REQUIREMENTS FOR THERMAL INSULATION ON PRESTRESSED CONCRETE REACTOR VESSELS

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ABSTRACT

During the past decade, extensive design, construction, and operating experience on concrete pressure vessels for gas-cooled reactor applications has accumulated. Excellent experience has been obtained to date on the structural components (concrete, prestressing systems, liners, penetrations, and closures) and the thermal insulation. Three fundamentally different types of insulation systems have been employed to ensure the satisfactory performance of this component, which is critical to the overall success of the prestressed concrete reactor vessel (PCRV). Although general design criteria have been published, the requirements for design, materials, and construction are not rigorously addressed in any national or international code. With the more onerous design conditions being imposed by advanced reactor systems, much greater attention has been directed to advance the state of the art of insulation systems for PCRVs. This paper addresses some of the more recent developments in this field being performed by General Atomic Company and others.

INTRODUCTION AND BACKGROUND

Thermal insulation is applied to the inner surface of the PCRV liner, and cooling water pipes are attached to the outer surface of the liner for all existing PCRVs except Marcoule. The Marcoule PCRVs are cooled by low-temperature CO_2 without a thermal barrier.

The primary function of the thermal insulation and cooling water system is to hold the PCRV steel liner and concrete at temperatures significantly below the reactor coolant temperature, and control temperature distributions in the PCRV, thereby facilitating a satisfactory structural design from the viewpoints of concrete strength, thermal stress, creep, and prestress relaxation. Typically, the concrete is maintained at an average temperature usually under 65°C (150°F), and the steel liner at a temperature less than about 120°C (250°F).

The majority of the PCRVs are for Magnox or AGR gas reactor systems using carbon dioxide coolant. The Fort St. Vrain and Schmehausen HTGRs use helium as the primary coolant. The primary coolant temperatures range from about 204°C (400°F) for core inlet conditions up to about 760°C (1400°F) for average core outlet conditions in the case of the HTGRs.

Three fundamentally different thermal insulation systems have been employed on PCRVs for existing reactors.

PUMICE CONCRETE

The French reactors EDF 3, St. Laurent 1 and 2, and Vandellos use pumice concrete as thermal insulation. The advantages claimed for pumice concrete are: (1) it is not subject to internal natural convection, provided it is properly grouted to the liner, (2) it has isotropic properties and is easier to adapt to any geometric shape, and (3) it suffers less from partial deterioration due to radiation damage, friction, decompression, or thermal cycling. The pumice concrete is encased to avoid introduction of moisture and dust into the reactor coolant; a flexible, pressure-tight casing was used in EDF 3, and a pressure-balanced casing with filters was used on the other subsequent three reactors. The drawbacks of pumice insulation are its relatively high price, the thickness required [about 50 cm (20 in.) or more], and the complex casings required, especially under high-temperature conditions.

METALLIC REFLECTIVE INSULATION

Metallic reflective insulation is used for Bugey 1 (France), Schmehausen (Germany), and the U.K. reactors at Oldbury, Wylfa, Dungeness B, Hartlepool, and Heysham. The stainless steel foil insulation used in the U.K. PCRVs is made of thin [0.1 mm (4 mil)] foils separated by a two-dimensional wire mesh [about 1.3 mm (50 mils) thick] fixed to the liner by studs with a cover plate on the gas side and with internal, bellows-type seals. The basic philosophy is to trap the primary coolant in cells within the insulation, and hence achieve a thermal conductivity approaching that of the stagnant gas. The design is susceptible to flow bypass through the insulation caused by pressure gradients in the primary circuit. Internal natural convection may also occur if the internal seals are not well fitted. It is also quite difficult to ensure that the insulation conforms to the liner surface. In spite of a great deal of experimental work performed out-of-pile, local problems have arisen in several vessels during startup. The design of the insulation has also been particularly difficult because of the high noise levels (greater than 160 dB) experienced in the CO_2 reactors which induces fatigue failures.

FIBROUS CERAMIC INSULATION

Fibrous ceramic insulation is used at Hunterston B, Hinkley B, and Fort St. Vrain. Fibrous ceramic insulation was chosen because of its low conductivity, ability to conform to the liner surfaces, resistance to permeating hot gas flow, compatibility and stability in high temperature gas, ease of installation, and its relatively low cost compared with the stainless steel alternative. The fibrous ceramic material is either an alumina silica mixture or a relatively pure silica felt. The material is attached to the internal liner surface in thicknesses from 5 cm (2 in.) to 15 cm (6 in.). It is compressed to approximately 70% of its free volume by thick cover plates, which are held against the liner by welded studs. Metallic components are designed to suit the temperature environment. Carbon steel is used up to temperatures of about 425°C (800°F) and Hastelloy X materials for temperatures up to about 800°C (1470°F). In the HTGRs, a special, high-temperature, rigid ceramic insulation is provided directly underneath the core. This insulation is designed for semipermanent hot streaks emanating from the core. A cast-fused silica block is used to cover the standard metallic-fibrous insulation system.

Drawbacks with the fibrous ceramic insulation are (1) ensuring compatibility of materials with the primary circuit, (2) limiting particulate or dust release to the primary circuit, and, most importantly, (3) maintaining resiliency of the insulation pack to conform to the liner surface thereby maintaining permeation resistance for the design life.

General reviews of the design and development of thermal insulation systems are well documented in the literature and are therefore not repeated here [1-7].

Design descriptions and performance assessments are also available for thermal insulation used in specific gas-cooled reactor applications: Oldbury [8], Wylfa [9], Hinkley B [10], and Fort St. Vrain [11, 12].

EXPERIENCE TO DATE

Experience to date has generally been good, although the need to pay attention to detailed design requirements is repeatedly emphasized in the literature. Several instances are noted where lack of adequate data in the formulative development stages or deviation from prescribed requirements have resulted in major design changes at a late date in construction and/or the need to accept local deviations (e.g., hot spots) in the completed PCRV. No major shortcomings in any design have resulted in unacceptable performance. Rather, the contrary is true, with, of course, the qualification that all systems have yet to demonstrate conclusively that design performance can be extrapolated from currently available development and performance data to the full reactor life requirement of 30 to 40 years.

Based on a broad assessment of the AGR experience accumulated to 1975, R. Vaughon [13] noted that the helium environment and the liner insulation should be rated as the highest in order of priority of components or systems requiring attention in the high-temperature reactor.

More recently, a Swedish report [14] providing a 1977 status review of high-temperature reactors identified "the steel liner and hot ducts including insulation on the inside of the prestressed concrete vessel" as having the greatest technical uncertainty.

In response to these concerns, research work and long-term testing is ongoing in several organizations to (1) qualify alternative materials, (2) confirm long-term performance, (3) establish performance under accident conditions, and (4) simplify the design and reduce costs. In addition, there is a continuing demand to develop thermal insulation systems that are capable of handling ever-increasing temperatures for the process heat and direct cycle applications without compromising performance for the reactor life.

A 1975 paper by Furber et al. [15] addressed the development of criteria for the design of insulation for nuclear reactors to that date. The need to extend these requirements and produce clearly defined criteria is increasingly important with the more onerous design conditions being imposed by advanced reactor systems. It is from the reference point of the current state of the art that this paper departs to identify the requirements in relation to HTGRs, and to discuss some of the more recent developments in this field.

CODIFICATION

The thermal insulation is generally considered an integral part of the PCRV. However, unlike the pressure-retaining structure, the liners, the penetrations, and the closures, the thermal barrier has largely escaped codification. At this point in time, although general design criteria have been published in the scientific community, no effort is proceeding nationally or internationally to codify the requirements for design, materials, and construction of this major component. The present status of code development in regard to PCRVs, and to insulation in particular, varies widely in the major countries in which PCRVs have been developed and constructed.

In the U.K., BS 4975, "Specification for Prestressed Concrete Pressure Vessels for Nuclear Reactors," was published in 1973. In preparing this standard, "the view has been taken in the U.K. that the best way of obtaining satisfactory PCPV designs is, firstly, to ensure that the designer is an expert in the field, secondly, to present to the designer the state of the art at the time the Standard was prepared, thirdly, to lay down only those detailed requirements which have been firmly established and, finally, to give to the designer as much guidance as possible and leave him to make and justify whatever judgements may be necessary." [16]. Consequently, the code contains few firm design requirements and much general guidance. Specifically, in regard to insulation, the requirements of Section 7 in BS 4975 are quite general and may be paraphrased as:

1. The degree of redundancy shall be determined by consideration of safety aspects and operational reliability.
2. A specification covering design and testing shall be produced by the supplier and approved by the purchaser.
3. The arrangement of attachment shall preclude consequential gross failure of the insulation in the event of failure of a single attachment.
4. The need to remove insulation for inspection purposes should be considered.

In the U.S., a comprehensive code covering concrete vessels (containments and PCRVs) was issued in 1975 as a companion code to the existing ASME Section III, Division 1, Code on Metal Components for Nuclear Service. The new code is included as Division 2 within the Section III document, and is subject to the same ongoing procedures for review and amendment as the Division 1 document. Comprehensive as this code is, it does not cover thermal insulation systems. "This area was omitted on the basis that it is a system feature. With temperature limits placed on the concrete, liner, tendons, etc., the choice of how to provide the protection required is left to the designer -- insulation, cooling tubes, a combination of both, or some other means. . .The Code does cover the way in which cooling tubes or thermal barrier attachments to the liner may be used when required by the designer to protect his structures from the system enclosed." [17]

Although no formal code as such was issued in France, an official decree was issued in 1970 [18]. This decree does not address insulation.

In Germany, a study report for the development of a standard for reactor pressure vessels made of prestressed concrete was issued in June 1972 [19]. This study group concluded that "the current status of our knowledge and the lack of experience with reinforced concrete reactor pressure vessels caused the commission to conclude that it is not yet ready to submit a proposed DIN standard. Specifically, the design criteria and methods of calculation must still be confirmed by prototypes, and further experience must be accumulated both at home and abroad." Nevertheless, the study report provides extensive guidelines for PCRVs, and identifies the requirements for thermal insulation more comprehensively than any other national document. The German report was also intended as a contribution to the International Standards Organization (ISO). Progress by the ISO in regard to concrete vessels has been slow, although a working group, WG-10, was formed under a U.K. Secretariat in 1977.

A comprehensive assessment of the design and construction of PCRVs was published by the Federation Internationale de la Precontrainte (FIP) in March 1978. This report is not a code. Its objectives are to provide "a resume of background material, a presentation of principles and guidance, and a source of reference material." [20] Although most comprehensive in coverage of PCRVs in general, the section on thermal insulation is limited to a brief description and selected references.

From the foregoing, it is evident that a need exists to establish common, acceptable rules and requirements for the design of insulation systems. Codification would eliminate different criteria being applied among the various nuclear suppliers, and the tendency for individual designs to become projectized. Benefits in terms of safety, ease of licensing, and better assurance of performance would accrue.

GENERAL REQUIREMENTS

The design requirements on the thermal barrier are many and complex. These requirements differ in various locations in the primary circuit and change under various normal and abnormal operating conditions. Of course, these requirements also vary for different gas reactor systems, as will be discussed. Although particular local requirements dictate each specific design, certain general requirements must invariably be considered.

The overriding general requirement, as noted in the introduction, is that the thermal barrier must be designed in conjunction with the liner cooling system to limit the PCRV temperature and temperature gradients to permissible levels. This requirement dictates the effective thermal performance of the insulation system, including the influence of conduction as well as natural and forced convection within the insulation. Experience has shown that the most important and difficult to control heat transfer mechanism is due to bypass or permeation of the primary coolant through or behind the insulation pack. Due consideration must be given to local details such as attachment fixtures penetrating the insulation and/or local discontinuities in the insulation system or cooling system. Such features must be adequately treated in the design to avoid unacceptable local hot spots in the PCRV.

The absolute temperature of the primary coolant dominates the structural design of the thermal barrier and invariably determines the materials of construction. Typically, under normal operating conditions three basic temperatures are defined: bulk core inlet temperature T_1, bulk core outlet temperature T_2, and local core outlet temperature T_2^1. Temperature T_2^1 may be a quite small or relatively large hot streak emanating from a particular core region. Temperature T_2^1 may be of brief duration during a load (power) change or effectively permanent due to fuel loadings or control systems.

Transient and abnormal conditions may also impose a significantly different and controlling temperature environment on the thermal barrier. For example, in the HTGR steam cycle, core auxiliary cooling systems (CACS) are provided to protect the plant in the event of loss of normal main loop cooling. One of the limiting conditions on the design of the CACS is the thermal safety limit on the thermal barrier. By definition, the thermal barrier must remain intact and perform its safety function at the limiting temperature condition of 1090°C (2000°F) for the duration of the accident (about 1 hr) in this example.

Absolute pressure has little effect on the insulation other than affecting the thermal conductivity of the coolant trapped in cells within the insulation pack. More important is the effect of pressure differentials in the primary coolant circuit. These pressure differentials are created by baffles, seals, or reactor internal components. Corresponding pressure gradients between sections of the thermal insulation may induce unacceptable permeation flows through the insulation unless special precautions (usually in the form of internal seals) are employed.

Turbulent flow conditions and noise levels within the primary circuit may impose significant mechanical loads on the insulation assemblies and attachment fixtures. The imposed loadings can be extremely damaging, and must be addressed in the insulation design.

Under abnormal conditions, additional and possibly controlling pressure loadings may exist due to rapid depressurizations of the primary circuit. In addition to the effect of temperature, the materials of construction must be compatible with the primary coolant environment in all other respects. From the reactor system viewpoint, materials that could increase activation levels in the reactor circuit, affect corrosion rates of reactor components, absorb neutrons, or release particulates to the primary coolant are undesirable. From the insulation performance viewpoint, the materials must be compatible with the irradiation levels and the primary coolant chemistry (and impurities contained there), which might induce oxidation, carburization, or instability during the design life of the component.

The design of a thermal barrier is generally such that it cannot be readily removed or replaced during reactor life. Therefore, the thermal barrier must perform satisfactorily for the design life of the reactor, usually 30 to 40 years.

DESIGN CONDITIONS

Before reviewing specific design criteria applied by General Atomic in the thermal insulation designs for HTGR systems, it is appropriate to review the design conditions imposed on this component in current and planned gas-cooled reactor systems. The design temperature conditions in the various HTGR reactor types (steam cycle, gas turbine, and process heat) are generally higher than in earlier Magnox and AGR reactors, as noted in Table 1. Hot streaks may be a further 100° to 200°C (180° to 360°F) higher than the values shown.

The insulation system defined for General Atomic's steam cycle HTGR is the product of Fort St. Vrain experience and many subsequent years of analytical and experimental development work. For this reason, a substantial foundation underlies the current basic thermal barrier design for the steam cycle HTGR, and considerable experience exists to identify the associated controlling design parameters for various locations and grades of thermal barrier.

An appropriate extension or adaption of this basic design is used in the advanced HTGRs. A summary of the major design conditions governing the selection of HTGR thermal insulation systems is given in Table 2 and discussed briefly below.

Steam Cycle HTGR

The basic thermal barrier design consists typically of multiple layers of fibrous ceramic insulation installed on the helium side of the PCRV liners. The insulation blankets are compressed uniformly against the liner by cover plates, seal sheets, and multiple attachment devices (see Fig. 1). The attachment fixtures consist of a center post, which locates an individual cover plate, and outboard attachments, which are designed to accommodate relative thermal movements between the cover plates and the liner. All attachments are designed to minimize heat transfer to the liner. The seal sheets prevent the fibrous insulation from migrating by overlapping the individual cover plates and thereby positively retaining the blankets. This allows the cover plates to be designed with relatively liberal edge clearances to minimize installation problems. The insulation blankets are beveled on all sides and mate with correspondingly shaped blankets to assure that there are no gaps within the assembly. This basic system, with modifications as dictated locally by geometric and environmental conditions within the primary circuit, is used throughout the steam cycle plant.

The low-temperature thermal barrier utilizes the above described design and employs carbon steel for all the metallic components. An alumina-silica blanket of the Kaowool type provides the insulation. This design is well suited, economically and technically, for the core inlet regions or where the normal coolant temperature does not exceed about 370°C (700°F). Design basis emergency and faulted steam cycle temperature transients could expose these regions for short periods of time (a matter of a few hours) to temperatures of about 480° to 590°C (900° to 1100°F). In general, the structural design in terms of the permissible accumulated damage factor tends to be dominated by the accident excursion temperatures. However, local sizing of the thermal barrier may be dictated by the sound pressure spectrum, especially in the vicinity of the main circulator. Irradiation and gas flow conditions are not design-controlling in a general sense.

The high-temperature metallic/fibrous thermal barrier is similar to the low-temperature design, but is distinguished by a different selection of materials. The nickel-base alloy Hastelloy X replaces carbon steel in the cover plates, seal sheets, and attachment fixtures. The blanket assembly is a composite of high- and low-temperature fibrous materials. The cooler portions [less than about 500°C (930°F)] employ the low-temperature type Kaowool, while the hotter portions are composed of high purity silica, alumina, or alumina-silica materials. This class of thermal barrier is suitable for service in areas on the core outlet side of the primary coolant loop where the hot face may be exposed to temperatures up to a mixed mean of about 800°C (1470°F). This design can also accommodate temperature excursions for at least 10 hours at about 980°C (1800°F) without any damage. It is also capable of withstanding shorter excursions (about 1 hour) somewhat in excess of 1090°C (2000°F) without failure.

The primary limitations of this design for the steam cycle HTGR plant conditions are encountered relative to (1) temperature, (2) carburization, (3) irradiation, and (4) primary coolant flow, as follows:

1. The allowable stress for Hastelloy X (as dictated by creep-rupture considerations), and indeed for most high-temperature metallic materials, falls off rapidly in the upper normal temperature regime noted above. This forces a practical temperature limitation not much in excess of 800°C (1470°F). It should also be noted that the available HTGR friction and wear technology (tribology) utilizing chrome carbide rapidly becomes exhausted in this same temperature range. The short-term accident excursions noted above have been found to govern the design to a lesser extent.

2. Carburization is very much a function of temperature as well as partial pressures of coolant impurities. Where, chemically, a carburization environment can exist, it is found that the temperature acts as a catalyst with a rapidly increasing rate of attack for Hastelloy X toward the upper normal condition temperatures. Fracture mechanics considerations of design must be addressed where a degree of carburization of the structural material may have occurred.

3. Irradiation damage of the thermal barrier metallic structures is much less a function of temperature than in the case of carburization. However, irradiation effects must be assessed in relation to the thermal and fast neutron fluences and to the degree of loss of ductility. Loss of ductility is related to the boron content in the metallic structure, and it must be accounted for in the design. A special low boron version of Hastelloy X, denoted Hastelloy XR, could become a preferred choice where the irradiation level may be of sufficient intensity to cause serious concern over loss of ductility.

4. Local primary coolant flow conditions may be such as to dictate the need for modifications to the design while still retaining the same basic concept. Such is the case in the design of the steam cycle hot duct.

The hot duct thermal barrier is distinguished from the conventional high-temperature insulation barrier by the addition of a flow shield. The design is depicted in Fig. 2. The normal flow velocity through the hot duct approximates 60 m/s (200 ft/sec) which is more than twice the maximum velocity encountered elsewhere in the loop. The shield is installed with an inlet fairing at the core cavity end, and it is supported primarily by an omega seal. Thus, in addition to providing a smooth flow passage, the shield protects the thermal barrier from local pressure gradients that could otherwise give rise to forced permeation within the insulation system.

The high-temperature ceramic thermal barrier in the steam cycle plant is designed for the same service environment as the conventional high-temperature thermal barrier in normal operation with respect to mean temperature. However, this design has the capability to withstand higher local temperatures in the range of 815° to 870°C (1500° to 1600°F) for normal conditions, but with capabilities extending to 1100° to 1600°C (2000° to 3000°F) for accident condition local transients. This system is used beneath the core to protect the bottom head of the PCRV, and to transmit the weight of the core to the vessel proper (see Fig. 3).

The nonload-bearing portion of this assembly consists essentially of a double-layered, conventional, metallic-fibrous buildup. The temperature capability of this installation is augmented by placing cast-fused silica blocks on top of the outer fibrous insulation layer.

The load-bearing portion of the installation is built up from a composite assembly of rigid insulating ceramic blocks. The materials considered are silica, alumina, and silica nitride.

The present nonload-bearing portion of the high-temperature ceramic design would probably be design limited by a concern over devitrification. Depending on the chemical composition of the atmosphere, this phenomenon is thought by some to initiate just in excess of about 870°C (1600°F). However, with due consideration given to permeation resistance, this portion of the thermal barrier is not generally considered temperature limiting.

The load-bearing ceramic assembly represents a more controlling condition. The makeup of this assembly has to be carefully assessed and optimized in order to satisfy thermal conductivity, primary and secondary stress, thermal shock resistance, material compatibility, residual stress, and manufacturability aspects to mention the most predominant. This whole complex of issues, together with the realities of nonductile material design, make it necessary to custom design the load-bearing assembly. The tensile strength of the ceramic materials and the manufacturability of sound blocks of these materials have been found to be the most limiting parameters.

Advanced HTGR

The preceding description of the grades of thermal barrier utilized in the steam cycle HTGR forms a substantial technical basis for the design concepts that can be utilized in the direct cycle and process heat application HTGRs. Clearly, however, modifications of the reference design are necessary in order to satisfy different environmental conditions encountered in the advanced systems.

The low- and high-temperature metallic-fibrous thermal barriers will require modification primarily to accommodate the different accoustic and depressurization conditions within their previously defined temperature regimes. It is anticipated that sound pressure levels in the gas turbine plant will be considerably higher than in the steam cycle plant. The design will require substantial stiffening, and there is concern about the integrity of fibrous materials under such extreme acoustic conditions.

Direct cycle depressurization rates in the 3.45×10^6 N/m^2 (500 psi/sec) range are expected. The conventional design concept described for the steam cycle plant cannot accept such rates of depressurization without modification. A vented cover plate/seal sheet design has been devised that includes a venting space behind the cover plate while still providing full containment of the fibrous materials.

Another important consideration intimately tied to the definition of the metallic-fibrous type of thermal barrier is that of material selection. It is desirable to extend the temperature capabilities of the low- and high-temperature grades of this design concept. The introduction of an intermediate grade metallic structure (such as, for example, 2-1/4 Cr - 1 Mo, stainless steel, or Incoloy 800) is readily feasible, but leads, of course, to additional design optimization and qualification. However, it is the temperature extension of the high-temperature design that presents the real problem. At a normal condition operating temperature in excess of about 800°C (1470°F), the viability of wrought superalloys for structural application rapidly becomes exhausted. Vacuum-cast nickel-base alloys are thought to be able to extend the viable temperature range suitable for application in thermal barriers by offering strength and environmental stability (carburization resistance) generally at the expense of ductility and fatigue characteristics. It should be recognized that this alternative would necessitate extensive qualification for the use of such materials. It is not believed, however, that this solution will offer temperature capabilities to satisfy completely the upper range requirements of the advanced HTGRs.

The hot duct thermal barrier and its associated extension to the turbomachine inlet (in the gas turbine plant) has come to be regarded as representing a special case thermal barrier assembly. Irrespective of whether the plant configuration dictates a coaxial or integrated hot duct per se, the design requirements for this assembly greatly exceed those normally considered in thermal barrier design for the steam cycle.

The particular challenges of design relate individually to high temperatures [850° to 1000°C (1560° to 1830°F)], flow velocities [90 to 120 m/s (300 to 400 ft/sec)], and sound pressure levels (160 to 170 dB). The above adverse conditions combine in the vicinity of the hot duct. A replaceable design is under active consideration for obvious reasons.

The extension of the steam cycle design in this region is highly questionable even with an upgrade of the metallic structure selection. Rather, the duct thermal barrier design is predicated on the use of either a ceramic assembly or carbon-reinforced carbon. This latter material can be woven into many shapes and tailored for specific material properties. Both of the above alternatives would also entail the use of fibrous insulation materials underlying the ceramic blocks or the carbon composite material.

The high-temperature ceramic thermal barrier in the region of the core outlet plenum would logically be an extension of the design concept evolving for the steam cycle plant. However, the ceramic designs for the process heat and direct cycle plants will involve a broader range of candidate material (ceramics, carbon-carbon) applied in considerably more challenging design configurations. Ceramic materials will be employed in both load-bearing and nonload-bearing design functions on horizontal and vertical cavity surfaces. The viability of the advanced HTGRs rests in part on the development of adequate thermal insulation designs.

STRUCTURAL DESIGN CRITERIA

General Atomic has been pursuing the development of structural design criteria for metallic and ceramic thermal barrier components since the early design phase of the Fort St. Vrain project. Since that time, a reasonably comprehensive set of structural criteria for the metallic components has been assembled. In the area of rigid ceramic component criteria, on the other hand, the development remains at a relatively elementary stage. This is not unexpected in view of the rather limited application of refractory materials in PCRV insulation design to date.

A brief summary of present structural criteria being employed by General Atomic for metallic and rigid ceramic components is outlined below.

Metallic Thermal Barrier Components

The criteria in this category have been extensively formulated along the lines of the ASME Boiler and Pressure Vessel Code, Section III, Divisions 1 and 2[*], and Code Case 1592. After careful evaluation of these criteria, and in the absence of other high-temperature criteria, relevant portions of this important Code have been adopted. While the Code is, strictly speaking, intended for pressure vessel design, its application would certainly seem to accommodate adequate conservatism of design when utilized in relation to the PCRV thermal barrier.

The following excerpts of the presently applied criteria have, for brevity, been referenced to the pertinent subsections of the Code and Code Case 1592. However, the thermal barrier metallic criteria are evolving as an independent entity without reference to the Code itself.

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[*] Hereinafter referred to as the Code.

The low-temperature criteria (time-independent stress/strain conditions) have been derived mainly from Sections NG-3228, NG-3223, and NG-3224 of the Code, where the allowable design stress intensity value S_m is defined as the lower of (1) one-third of the minimum ultimate strength, or (2) two-thirds of the minimum yield strength for ferritic steels and nine-tenths of the minimum yield strength for austenitic steels and nickel-base alloys.

For normal and upset operating conditions, the following criteria shall be satisfied:

$$P_m \le 1.0\ S_m,$$

$$P_m + P_b \le 1.5\ S_m,$$

$$P_m + P_b = Q \le 3.0\ S_m,$$

where P_m = membrane stress,
P_b = bending stress,
Q = secondary (thermal) stress.

Special sections have been included in the structural criteria to account for:

1. Failure of an attachment fixture.
2. Threaded fasteners (based on Section NG-3230).
3. Welded joints (based on Section NG-3352).

The high-temperature criteria (time-dependent stress/strain conditions) have been derived from Code Case 1592, including Appendix T as well as Sections NG-3223 and NG-3224 of the Code. The basic time- and temperature-dependent allowable stress intensity S_t is defined as the lower of (1) two-thirds of the minimum stress to cause rupture in time t, (2) eight-tenths of the minimum stress to cause the onset of tertiary creep in time t, or (3) minimum stress to produce 1% total strain in time t.

Again, special sections have been developed to account for:

1. Failure of an attachment fixture.
2. Threaded fasteners (based on Code Case 1592, Section 3233).
3. Welded joints (based on Section T-1713).

The above discussion of the structural criteria for metallic thermal barrier components covers the subject in a cursory fashion only. It would be beyond the intended scope of this paper to go into greater detail.

Rigid Ceramic Thermal Barrier Components

The nonductile behavior of rigid ceramics makes these materials highly unforgiving. Ceramic materials are unable to relieve local stress concentrations by plastic flow, and they will consequently fracture due to overloading. The strength data for such materials will exhibit a wide scatter, and the variability in strengths must be handled statistically such as by the Weibull approach [21].

The Weibull statistical theory associates the strength of the material with a probability of survival that depends on the internal stress distributions within the ceramic element and its associated material volume. This theory is particularly useful in ceramic design because it accommodates the statistical strength data directly into the structural design equations. The Weibull model replaces the traditional safety factor or load factor approach commonly used in design as exemplified by the metallic design criteria previously discussed.

Without intending to explain the Weibull theory here, a few basic steps of this method will be illustrated.

The probability of survival S of an assembly of n individual ceramic components, each with an associated survival probability S_i, is as follows:

$$S = \prod_{i=1}^{n} S_i \quad ,$$

Based on the Weibull theory,

$$S_i = \exp\left\{-\sum_{j=1}^{N}\left(\frac{\sigma_j}{\sigma_o}\right)^m V_j\right\} \quad ,$$

where N = number of volumes associated with a tensile stress (the critical strength characteristic in ceramic design),

σ_j = average tensile stress associated with a volume of material V_j,

V_j = volume over which σ_j acts,

m = Weibull modulus for a given material (an expression of scatter in tensile strength data),

σ_o = normalized stress parameter expressing material strength distribution.

Both σ_o and m are derived from experimental strength data based on the Weibull theory.

The tensile strength of the rigid ceramic material being the limiting design characteristic, this property is normally measured in a modulus of rupture test. Based on such testing, and subsequently applying the Weibull theory to the probability of survival of representative load-bearing ceramic components, General Atomic has found the Weibull statistical theory to provide a very promising basis for establishing structural design criteria for such materials.

DEVELOPMENT PROGRAMS

The development basis for General Atomic's PCRV thermal barrier designs using compressed ceramic fiber insulation in conjunction with metallic structural components, and ceramic block insulation, rests largely on the Fort St. Vrain HTGR design. The present design concepts, however, incorporate improvements based on upgraded material optimization, design simplifications (without sacrificing conservatism), and enhanced redundancy, but substantially utilizing the same general concept. These advances are the result of continuing development efforts in which General Atomic has been engaged since the qualification of the Fort St. Vrain thermal insulation.

The extensive experimental program conducted in support of the Fort St. Vrain thermal barrier has been documented elsewhere [5, 11]. Some of the more important development programs conducted since that time will be summarized here. The tasks range from basic materials investigations to performance demonstrations on full-scale models.

Recent empirical efforts have been directed primarily towards the qualification of the thermal insulation proposed in the second generation steam cycle HTGR. However, these programs also have a considerable degree of applicability to the advanced HTGR concept requirements.

MATERIAL DEVELOPMENTS

The changes in quality and grades of commercially available ceramic fiber blankets make it necessary to continually evaluate and upgrade the selected reference materials. High-purity aluminum and silica fiber blankets have been qualified for high-temperature steam cycle service, while the alumina-silica blankets are favored at lower temperatures [less than about 500°C (930°F)]. These materials are being evaluated most extensively for their resiliency characteristics, primarily as a function of time up to 20,000 hours and temperature up to 980°C (1800°F), but also relative to thermal cycling and vibration. These materials are also frequently tested for permeability, conductivity, and chemical compatibility with the HTGR environment.

Recent years have seen a considerable emphasis on the characterization of rigid ceramic materials. These investigations are logical in view of the design dependency on silica, alumina, and silica nitride materials in the steam cycle core support insulator design, as well as for the potential increased utilization of these materials in direct cycle and process heat applications. Various grades of rigid ceramics from several U.S. suppliers are being evaluated in relation to all relevant mechanical and physical properties. These materials are being assessed for application in a temperature range that completely envelopes steam cycle and advanced HTGR requirements.

As previously mentioned, the steam cycle thermal barrier employs only two different metallic materials: carbon steel and Hastelloy X. The existing data bases for these two materials are extensive indeed, although Hastelloy X is not a coded material. It is beyond the scope of this paper to iterate General Atomic's material investigations in relation to these conditions. It is relevant, however, to note two general areas of current investigations of these materials for their proposed usage in future HTGRs: (1) mechanical properties in relation to specific exposure conditions and (2) tribology. The former category encompasses studies to determine the creep characteristics of carbon steel up to about 600°C (1100°F), thermal neutron irradiation effects on Hastelloy X, carburization of Hastelloy X as a function of temperature and environment, and Hastelloy X creep-fatigue interaction. The tribology issue addresses the application and friction/wear characteristics of nitralloy inserts and chrome carbide coatings on carbon steel and Hastelloy X, respectively. This work is necessary in order to satisfy the sliding interface requirements of the cover plates at the peripheral attachment fixtures of the metallic-fibrous thermal barrier design concept.

The incentive to extend the temperature capabilities of the thermal insulation has led to further studies of alternative wrought nickel-base alloys, as well as the initiation of studies of cast superalloys and carbon-carbon materials.

PERFORMANCE DEVELOPMENTS

As noted previously, the metallic-fibrous insulation concept relies on the ability of the design to accommodate cover plate sliding expansion and contraction with changing coolant temperatures. The performance aspects, including static and dynamic friction and resulting loading on full-scale attachment fixtures and assemblies, are presently being studied in a low-pressure, high-temperature [815°C(1500°F)] helium autoclave. Test results to date show no adverse performance up to 400°C (750°F).

The metallic-fibrous insulation system relies on the permeation resistance of a single-layer cover plate/seal sheet arrangement, unlike the Fort St. Vrain design, which employed a two-layered buildup [11]. This design simplification resulted from tests on a full-scale thermal barrier assembly.

The hot duct insulation represents a special case thermal barrier in a region where the core exit gas is at a high velocity [60 m/s (200 ft/sec)] (see Fig. 2). A 0.6-scale thermal performance test of the proposed hot duct design was tested in cooperation with the Commissariat a l'Énergie Atomique (CEA) utilizing the Chela loop at Saclay, France. The test assembly was exposed to flowing helium at a pressure of 5.07 MN/m^2 (50 atm) and cycled in the temperature range of 100°C (212°F) to 760°C (1400°F). The measured thermal performance compared extremely well with analytical predictions.

Preliminary structural performance of representative full size ceramic load bearing pads have been assessed recently (see Fig. 3). These pads represent the largest ceramic components of their type manufactured by five major U.S. suppliers engaged in General Atomic's ceramic program. Eight different types of pads (either by geometry or material) were subjected to nondestructive evaluation. These pads were subsequently loaded mechanically and thermally. Detailed analytical correlations with test results and close cooperation with the manufacturers have yielded valuable insight into this challenging field of design. Manufacturability, residual stresses, and tensile strengths of ceramics are inseparable considerations from the design requirements in any successful application of these materials.

PROTOTYPE DEVELOPMENTS

A full-scale hot duct assembly is currently under construction. This program, also performed in conjunction with CEA, will utilize the Carmen loop facilities at Saclay. The manufacture of fully representative thermal barrier hardware, including Hastelloy X flow shield, omega seal, and inlet fairing (see Fig. 2), is nearing completion. The objective of the upcoming test is to demonstrate structural and thermal performance adequacy at and beyond the requirements of steam cycle reactor operating conditions. Initially, the test assembly will be heated to 815°C (1500°F); subsequently, it will be cycled between this condition and a simulated shutdown condition until thermal stability and reactor design life shutdown cycles have been accumulated. In the final stage, the duct will be exposed to 925°C (1700°F) with some cycling between this temperature and 815°C (1500°F). Following elevated temperature testing, vibration studies of the free-standing flow shield structure will be performed.

Verification of the structural design adequacy of the low- and high-temperature metallic-fibrous thermal barrier designs for their postulated temperature exposures in the steam cycle plant are in progress. Long-term exposures (20,000 hours) of full size assemblies in purified helium autoclaves under normal operating conditions are underway at CEA. Accident condition exposures have already been completed. A low-temperature (carbon steel) assembly was exposed to 540°C (1000°F) for 10 hours, 665°C (1230°F) for 1 hour, and 760°C (1400°F) for 1 hour. A high-temperature (Hastelloy X) assembly was exposed to 980°C (1800°F) for 10 hours, 1090°C (2000°F) for 1 hour, and 1260°C (2300°F) for 1 hour. The first two temperature and duration increments in each test are representative of conservatively postulated emergency and faulted conditions. The last increment in the two tests is representative of an ultimate (beyond accident) exposure condition. Both test assemblies satisfied all requirements for the design conditions and, in fact, survived the complete range of exposures without any structural failure.

CONCLUSIONS

As noted in this paper, a considerable body of data exists on the design, development, and performance of thermal insulation systems for existing gas reactors.

Despite the commercial setbacks (circa 1975) in introducing the family of HTGRs in the U.S. and Europe, further development has continued to advance the state of the art and thereby ensure an adequate technical basis for this critical component. A major element in this ongoing research and development program has been the highly successful cooperative program between General Atomic and CEA initiated in 1972. Another more recent development is the four-party (U.S., Germany, France, and Switzerland) government level Umbrella Agreement to participate in cooperative gas-cooled reactor development programs. In the area of criteria, General Atomic has recently taken the initiative to propose joint development of thermal barrier structural criteria for HTGRs under the Umbrella Agreement. Emphasis is placed on the obvious benefits of being able to share more extensively in joint design and development programs in the near term, and subsequent practical experience in the long range. Continued research, development, prototype testing, and shared experience on operating reactors are needed to strengthen the technological basis of insulation systems, and thereby contribute toward the successful future deployment of advanced gas-cooled reactors.

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TABLE 1
HTGR PLANT BULK CORE INLET (T_1)
AND OUTLET (T_2) TEMPERATURES

Plant	T_1, °C (°F)	T_2, °C (°F)
Magnox	204 (400)	415 (780)
AGR	285 (545)	640-675 (1180-1250)
HTGR		
Steam cycle	318 (605)	685-760 (1266-1400)
Gas turbine	454 (850)	850 (1562)
Process heat	475 (887)	950 (1742)

TABLE 2

MAJOR DESIGN CONDITIONS GOVERNING THE SELECTION OF HTGR THERMAL BARRIERS

Type of Thermal Barrier	Design Temperature/Design Life Normal/300,000 h °C (°F)	 Accident/Accum. Time (h) °C (°F)/h	Additional Major Considerations
Low-temperature fibrous-metallic (carbon steel)	370 (700)	480 (900)/10 590 (1100)/1	Acoustic loading for all plants. Depressurization for direct cycle plant.
Intermediate temperature fibrous-metallic (2-1/4 Cr - 1 Mo, stainless steel, Incoloy 800)[a]	370 (700) to 760 (1400)	480 (900) to 870 (1600)/10 590 (1100) to 980 (1800)/1	Acoustic loading, carburization, and irradiation damage for all plants. Depressurization for direct cycle plant. Flow-induced loading for hot ducts for all plants.
High-temperature fibrous-metallic			
• Hastelloy X	700 (1300) to 800 (1470)	870 (1600) to 980 (1800)/10	
• Vacuum cast nickel base alloys	700 (1300) to 870 (1600)	980 (1800) to 1090 (2000)/1	
High-temperature ceramic (optimized assembly using silica, alumina, silica nitride, carbon-carbon)	815 (1500) to 980 (1800)	980 (1800) to 1370 (2500)/10 1090 (2000) to 1650 (3000)/1	Thermal transients and flow permeation for all plants. Depressurization for direct cycle. plant.

[a] Selection of material depends on specific range of thermal barrier design temperatures.

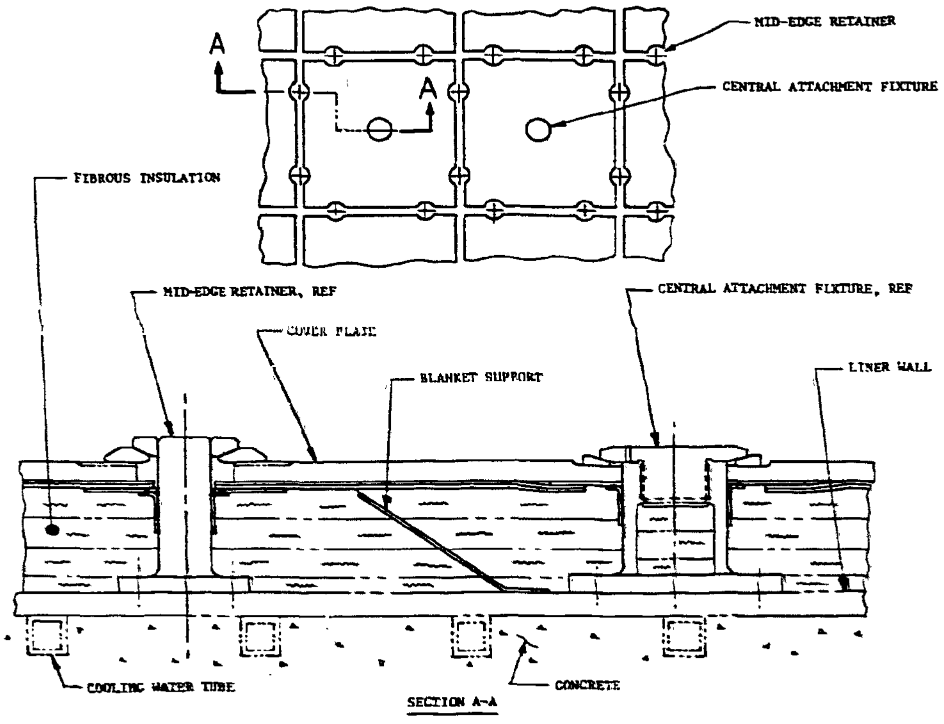

Fig. 1. Typical thermal barrier arrangement

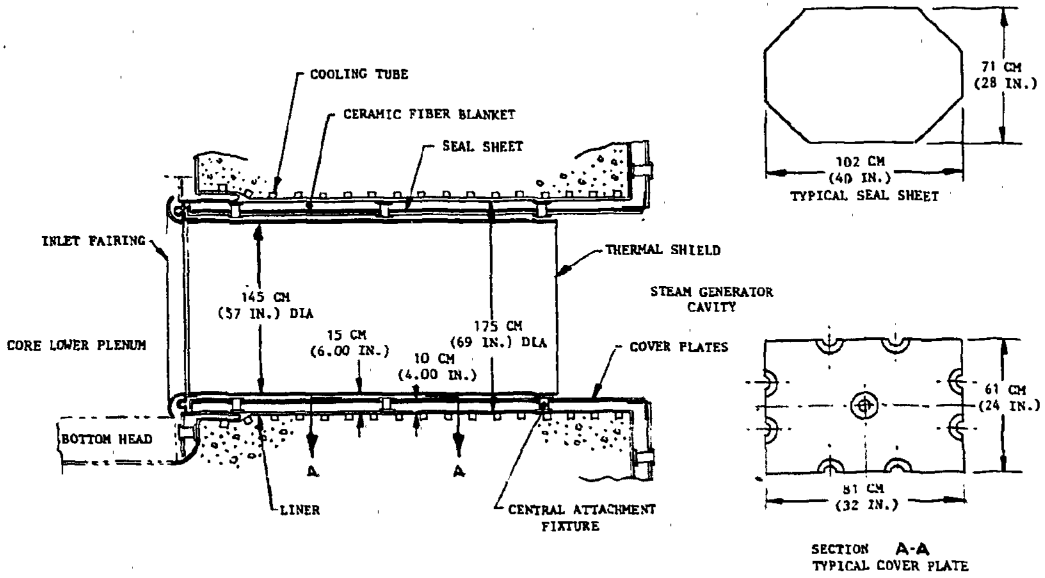

Fig. 2. Lower main cross duct

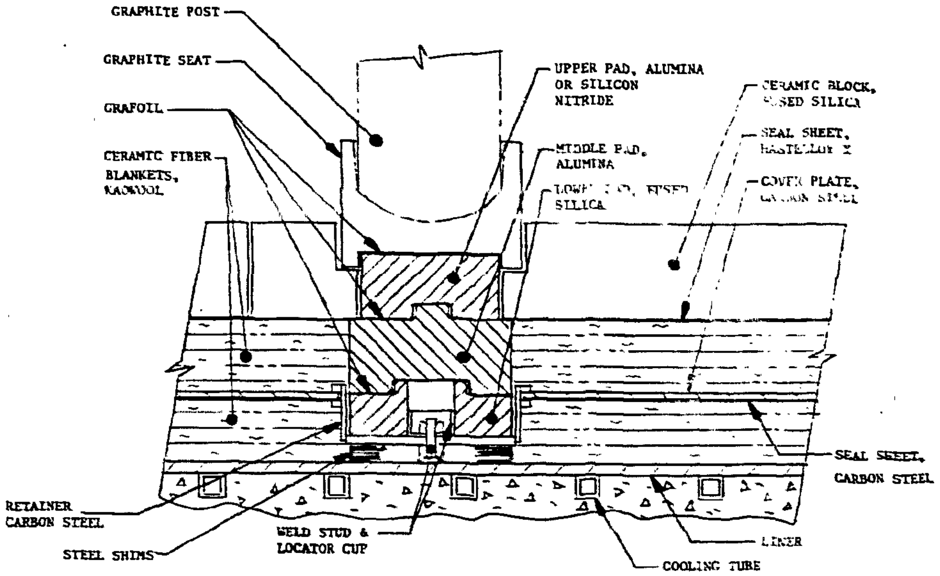

Fig. 3. Elevation view of bottom head