Considering the level of reliability needed, it may never be possible to soften these requirements. However, much can be done to ease the dependence on detailed scrutiny of design during the engineering process with the resultant savings for power plant installations through a reduction in lapsed time from project conception to power plant operation. Perhaps some reduction could also be made in the actual material costs for these structures if the structural action under accident conditions could be defined more clearly.

One of the biggest concerns is related to failure modes. Great progress has been made in showing how concrete pressure vessels for

power reactors fail,¹⁵ and some of this information may be extrapolated to concrete containment structures. However, the two types of structures have some basic differences that require separate study. In containment installation, the nature of the loading conditions is more abrupt and symptoms of deterioration are difficult to identify. Economic considerations greatly favor minimal surveillance provisions. Consequently, the technology would benefit from a better understanding of the tolerance for structural flaws without loss of containment capability. Modeling or analytical methods that treat flaw evaluation rationally would help to strengthen confidence in the structural adequacy of concrete containment structures and simplify the procedure for correcting unintentional construction flaws.

Stiffness compatibility is a fundamental consideration in the design methods. Most analysis techniques apply the principle of virtual work or a comparable approach involving energy conservation. The conventional elastic analysis techniques are not directly suited to application in concrete structures where strain effects at discontinuities lead to cracking. An iterative method that permits sequential loading of the structure to follow the cracking process analytically is coming into use.¹² This type of analysis requires that tensile cracking limits be arbitrarily fixed in order to provide a mechanism for introducing structural steel action across cracks. The method is certainly rational, but little attention has been given to the matter of variable material properties and how this might influence structural behavior.

The inelastic behavior of prestressed concrete under elevated temperatures still needs clarification. As in reactor vessels, the allowances for creep and shrinkage needed for long-term application require quantitative treatment. This is only a matter of data collection and evaluation, but experiments over long periods are needed and time must be allowed for these continuing experiments.

Thermal strain effects are still poorly defined. Structural response to such effects is not necessarily elastic in character but practices are currently premised on elastic action until cracking occurs. Probably, this approach has only the effect of conservatively proportioning the

temperature steel. Nevertheless, thermal stress reversals are involved and they raise questions concerning the deleterious effect of over-reinforcement. Methods which allow treatment of inelastic behavior in the thermal stress analysis would permit a more realistic analytical model to be used.

Methods for evaluating the composite structural action of reinforced concrete and attached thin steel and plastic liners need definition and experimental confirmation. The design methods being used seem more than adequate to experienced structural designers, but the reliability requirements of these structures warrant indisputable proof of adequacy. Consequently, it would be very desirable to obtain some completely instrumented tests of these structures in which all important conditions of composite structural action are investigated to show stress-strain behavior up to ultimate design loads.

In conjunction with the liner-concrete composite structural evaluation, the behavior of liner anchorages deserves attention. The manner in which the anchorage carries the load varies with the design. One method not yet fully reported in the literature treats the anchorage in two forms. One controls buckling of the liner, while the other carries a major fraction of the loads on the liner from its own weight and the attachment forces. Other designs use a uniform anchoring system in which each anchor carries an approximately equal share of all loads. The analysis methods for these designs are obviously different, but all depend on compressive loading of the liner wherever it is unsupported by the concrete shell. A concise definition is needed of the load carrying capability that accounts for potential anchorage failure and allows for realistic rather than idealized strain and deflection in the liner-anchorage system.

For a number of years, the ACI 349 Committee on Concrete Nuclear Containment Structures has been trying to establish criteria for containment structures. Much progress has been made in establishing a mutual agreement among designers with respect to the superposition of concurrent loadings. The design methods still lack the uniformity needed to simplify and expedite safety review. Proof testing methods are still developed on a case-by-case basis. The question of shear resistance, particularly

with respect to combined lateral and radial shear forces induced by seismic and internal pressure forces remains hazy in spite of exhaustive analysis of specific cases and recent experimental work. A more general treatment of the subject that establishes an engineering approach suited to all of the designs currently being used would take away much of the confusion in this matter.

The nature of proof testing that best suits the application needs more study. It is well known that pressure tests do not simulate accident conditions since they do not impose lateral shear or thermal stress. The relationship between leak tightness and strength testing remains nebulous. Consequently, the whole problem of performance verification haunts the designers. Development of a rational basis for proof testing would take away some of the mystery that permeates safety evaluation activities related to containment.

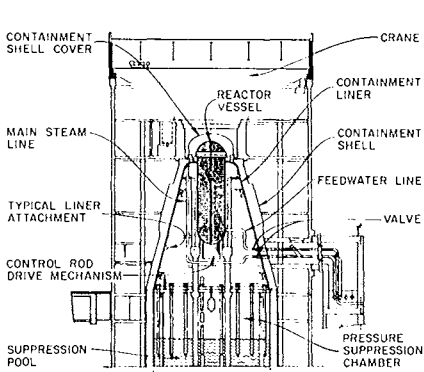
Summary

Retrospective examination of this discussion unveils some inconsistencies in the technological appraisal of containment. There is a deep-seated feeling among those who have been close to its engineering development that the practices followed are founded on the highest grade of structural treatment. But some uneasiness concerning containment engineering arises from the level of reliability credited to the structure; a level that is beyond statistical experience. Experience with reinforced concrete in other applications has shown its ability to survive the types of structural contingencies that can be visualized in containment applications if the design treatment is correct. Hence, what seems to be needed is only stronger assurance that the design approaches are well founded through appropriate experimental verification that allows for time-dependent deterioration factors. Much would be gained by establishing design uniformity that permits the development of meaningful statistical experience with early structures. The use of concrete containment will continue to grow along with nuclear power. Considering the importance of safety in this growth process, it is only fitting that the fundamental knowledge on which safety depends be pursued vigorously.

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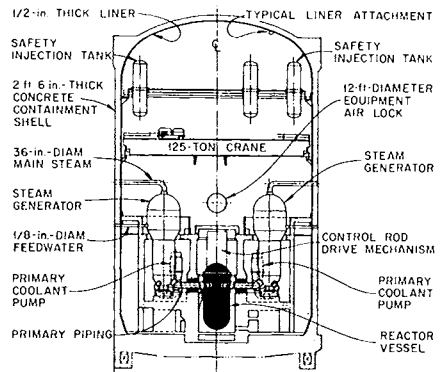
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APPROXIMATE CONTAINMENT SHELL DIMENSIONS: HEIGHT = 165 ft, BASE ID = 80 ft, DOME OD = 25 ft, DESIGN PRESSURE = 48 psig

Fig. 1 Concrete containment for boiling-water reactor system



CONTAINMENT SHELL IS APPROXIMATELY 190-ft HIGH WITH 110-ft INSIDE DIAMETER. DESIGN PRESSURE = 55 psig

Fig. 2 Concrete containment for pressurized water reactor system