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PRESTRESSED-CONCRETE PRESSURE VESSELS AND THEIR APPLICABILITY TO ADVANCED-ENERGY-SYSTEM CONCEPTS

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ABSTRACT

Prestressed concrete pressure vessels (PCPVs) are, in essence, spaced steel structures since their strength is derived from a multitude of steel elements made up of deformed reinforcing bars and prestressing tendons which are present in sufficient quantities to carry tension loads imposed on the vessel. Other major components of a PCPV include the concrete, liner and cooling system, and insulation. PCPVs exhibit a number of advantages which make them ideally suited for application to advanced energy concepts: fabricability in virtually any size and shape using available technology, improved safety, reduced capital costs, and a history of proven performance. PCPVs have many applications to both nuclear- and non-nuclear-based energy systems concepts. Several of these concepts will be discussed as well as the research and development activities conducted at ORNL in support of PCPV development.

INTRODUCTION

The concept of a concrete primary containment structure originated independently in France and England over twenty-five years ago and led to the first PCPVs in 1960 at Marcoule, France. The motivation for employing a concrete pressure vessel was the direct result of the size requirements for gas-cooled reactors (GCRs) and the existing limitations on the fabricability of large relatively thick-walled steel vessels. The original designs were based on a one-to-one substitution for a conventional steel vessel and involved a variety of vessel geometries, with each new application evolving to meet the design and construction requirements of a particular nuclear system.

GENERAL DESCRIPTION

The PCPV shown in Fig. 1 is, in essence, a spaced steel structure, since its strength is derived from a multitude of steel elements made up of deformed reinforcing bars and prestressing tendons which are present in sufficient quantities to carry tension loads imposed on the vessel. Functions of the PCPV for nuclear applications are to: (1) resist the internal pressure of the process contained; (2) provide radiation shielding for the reactor core; (3) contain radioactive products; and (4) contain the entire primary cooling system-reactor, heat exchangers, and circulators.

A PCPV consists of five major components: (1) concrete, (2) post-tensioning system, (3) conventional mild steel reinforcement, (4) liner and cooling system, and (5) insulation between the core and inner concrete surface. The concrete provides radiation shielding, temperature shielding for the steel, a reaction medium for the prestress, and contributes to the overall strength of the vessel. The post-tensioning system provides both longitudinal and circumferential prestressing to carry tensile forces associated with internal pressurization and to inhibit concrete cracking. Conventional mild steel reinforcement controls cracking and crack widths of the concrete, helps carry tensile forces where concrete has cracked, and can be used to assist in carrying excess compressive forces. The liner provides a leak-tight barrier for the vessel coolant and forms a barrier against the release of radioactive fission into the concrete. The cooling and insulation systems prevent excessive temperatures in the concrete and steel.

DESIGN CONSIDERATIONS

Current designs of PCPVs for GCRs are based on the integral concept; that is, the entire pressurized circuit composed of the reactor core, primary coolant system and portions of the secondary coolant system are contained within a single vessel. For safety, the structural integrity of the PCPV and its support must be assured during the design life and it must have specified ultimate load capacities. Overall structural response of a PCPV to increasing cavity pressure, as depicted in Fig. 2, is to be gradual, observable and predictable as its ultimate structural capacity is approached. As shown in the figure, the response exhibits three distinct regimes prior to leakage. For design and analysis purposes two conditions are considered: elastic, and to provide an adequate factor of safety against failure.

The PCPV is first designed for elastic response to establish loading distributions under pressure, dead load, prestress, thermal and other mechanical and dynamic loads. The analysis for service load conditions takes into account the time- and temperature-dependent characteristics of the concrete in addition to the complexity of the geometry and the loading conditions. For loads resulting from prestressing and dead loads during construction and up to the time of the pressure test, the concrete may be assumed to be linearly elastic. For all other service load conditions, the concrete stress-strain relation includes effects for age, temperature, and time under load. Although net compression in the concrete should be maintained under service load conditions, localized cracking is not detrimental if passive steel reinforcement is provided and due regard is given to stress redistribution and the integrity and leaktightness of the liner are maintained. Local stress concentrations are individually addressed and localized self-limiting stress concentrations may be ignored. Increased values of concrete compressive stress due to multiaxial loading conditions are permissible. Maximum concrete strengths are based on values obtained under sustained-loading tests. Basically, in the working stress design approach, stresses for construction, test, service load, and design load conditions are evaluated and compared with allowable stresses for the concrete, reinforcing steel and prestressing steel.

Ultimate strength design of PCPVs is based on a load factor approach. Basically this involves comparing factored design forces and moments at given sections in the vessel with the ultimate design

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capacity of the section for test, service, design, accident and extreme loading conditions. Ultimate capacity of the PCPV is determined through the assumption of failure mechanisms. Designers generally proportion PCPVs so that the ultimate pressure capacity will be at least twice the maximum cavity pressure and that failure will be in a ductile manner; that is, in the barrel region of the vessel as opposed to the head. This provides adequate design margin against hypothetical over-pressurization, potential material deficiencies, and design and construction deficiencies.

Existing codes for design of PCPVs have been developed for nuclear PCPVs. Subsection CC of ASME Section III, Div. 2 (1) covers thin shell PCPVs of the type used as secondary containments for light-water reactors. Thick-walled vessels such as used for GCRs are covered by Subsection CB of ASME Section III, Div. 2 (1). Other codes that have some applicability include ACI 318 which provides requirements for reinforced buildings (2), and ACI 349 which provides requirements for nuclear safety related concrete structures. (3) Through a joint American Concrete Institute Committee and American Society of Mechanical Engineers Special Working Group on "Composite Concrete and Steel High Pressure Vessels for General Industrial Use" work has been initiated to develop a code for non-nuclear PCPVs.

MATERIALS AND FABRICATION

Concrete used in the construction of PCPVs is of high quality having relatively high strength (44.8 to 55.2 MPa for current designs), good mix workability, low creep, low thermal expansion and low drying shrinkage properties. It is prestressed both longitudinally and circumferentially by post-tensioning. The longitudinal prestressing generally consists of groups of high strength steel wires or strands which are positioned within ducts contained in the walls of the PCPV. Tendon materials are protected from hostile environments by specially formulated organic petrolatum-based compounds (greases). A continuous-welded thin steel liner fabricated from materials such as listed in Appendix 1 of Ref. (1) is used to contain the process environment. Attached to the process side of the liner is the insulation system which may be in the form of metallic reflective foils (stainless steel), fibrous ceramic (alumina-silica mixture or silica felt), or refractory concrete. Excess heat generated by heat transfer from the hot reactor gas or neutron and gamma energy is removed by a cooling system which is either attached directly to the liner or located in close proximity to the liner.

Fabrication of a PCPV is primarily performed at the construction site using standard civil engineering procedures. After site and foundation preparation, construction of the PCPV is initiated with fabrication of the liner, to which may be welded cooling tubes, studs for tying liner and concrete deformations together and preventing liner buckling, structural elements required for load transfer around penetrations and closures, etc. Next, tendon ducts and bonded steel reinforcement are positioned and the concrete is placed in a series of lifts to reduce heat buildup due to cement hydration effects. After curing, the concrete is prestressed both axially and circumferentially. Finally, other equipment, piping connections, and insulation are erected.

ADVANTAGES AND LIMITATIONS

PCPVs have a number of advantages which makes them amendable to advanced energy systems concepts. Vessel dimensions in combination with operating pressures remain virtually unrestricted, within the ranges of interest. Virtually any shape known to be advantageous from a structural and/or functional sense can be realized. PCPVs exhibit unique and highly desirable performance features from the standpoint of operational safety; that is, strength is derived from several materials, structural redundancy with prestressing systems inspectable and replaceable, ductility with failure gradual and predictable and leak occurs before break, operation represents lowest stressed condition, integral design with entire pressurized circuit contained within one vessel, and primary strength producing members are protected from heat and corrosion. PCPVs generally can be constructed using aggregates and cements available in the immediate region, and the steel elements used are relatively simple standard structural shapes which are easily transported to relatively inaccessible locations by conventional methods. PCPVs are corrosion resistant, durable with low maintenance requirements, and provide radiation shielding. Also PCPVs have a history of proven performance.

PCPVs, however, also have their limitations which must be addressed. Construction of PCPVs requires careful planning and execution in coordinating and controlling simultaneous fabrication of several functional components within a single vessel. Calculations and analyses of PCPVs are complex because of the time-, temperature-, and moisture-dependence of the concrete. Penetrations and openings present design and construction problems with respect to reinforcement and prestressing congestion, circumferential prestressing and closures. A thermal protection system is required to limit the concrete temperatures to approximately 65°C and to limit thermal exposure of the prestressing system. In the unlikely event that the liner would develop a leak, there is the possibility of a pressurized crack; that is, build-up of internal pressure in the concrete wall up to the outer diameter.

FAILURE MODES AND REPAIR CONSIDERATIONS

Catastrophic failure of a PCPV is virtually impossible due to the redundant nature of its design; that is, prestressing steel, reinforcing steel, concrete, and liner all contribute as strength producing members. In the unlikely event that conditions which could lead to failure were to occur, the failure process would be gradual with deformations and cracking indicating distress so that safe shutdown procedures could be implemented; however, merely the appearance of surface cracks does not represent failure because as long as their opening is small, rupture of the steel liner has not occurred, and the tensile loads across the cracks are carried by the prestressing and mild steel reinforcement. As the pressure decreases, the cracks will close under the influence of the prestressing tendons.

Repair of the prestressing system of the PCPV is relatively easy in that it merely involves replacing defective components. External repairs of the concrete surface can also be made with relative ease, although as noted above, the appearance of cracks does not necessarily indicate structural distress [cracked section PCPV design is based on allowing controlled concrete cracking globally at service load conditions through proper proportioning of the PCPV structure and the magnitude of the prestressing (partial prestressing)]. Repair of the insulation, liner and cooling system is considerably more difficult. Current generation PCPV thermal barrier designs generally utilize either a metallic foil or fibrous ceramic material which is contained behind cover plates (cold liner), thus limiting accessibility for repair or replacement. [Concepts have been developed for replaceable thermal barriers (4) which could facilitate liner inspection and repair. Also, hot liner designs (5) have been developed which make the liner accessible for inspection and repair.] Redundency is built into most cooling system designs, but should a leak develop techniques for in-place repair have been developed in both the United Kingdom and United States.

REVIEW OF APPLICATIONS OF PCPVs TO ENERGY SYSTEMS

The first PCPVs (Marcoule G2, G3) were developed in France and commissioned in 1960 to contain low pressure platonium producing reactors (6). Shortly followed the Electricite de France boiler reactor pressure vessel at Chinon (7) in 1967 and the United Kingdom station at Olbury-upon-Severn (8) in 1968. The Oldbury station was unique in that it was the first to incorporate the "integral" design concept in which both the reactor and steam generators were housed within a single vessel. Concurrent integrated designs also occurred in France at St. Laurent (9) in 1969 and Bugey (10) in 1972, and in Spain at Vandellos (11) in 1972. In each of these designs the steam generators were located below the reactor to minimize the vessel diameter. The next design innovation was the "podded" vessel, with wire winding to provide hoop prestress, which was introduced at Hartlepool and Heysham in the United Kingdom (12). In this design the steam generators were located in separate cylindrical cavities formed within the thickness of the vessel wall, thus making it more readily possible to replace components such as steam generators, if required. To date approximately twenty-seven PCPVs are utilized as primary containments of GCRs which are either on-line or in various stages of construction (Table 1). In addition, conceptual designs have been developed for PCPVs as containments for light-water reactors (13), liquid metal fast breeder reactors (14), gas-cooled fast breeder reactors (15), and an urban district heating reactor (16).

In the United States, with the exception of prestressed concrete secondary containments for light-water reactors, the primary application of PCPVs to energy production has been through the high-temperature gas-cooled reactor (HTGR) at Fort St. Vrain. [Considerable reasearch and development effort has also been devoted to a gas-cooled fast-breeder reactor (GCFR) which would utilize a PCPV for primary containment, but uncertainity in total development costs for the GCFR relative to the more fully developed liquid metal fast breeder reactor (LMFBR) recently resulted in the entire U.S. Government breeder reactor program being devoted to the LMFBR.] The Fort St. Vrain 330-MW(e) Nuclear Generating Station, which initiated power generation in late 1976, houses all major components within a PCPV whose general arrangement is shown in Fig. 3 (17). The PCPV is hexagonal in cross-section, the external dimensions are 15 m across the flat of the hexagon and 323 m high. Top and bottom heads, which contain multiple penetrations, are 4.7 m thick and the wall is 2.7 m thick. Peak working pressure is 4.85 MPa. Throughout production of over 3 billion kilowatt hours of net electrical energy, performance of the PCPV has been excellent (18).

PCPVs AND ADVANCED ENERGY SYSTEMS CONCEPTS

High-Temperature Gas-Cooled Reactors (HTGRs)

Increasingly favorable experience resulting from Fort St. Vrain coupled with the high temperature capabilities of HTGRs has resulted in applications studies in the United States related to: steam cycle/cogeneration nuclear heat source and the potential for advanced systems (19). A vital component of each of these applications is the PCPV which contains the entire primary coolant circuit and provides the necessary biological shielding and pressure containment.

Steam Cycle/Cogeneration. In the steam cycle/cogeneration design the reactor thermal energy is used to generate high quality steam at elevated temperature conditions of 17.2 MPa/540°C for either high efficiency electricity production (38.2% net efficiency) or for cogeneration of steam and electricity for process applications (93% net efficiency at full cogeneration potential). The nuclear steam supply system (NSSS) is being developed as a modular, four primary loop design that can be scaled up or down by the addition or subtraction of loops while maintaining configuration. The current lead plant system has a reactor power of 2240 MW(t) [855 MW(e)] and contains all major components of the NSSS in a PCPV. The PCPV is a multicavity structure similar in concept to those at the Hartlepool and Heysham plants but incorporates advances in layout (asymmetrical design with offset core), concrete (increased compressive strength), and prestressing tendons (higher capacities). In addition to the general process steam/cogeneration mode, other potential applications include in-situ petroleum products recovery (heavy oil, oil sands, shale oil) and synfuels processes [catalytic coal gasification, coal liquids (H-coal, donor solvent, syngas]. Current plans call for completion of the conceptual design in FY 1983 and construction of the plant in the early 1990's.

Process Heat. Two versions of a process heat HTGR have been under consideration: an 850°C core outlet temperature with an intermediate helium loop and a 950°C core outlet temperature with a reformer and steam generator in the primary circuit (20). The high grade heat can be used to produce hydrogen and synthetic fuel, with coal, lignite, residual oil, or oil shale as the carbon source. It can also serve as the heat source for thermochemical water-splitting processes to produce hydrogen without carbon. In the steam methane reforming process a portion of the reactor thermal energy is used to convert methane and steam to carbon monoxide and hydrogen in the presence of a catalyst. The resulting synthesis gas can be transported and/or stored at ambient temperatures. The reactor energy can subsequently be recovered through the reverse reaction (methanation) or the sythesis gas can be utilized directly in a chemical process. Through the thermochemical pipeline concept (TCP) the products of the methanation reaction are recycled to the reactor forming a closed loop. Also using the TCP concept reactor energy can be transported over long distances (>100 km) and distributed to industrial users in the form of direct heat or steam at temperatures up to 540°C. Advantages of steam production and cogeneration can also be extended by use of a heat transport and storage medium such as sensible energy transmission and storage (SETS). In this variation, the reactor thermal energy is transferred to a molten salt energy transport medium (mixture of sodium nitrate and potassium nitrate) where it is transported (<40 km) and/or stored to meet cyclic loads. The stored energy is recovered at the point of use through a salt to steam or salt to process steam heat exchanger. The PCPV for process heat applications would be basically the same for the steam cycle/cogeneration version.

Gas-Turbine. In the gas turbine system the helium, in addition to being used as the coolant, is also used as the working fluid with an integrated gas turbine. The reference plant configuration is rated at 2000 MW(t) and has two power conversion loops with each containing a helium gas turbine coupled to a 60 Hz generator rated at approximately 400 MW(e). Coupling a "Brayton" cycle with the gas turbine results in a high heat rejection temperature in addition to the 40% efficiency and facilitates the economic use of dry cooling for electric power generation in water-scarce areas. High reject heat can also be used in a bottoming cycle for cogeneration of process steam, district heating or water desalination. Interest in this plant stems from the potential for improved efficiencies at higher core outlet temperatures, the basic simplicity of the gas turbine cycle (potential for lower maintenance, higher capacity factors), low water use requirements, and potential cogeneration characteristics. All power conversion loops, except the generator, and the entire helium inventory are contained within a PCPV of similar design to those for the previous applications.

Modular Reactor System (MRS). Recently there has been a renewed interest in small or modular HTGR reactor systems because of a potentially higher degree of safety assurance and improved reliability characteristics for aggregate process energy systems. The MRS also offers the potential for improved capability to match the user heat load and availability requirements by varying the number of reactor modules at the nuclearisland. Two particular designs of the MRS are being studied to determine cost effectiveness and market penetration. The very high temperature reformer system which applies one or more 250 MW(t) modules for the same applications as the previously described 2240 MW(t) HTGR reformer system. Similarly, a 300 MW(t) steam cycle/cogeneration version of the MRS supplies high quality steam for the same applications as the previously described larger steam cycle/cogeneration system. Currently a vertical in-line configuration with control rods on the bottom and heat exchangers above the core is being considered to take advantage of natural circulation to remove decay heat in the event of a loss of forced circulation accident. Although steel reactor vessels are currently being considered as the primary containment for the MRS because they can be prefabricated and assembled at the site and a steel vessel allows heat removal by radiation to prevent core heatup beyond temperatures where significant fission product releases would occur from the fuel elements, the use of a PCPV as the reactor containment vessel is also being pursued and a conceptual design for a 250 MW(t) HTGR plant has been developed (*21*).

Coal Conversion Process

Oak Ridge National Laboratory (22). A feasibility study was conducted to investigate the use of PCPVs for gasifier vessels in coal conversion systems. Two processes were considered: Hygas with an output of 2.64 x 10^8 MJ/day and Synthane with an output of 1.32 x 10^8 MJ/day. Operating conditions for the Hygas process were a peak temperature of 1010°C and pressure of 8.96 MPa, and for Synthane process these conditions were 982°C and 7.41 MPa. Conceptual designs for the PCPVs for these processes are presented in Figs. 4 and 5. Liners for the gasifier vessels are protected from the process temperature and deleterious effects of the process media by refractory lining systems. Capital cost comparisons for equivalent steel and concrete vessels for HYGAS gasifiers indicated that they were virtually equivalent. Although results of the study demonstrated that PCPVs are potentially both technically and economically feasible for gasifier applications, it was pointed out that the technical conclusions reached should be confirmed; that is, performance of the liner-thermal barrier system in a high temperature and erosive-corrosive environment should be demonstrated.

University of Kentucky (23). A comprehensive study of alternate structural designs for large pressure vessels for use in processes for gasification and liquifaction of coal was conducted with the aim of establishing optimum designs for given size, pressure, temperature and other needs. Single wall steel vessels, layered wall steel vessels, prestressed concrete vessels and prestressed cast iron vessels were described with respect to: (1) structure and materials, (2) fabrication, (3) limitations and constraints, (4) pre-service inspection and testing, (5) in-service inspection, (6) shutdowns for periodic inspection and maintenance, (7) types of failure and their repair, (8) methods of design and analysis, (9) example simple design and analysis, (10) experience, and (11) advantages and disadvantages. Table 2 presents a summary comparison of the study results for the vessel types considered.

T. Y. Lin (24). Conceptual designs and economic comparisons of PCPVs with equivalent steel vessels were made for four coal conversion plants: (1) integrated gasifier reactor vessel (IGRV), (2) combined disolver-separator vessel (DSV), (3) absorber column vessel (ACV), and (4) gasifier vessel only (GV). Current nuclear codes could not be directly applied to the non-nuclear PCPVs because of the extreme operating pressures and temperatures involved. To conform with the nuclear code requirement of zero membrane tensile stress would require excessively thick walls and/or a much higher level of prestressing which in turn would result in the PCPVs not being economically competitive. The approach adopted to counteract this was to design a high-pressure PCPV that accepts tension and tension cracks in the outer region of the PCPV. The possibility of incorporating artifically-introduced preformed separations that pre-defined crack locations to simplify the vessel design and analysis was investigated as a method of controlling high tensile stresses generated by internal pressure and temperature. Results of this preliminary study established the feasibility of this design approach and the potential economic advantages of PCPVs relative to steel vessels, that is, in the extreme case of the DSV the PCPV was estimated to be approximately 70% cheaper than the eighteen steel vessels of equivalent capacity it replaces.

Magnox Reactors for Heavy Oil Recovery (25)

A study has been conducted at Taylor Woodrow Construction Ltd. (South Middlesex, United Kingdom) to utilize nuclear energy to generate steam for injection recovery of heavy oil. (Relative to the current practice of producing steam by burning a portion of recovered oil, nuclear energy was estimated to provide steam at only one-fifth the cost.) A Magnox GCR was selected as the nuclear heat source since it could provide the range of steam conditions required, but the steam is required at pressures to 15 MPa which is considerably higher than in existing Magnox plants and the injection steam generation must be by a "once-through" system using feedwater from a natural water source. A principal design modification involved location of the injection steam boilers outside the main reactor vessel by either using primary heat exchangers connected to external boilers via an intermediate heat transfer circuit, or by ducting the reactor coolant gas directly to external boilers (preferred). An economic analysis was conducted which showed that the capital payback times and the projected earning rates were consistently better for an oil field development which employs a central nuclear steam generator as compared to burning oil (over a projected 25 year lifetime the economic model used in the study projected up to $10B improved earnings for the nuclear option). Although past Magnox reactors have utilized steel as well as prestressed concrete as pressure vessel materials, a PCPV was selected because of its inherent safety features and its history of proven performance with GCRs.

PCPV RESEARCH AND DEVELOPMENT STUDIES AT ORNL IN SUPPORT OF PCPV DEVELOPMENT

Since the mid 1960's, the ORNL has engaged in a comprehensive concrete research program in support of energy systems developments. Over the years the program has included studies related to: design, construction, and safety evaluations of prestressed and reinforced concrete containments; model testing; behavior of concrete at elevated temperatures; and assessment and state-of-the-art reports.[1] The current emphasis of the program is related to the development of PCPVs for HTGRs.

Review of PCPV Studies

Prestressed and reinforced concrete containments. Several years ago a study was conducted to review current practices in the design and construction of prestressed and reinforced concrete containments for water-cooled nuclear reactors. The review included identification of: different containment types; normal and extreme environmental conditions; modes of failure; design criteria; materials criteria; quality assurance criteria; applicable codes and standards, plus areas where argumentation and/or revision appeared warranted; and need for development of operational testing requirements. Results of this study are contained in Ref. (26).

Model tests. Several types of model tests have been conducted in support of PCPV development. These have included: model size effects evaluation, thermal cylinder model, head failure models, moisture migration model., and closure models. A series of small PCRV models was designed, analyzed, constructed and tested to investigate the suitability of small-scale ($\leq$1/20) mortar models and epoxy models for determining elastic stress distributions and cracking and failure modes of concrete vessels, and to demonstrate the adequacy and relative accuracy of two- and three-dimensional finite-element structural analyses when applied to relatively complex structural shapes. Five models were studied: a prototype; two 1/2.75-scale mortar models; a 1/5-scale prestressed epoxy model; and a 1/5-scale, idealized, unprestressed, axisymmetric epoxy model. Results, presented in Ref. (27), indicate close correlation between the models and prototype, and reasonable agreement between analytical and experimental results.

A thick-walled prestressed cylinder model having a height of 1.22 m, a thickness of 0.46 m, and an outer diameter of 2.06 m was subjected to 4.83 MPa internal pressure and a thermal crossfall imposed by heating the inner surface to 65.6°C and cooling the outer surface to 24°C. The ~1/6-scale model experiment was designed to provide information for evaluating the capability of analytical methods to predict the time-dependent stress-strain behavior of the barrel section of a single-cavity PCRV, and to demonstrate structural behavior under design and off-design thermal conditions. Results, presented in Ref. (28), showed that comparisons between experimental data and calculated values were reasonable in a vessel subjected to normal operating conditions.

Thirty-eight small-scale cylindrical vessels with flat end slabs were tested to failure to provide data for development of a method to permit reliable calculation of the strength of end-slabs of PCRVs. The models were prestressed circumferentially and longitudinally. Variables included end-slab thickness, size and arrangement of penetrations in the end slab, and concrete strength. Each vessel was pressurized to failure over a period of approximately three hours. Test results presented in Ref. (29) were used to develop an axisymmetric nonlinear finite element model for predicting vessel behavior.

In an effort to obtain information regarding the nature ofmoisture movement and the rate of moisture loss in a PCRV, an experimental study of moisture migration in a pie-shaped specimen representing the flow path through a cylindrical wall in a PCRV was conducted. The test specimen was 2.74 m in length with cross-section dimensions of 0.61 by 0.61 m on one end and 0.61 by 0.81 m on the other end. A temperature gradient of 44°C was applied to the specimen and temperature and moisture distributions were determined as a function of time. Results presented in Ref. (30) shows that moisture migration in thick concrete sections is a slow process and not likely to be a significant factor with a temperature difference of 44°C or less.

Under the Gas-Cooled Fast Breeder Reactor program three small-scale model tests have been conducted: (1) 1/15-scale steam generator cavity full-thickness closure model, (2) 1/15-scale steam generator cavity half-thickness closure model, and (3) 1/20-scale central core cavity closure model. The first model was pressurized to 7.5 times maximum cavity pressure (MCP) at which time the test was terminated. The second model, which differed from the first in that the model thickness was reduced by a factor of two and the shear console was removed, failed at 9.9 MCP. Testing of the third model was terminated at 4.8 MCP due to failure of an end cap on a penetration tube (31-33).

Behavior of Concrete at Elevated Temperature

Three studies have been conducted to assess the behavior of concrete in a nuclear environment: (1) effects of thermal exposure on mechanical properties, (2) time-dependent deformations of concrete under elevated temperature and multiaxial loadings, and (3) property development in support of the Clinch River Breeder Reactor (CRBR).

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[1] Feasibility of PCPVs for coal gasifiers was also investigated, but results were reported previously.

Cylindrical concrete specimens 152-mm diam. by 457mm were tested to determine the effect of the following on the concrete stress-strain relationship: (1) sustained temperature of 149°C, (2) thermal cycling, (3) sealed vs unsealed concrete specimens and (4) specimen testing at temperature vs testing after cooling to room temperature. Results presented in Ref. (34) show that: (1) the coefficient of thermal expansion increased with a decrease in rate of heating; (2) when moisture is not permitted to escape freely, significant residual expansion occurs with subsequent thermal cycling, and (3) when moisture was contained within the specimen the compressive strength and stiffness were significantly affected by a longer duration of exposure at 149°C.

The time-dependent deformation of concrete was investigated by subjecting 152-mm diam. by 406 mm cylindrical specimens to various stress conditions and elevated temperatures. Variables included temperature (23.9 and 65.6°C), age at loading (90,183 and 365 days), a variety of axial and radial load combinations from 0 to 24.8 MPa, and curing history (air-dried and as-cast). Results of the investigation (35, 36) indicated that compressive and tensile creep strains were generally larger for: (1) test temperature of 65.6°C vs 23.9°C, (2) an air-dried concrete vs an as-cast concrete (except for low tensile creep), (3) increased time after loadings, and (4) higher stresses for uniaxial and biaxial states of stress.

In support of the design of the CRBR with respect to postulated accident conditions, the effect of elevated temperature exposure on the mechanical properties of a limestone aggregate structural concrete and an insulating lightweight concrete were determined. Four test series were conducted: (1) unconfined compression, (2) shear, (3) concrete-rebar bond and (4) sustained loading (creep). Standard 152-mm diam. by 305 mm cylindrical concrete test specimens were used in the unconfined compression and sustained loading test series. An "S-shaped" parallelepiped specimen was used in the shear test series and a 0.30-m concrete cube containing a No. 11 rebar was used in the concrete-rebar bond test series. Thermal stabilization temperatures up to 621°C were used in the test series. As a result of the temperature exposure level of interest, the program required both the development of test methods and instrumentation systems. Details can be obtained from Ref. (37).

Assessment and State-of-the-Art Reports.

In support of the development of PCPVs for advanced energy systems concepts a number of state-of-the-art reports have been developed. Subjects have included: structural model testing (38); concrete embedment instrumentation systems (39); acoustic emission monitoring of concrete structures (40); grouted and nongrouted tendons (41); corrosion inhibitors for prestressing steels (42); concrete properties in a nuclear environment (43); liner, cooling and insulation systems for PCRVs (44); steel reinforcement and prestressing for PCRVs (45); pebble bed vs prismatic-fueled HTGRs (46), optimized PCRV for HTGR plant (47); analysis methods for PCRVs (48); and modular reactor systems (49).

Current Research in Support of PCPV Development for HTGRs

Research and development activities in support of PCRV development consist of generic studies to provide technical support for ongoing PCRV activities, to contribute to the technological data base, and to provide independent review and evaluation of the relevant technology. Current activities conducted in support of the development of HTGRs include: analysis methods development, concrete property determinations, model testing, and structural component testing.

Analysis Methods Development. There are a number of sophisticated methods for analyzing both the short-term elastic and long-term time dependent loading of complex structures. However, the finite element method is the numerical procedure which is most capable of providing a realistic model for a structure having the geometric intricacy of a PCPV. Finite element methods are sufficiently developed for three-dimensional elastic, short-term deformations, but for determination of long-term time dependent behavior and response predictions of complex structures for inelastic loading conditions further development and verification is required. In line with this, techniques are being developed for incorporation into existing modern finite element computer programs to improve their accuracy and efficiency. Items currently under investigation include: (1) concrete constitutive models, (2) modeling of reinforcing bars in reinforced concrete structures, and (3) computation of creep effects in concrete structures.

The basic constitutive equations contained in the endochronic model (50) have been modified to include inelastic volumetric strains due to hydrostatic stress and tensile cracking of concrete (51). The revised endochronic model and the hyperelasticity model contained in the ADINA finite-element code (52) were then used to analyze concrete test specimens subjected to uniaxial and multiaxial loadings, and relatively simple concrete structures. Correlations between analytical and experimental results were reasonable in the elastic range but ranged from fair to poor in the inelastic range. These results indicated the need for further model development to include effects for determining creep and aggregate interlock effects, and methods for controlling the shape of the concrete stress-strain curve.

When conducting finite-element analyses of PCPVs and their related components, correct representation of individual reinforcing bars with truss elements included in most finite-element codes is virtually impossible. Usual practice is to model the component with relatively large isoparametric elements, each of which may contain portions of several reinforcing bars which must be positioned along the edges of the continuum elements. To alleviate this difficulty, a procedure has been developed which allows arbitrarily oriented rebars to be embedded in the isoparametric continuum elements (53). This was accomplished through an algorithm which introduces positional nodes to define the location of the rebar and an additional basis coordinate. The method developed provides improved analysis capabilities for structures as they are approaching failure where the position and orientation of the rebars becomes more important.

Evaluation of the full benefit of the safety and reliability of concrete containment structures requires consideration of the inelastic behavior of the concrete and reinforcing materials as well as their strength effects. In concrete vessels acting as primary or secondary containments, creep of concrete is the major cause of inelastic behavior during the vessel's service life. Through a subcontract with Bazant and Rossow, a set of computer subroutines for creep analysis of concrete structures was completed (54). The program accomodates structures with reinforcing steel, prestressing steel and axially symmetrical thin shell elements (liner elements). Structures may be subjected to external static time-dependent loads and temperature changes (fixed or variable spatial distributions with time). Validation of the program was demonstrated through a series of simple test problems and one large reactor vessel problem.

Concrete Property Determinations. Information on the effects of elevated-temperature and multiaxial loadings on concrete's properties is being assembled. With increasing interest in the use of high-strength concretes (≥55.2 MPa), data are being assembled on requirements for producing these concretes, typical properties, and research requirements. An interim report presenting information assembled to date has been published (11). In the report, concrete material systems are reviewed with respect to constituents, mix design, placing, curing and strength evaluations, and typical concrete property data are presented; effects of extreme loadings (elevated temperature, multiaxial, irradiation) on concrete behavior are described; and specialty concrete material systems (high strength, fibrous, polymer, lightweight, refractory) are reviewed. A complementing report on the effects of multiaxial loadings on concrete properties is being developed. Results of this report, as well as a comprehensive evaluation of the systems used to obtain concrete multiaxial data, will form the basis for development of a performance specification for procurement of an elevated-temperature (≤316°C) electro-hydraulic servo-valve concrete multiaxial testing system. Data obtained with the system will be utilized to develop improved constitutive relationships for concrete.

Model Testing. Because the newer generation PCRV designs include an asymmetric cavity arrangement and offset core, existing model test data might not meet the intent of ASME Section III, Div. 2 requirements. In addition, the complexity of the new designs will require further development and verification of 3-D finite-element analytical codes. Contingency plans are therefore being developed so that a PCRV model test can be conducted in a timely manner should it be established as a requirement for licensing. These plans are addressing two areas which have been identified as potentially requiring additional development: wire winding of models and liner systems. Techniques which have been developed to meet these requirements include the use of a prestressed concrete pipe vendor to circumferentially prestress the models, and a 12-gage AISI 1008 drawing quality steel material for the liner which consists of a flanged head to which a skirt section is joined. Verification of these techniques is being made by fabricating and testing to failure two PCRV models approximately 1 m diam. by 1 m high. Because one of the two models tested is to be fabricated from fibrous concrete, the results obtained will also provide an indication of the effectiveness of fibrous concrete for application to PCRV construction.

Structural Component Testing. The ability of candidate ceramic pad configurations used to support the graphite posts in the bottom head region of the core outlet plenum of the PCRV for an HTGR is being evaluated through a cooperative program with General Atomic Technology. Hard ceramic materials being investigated include 85% and 99.5% pure alumina. Interface materials to provide a more uniform loading environment and permit more pad rotational freedom are also being investigated: a woven silica fabric and a graphite cloth. Representative loadings are being applied to the pads using a test fixture which incorporates conical platens so that the contact angle between the platens and the pads can be changed. Results of the first series of tests to determine the ability of the pads to withstand mechanical loading conditions representative of those imposed on the pads due to thermal gradients are reported in Ref. (55).

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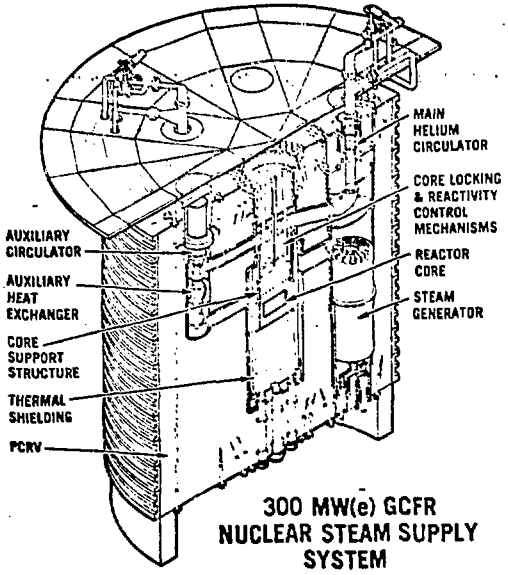

Fig. 1. PCPV for NSSS

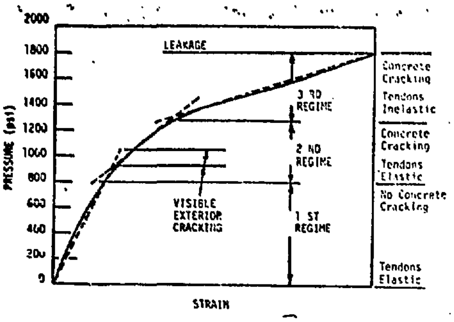

Fig. 2. PCPV Overall Structural Response

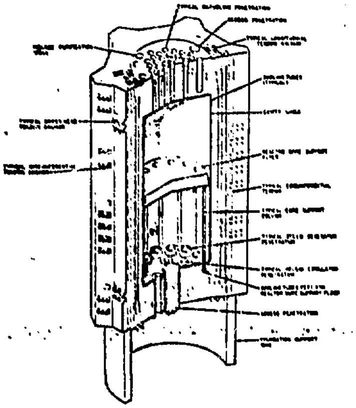

Fig. 3. Fort St. Vrain PCPV General Arrangement

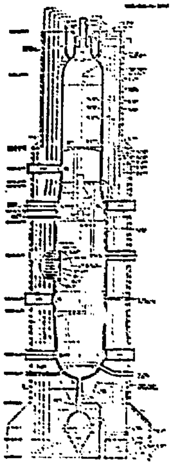

Fig. 4. Hygas Gasifier PCPV Cross Section

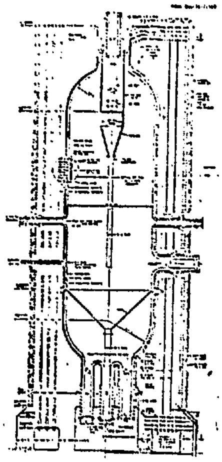

Fig. 5. Gasifier PCPV Cross Section Synthane

Table 1. Prestressed Concrete Reactor Vessels

Station/Reactor	No. PCPVs	Country	Output MW(e)	Normal Op. Pressure, MPa
Marcoule G2, G3	2	France	37	1.47
Chinon (EDF 3)	1	France	480	3.04
Oldbury	2	UK	300	2.41
St. Laurent 1 (EDF 4)	1	France	487	2.60
Wylfa	2	UK	590	2.76
St. Laurent 2	1	France	515	2.76
Vandellos	1	Spain	515	2.76
Bugey 1	1	France	540	4.48
Fort St. Vrain	1	USA	330	4.86
Hinkley Pt. B	2	UK	616	4.24
Hunterston B	2	UK	616	4.24
Dungeness B	2	UK	607	3.38
Hartlepool	2	UK	625	4.14
Heysham 1	2	UK	622	4.14
Heysham 2	2	UK	620	4.38
Turness	2	UK	620	4.38
THTR	1	Germany	300	4.00

Table 2. Comparison factors for three types of pressure vessel construction

	Type of Construction			
Comparison Factors	Single Wall Steel	Prestressed Concrete	Prestressed Cast Iron	Layered Wall Steel (Shrunk fit)
Part of ASME Code	++	+	--	++
Experience	++	++	-	++
Size Constraints (pressure x radius)	+	++	++	++
Penetration Accomodation	++	+	+	++
Field Fabricability	-	++	++	+
Temperature Limit	+	--	-	+
In-service inspection	+	++	++	++
Materials Availability	-	++	?	++
Material Uniformity	-	++	++	++
Manufacturing Capacity	-	++	+	++
Safety	+	++	++	++
Repair	-	+	++	-
Weight	+	--	-	+
Time to Manufacture	-	-	+	+

+ = favorable, ± = very favorable, ? = unknown
- = unfavorable, -- = very unfavorable

DISCLAIMER