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PRELIMINARY DESIGN OF THE CIT CRYOSTAT*

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ABSTRACT

For the Compact Ignition Tokamak (CIT) to achieve the performance goals set forth, the toroidal field (TF) and poloidal field (PF) coil systems must operate in a cryogenic temperature regime. The cryostat has been designed to provide and maintain this environment. The preliminary design activity is addressing the design issues and interfaces necessary to provide a cryogenic vessel that will (1) maintain a maximum temperature differential of 8°C between the outer vessel wall and the ambient test cell conditions; (2) operate in a pressure range of +5 psig to −2 psig; (3) accommodate numerous penetrations, including cooling, diagnostic, and gravity support items; and (4) maintain a maximum leak rate of gaseous nitrogen at 1 l/s at 1 atm.

Conceptually, the cryostat consists of thermal insulation sandwiched between an inner primary stainless steel pressure vessel and a thin outer stainless steel wall. Design activities have concentrated on determining the size and shape of the primary vessel wall and selecting the best candidate thermal insulation materials for future irradiation testing. The following shapes of the upper and lower cryostat structure were analyzed: (1) a standard ASME torispherical domed top and bottom; (2) a nonstandard domed top and bottom; and (3) a 2° sloped conical top and bottom contour.

Screening of candidate insulation materials was based on (1) lowest thermal conductivity over the range of temperatures anticipated in the CIT environment; (2) low material cost and apparent ease of assembly; and (3) survivability of material in the CIT irradiation environment.

This paper presents the configuration development of the cryostat used to maintain the cryogenic temperature environment for CIT.

INTRODUCTION

As the CIT device matured, the system requirements of the cryostat were modified to support a change in how the tokamak device was to be cooled. Instead of merely providing for thermal insulation of the cryogenically cooled internal machine, the cryostat system now must also provide the vessel for collecting the liquid nitrogen that has not changed phases during the cooldown cycle.

With the advent of the new requirements, a trade study to optimize the design for shaping the pressure vessel was conducted. Three cryostat configurations were evaluated during this study. Standardized assumptions were placed upon each concept to evaluate the results equally. The general constituents are: configuration 1, torispherical domed bottom and top with a cylindrical midsection; configuration 2, torispherical domed top with a cylindrical midsection and a 2° sloped conical bottom; and configuration 3, a 2° sloped conical top and bottom with a cylindrical midsection; stiffeners, running from top to bottom radially every 18°, were included.

The initial modeling was conducted to compare the concept of a domed top and bottom (see right-hand side of Fig. 1) with that of a conical bottom and domed top. Wall thicknesses for each component were held constant at an arbitrary thickness of 0.5 in. The maximum principal stress in configuration 1 was ≈6800 psi, occurring where the top and bottom domed sections blended into the cylindrical midsection. The maximum stress in configuration 2 was ≈86,000 psi, occurring, as before, where the bottom conical section blended into the cylindrical midsection. Since this stress level was about eight times as high as that allowed by the original analysis criteria, external stiffeners were added to distribute the load better in the transition region.

With the stiffeners, stresses were reduced to ≈13,000 psi and were localized in the outer surface of the stiffener. Overall stress levels in the primary structure of the vessel were somewhat lower than those

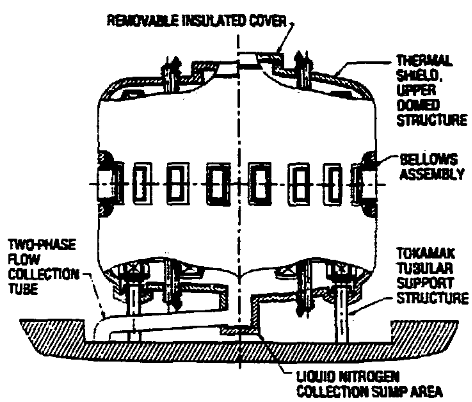

Fig. 1. Thermal shield concept. Left side, conical top and bottom shape. Right side, torispherical top and bottom shape.

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of configuration 1. The stiffeners also reduced vertical displacements of the structure. For a given wall thickness and pressure, configuration 2 was comparable to configuration 1 when stiffeners were incorporated. An estimated added cost of $175,000 is associated with configuration 2 by adding 20 stiffeners radially around the vessel. Configuration 3 was analysed and compared with configuration 2 as a means of reducing the overall height of the vessel. The left-hand side of Fig. 1 depicts this configuration and its impact on the height of the cryostat. Stress levels in the cylindrical midsection and the lower conical section were nearly identical. The major problem occurred in the upper structure, where the stiffeners were attached to the center flange. Here, stress levels approached nearly 47,000 psi. As in earlier analysis, if the center flange of the upper dome was restrained from moving vertically, stresses of ≈13,500 psi were obtained in the midsection of the upper stiffeners. If this can be accomplished by attaching the flange to the TF coil structure without inducing additional load due to thermal contraction, this concept will be comparable to configuration 2. The only additional cost for configuration 3 would be associated with the thicker upper shell structure. By comparison of the appropriate runs, it appeared that the upper structure must be 0.125 in. thicker. Therefore, configuration 3 costs approximately $70,000 more than configuration 2.

The torispherically dome-shaped contour is now established as the baseline configuration. Configurations 2 and 3 represent less desirable alternatives owing to their additional cost and the interference of the stiffeners with the insulation.

PENETRATION INTERFACES

Significantly influencing the cryostat are the interface issues associated with penetrations of the vacuum vessel and the gravity support structure of the CIT device. Figure 2 illustrates the approach developed for the cryostat design.

Vacuum vessel interfaces are concentrated in two major categories: (1) the vertical viewing ports located along the top and bottom of the CIT device and (2) the midplane horizontal ports located radially around the device. To maintain the cryogenic environment and to allow for differences in thermal expansion or contraction, bellows were used to isolate the cryostat structure from all penetrations. The vertical viewing ports are welded to a permanent flange on the cryostat. Bellows are incorporated in the tube assembly to provide for thermal growth problems.

Reinforced, circular flanged areas were incorporated in the cryostat design, at the gravity support structure interface, to provide room for the bellows assembly. These flanged areas also support the weight of the cryostat, isolating the cryostat from the primary structure of the CIT device. Since liquid nitrogen will be collected in these flanges during the cooldown phase, this liquid will be siphoned off (prior to a pulse).

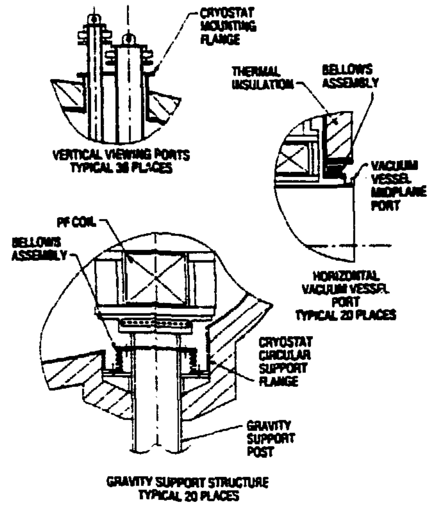

Fig. 2. Penetration interfaces.

INSULATION MATERIAL EVALUATION

Figure 3 depicts a typical cross section of the cryostat, showing the sandwich construction. A literature survey was undertaken to find an acceptable material for thermal insulation. Materials normally used in a cryogenic environment were selected and screened with respect to the previously mentioned criteria. In most of the documents surveyed, radiation damage was measured on the basis of reduction in the mechanical properties of the candidate material. Since the baseline concept for the thermal insulation material does not require significant mechanical strength, the limits of irradiation imposed on these materials may not be warranted for the CIT design. Thermal conductivity, embrittlement, and water absorption are more important than mechanical strength. Most of these these materials will require some type of reflective material to reduce heat transfer due to thermal radiation and a gaseous nitrogen purge to prevent condensation of air between the two shells.

Insulation materials that can be used for this cryogenic application include expanded foams, gas-filled powders, fibrous felts, vacuum alone, evacuated powders and fibrous felts, and multilayer insulations. Owing to the unique design configuration and interface

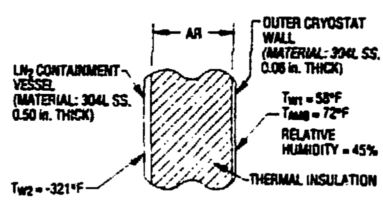

Fig. 3. Typical composite construction of cryostat vessel.

problems, more than one type of insulation may be required to satisfy the requirements. A preliminary list of candidate materials was generated on the basis of thermal conductivity and use in other areas of CIT. Absorbed dose levels predicted for each material are given in Table I.

Table I. Peak radiation dose of candidate material

Material[a]	Neutron dose (Gy)	Gamma dose (Gy)	Total dose (Gy)
Q-fiber felt	2.0×10^7	7.3×10^6	2.7×10^7
Perlite	2.0×10^7	7.1×10^6	2.7×10^7
Cryo-Lite	6.5×10^7	8.0×10^6	7.3×10^7
Polystyrene foam	8.5×10^7	8.3×10^6	9.3×10^7

[a] Radiation doses for polyurethane and polyimide foams are being evaluated.

Additional materials have been reviewed, but dose levels have not been analyzed. This survey presents the characteristics of the following materials as applied in the CIT: perlite, expanded polystyrene foam, polyurethane foam, Q-fiber felt, Cryo-Lite, and polyimide foam. Thermal conductivity values and the chemical compositions of these materials (if known) are given in Table II.

Table II. Chemical composition and thermal conductivity of candidate insulation materials

Material	Chemical composition	Thermal conductivity [Btu/(h·ft·°F)]
Perlite	SiO_2, 75%; Al_2O_3, 17%; Fe_2O_3, 0.04%; MgO, 0.14%; CaO, 0.22%; Na_2O, 2.81%; K_2O, 3.06%	0.015
Cryo-Lite	SiO_2, 58%; B_2O, 11.3%; Na_2O, 10.1%; Al_2O_3, 5.8%; BaO, 5.2%; ZnO, 4.0%; F_2, K_2O, CaO, MgO, and Fe_2O_3, 5.7%; binder, 11.0%	0.019
Q-fiber felt	SiO_2, 98.5%; B, 0.01%; Fe, 0.06%; Al_2O_3, 0.5%; CaO, 0.35%; MgO, 0.35%; Na_2O, 0.15%	Unknown at cryogenic temperatures
Polystyrene foam		0.019
Polyurethane foam		0.019
Polymide foam		0.024

Expanded Polystyrene

Polystyrene foam (also called styrofoam) is commonly used in cryogenic applications, and bulk polystyrene has excellent resistance to radiation damage compared with other organic insulators. The thermal conductivity of this material is comparable to that of the other candidates (see Table II). Expanded polystyrene is fabricated by expanding pure polystyrene pellets into large beads by various blowing agents. It is readily obtainable commercially and has very low initial material cost.

Three major problems in using polystyrene foam in the CIT cryostat environment are: (1) Its coefficient of thermal expansion is much higher than that of stainless steel. Over temperatures ranging from 300 to 77 K, this foam has a value of 4.0×10^{-5} in./°F compared with 0.64×10^{-5} in./°F for stainless steel. If fitted closely around the liquid nitrogen vessel, this foam might crack during cooldown and seriously degrade the insulation performance. (2) The high end of the service temperature for foam is ≈80°C. Areas around the various viewing ports and vacuum ports could exceed 80°C and thus require some other insulation. (3) Experimental data [1] show that expanded polystyrene foam seriously degrades when subjected to an irradiation environment. In the unexpanded format, polystyrene exhibits high resistance to irradiation damage [2], based on the cross-linking of the polymer chain. The unexpected response in the expanded foam was explained as follows: the blowing agents used to expand the foam degrade and attack the polymer when it is irradiated at or near room temperature. As stated before, irradiation of this foam causes a cross-linking effect which, at some levels, produces higher strength but reduced elongation. This may cause embrittlement of the outer surfaces of the foam and cracking. Therefore, this product is not recommended for applications involving irradiation over 10^8 rads of absorbed dosage [3].

Polyurethane Foam

Polyurethane foam possesses the same basic advantages of polystyrene foam, but it has a higher service temperature than polystyrene. Its thermal conductivity is comparable to that of the other screened materials. The high-end service temperature for continuous use is approximately 120°C. Material cost is similar to that of polystyrene and is on the low end of the materials evaluated.

The disadvantages of polyurethane foam are similar to those of polystyrene foam in the areas of thermal contraction and severity of damage due to irradiation. Again, its coefficient of thermal expansion is much higher than that of stainless steel. Bulk polyurethane has good resistance to irradiation damage but is similar to polystyrene when a blowing agent is used to produce the foam format. A blowing agent remains trapped in the closed cell structure. Under irradiation at or near room temperature, the foam degrades significantly in mechanical strength [3]. As a result of these data, polyurethane foam is not recommended for an absorbed dose above 10^6 rads.

Perlite

Perlite is commonly used as cryogenic insulation for storage tanks and nuclear facility hardware. Inorganic compounds, in general, do not degrade significantly when subjected to the dose shown in Table I. Its thermal conductivity in a gas-filled environment is similar to that of the other evaluated materials. Other beneficial characteristics of perlite are that it is low in density, very low in raw material cost, readily available as a commercial product, nonflammable, and nontoxic. It is easy to install, flows readily when new, and is easily conveyed pneumatically.

Some disadvantages of perlite are derived from the very nature of the format. Since perlite is a very fine powder, personnel must guard against inhaling it during installation. Also, if maintenance of the vessel or outer shell is required, all insulation must be removed from the space. This may require partitioning of various areas in the cryostat. Owing to the size and shape characteristics, extreme care must be taken during installation to ensure that the insulation cavity is completely filled. Since the inner vessel will contract during cooldown, some means of maintaining the dimensional aspects (i.e., required thickness) of the perlite is required, or the insulation will settle and provide voids.

Cryo-Lite

Cryo-Lite, a new product being developed and marketed by the Manville Corporation, is predominantly silica oxide. However, it contains some resin or binders (melamine-formaldehyde and urea-formaldehyde) that break down at lower irradiation dose levels than pure silica oxide compounds do. The material is being developed for cryogenic temperature use in storage vessels and transport tankers.

Cryo-Lite is produced in a fibrous felt (bat) that provides a dimensionally stable format. Tests to determine thermal conductivity at various pressures and temperatures are being conducted. Results from these tests have not been formally published by Manville. Cryo-Lite is moderately cheap and, being a fiber bat product, should be relatively inexpensive to install. Settling and thermal expansion should not be an inherent problem. The material is not hygroscopic, and it contains certain binders to deter flammability.

Since Cryo-Lite is mostly silica oxide, presumably it could survive the CIT environment. But with the presence of relatively high levels of binders and boron, the degree of damage is unknown and would best be evaluated by radiation testing.

Q-Fiber Felt

Q-fiber felt, chosen for evaluation because of its intended use as insulation material around the vacuum vessel in CIT, is also developed and manufactured by Manville. It is produced by water deposition of fine, 98.5+% pure silica fiber.

As a result of the water deposition process, the material is clean, flexible, and free of binders of any kind. Having the thermophysical and chemical stability of pure silica, Q-fiber felt is strong enough for this application and is unaffected by moisture. This material will not accelerate or cause corrosion, and the chemical composition makes it incombustible. Because of its similarity to alumina in irradiation damage resistance, no testing in an irradiation environment was required. Temperature limitations are nonexistent; Q-fiber fiber felt has been used in many applications up to and above 1800°F.

Thermal conductivity values in the cryogenic range are not available from Manville. Raw material costs are about 20–30 times that of Cryo-Lite. Also, compared with the thermoplastics and bat materials, Q-fiber felt is easily compressed and does not return to its original thickness after the load is removed. Therefore, installation of this felt would require significant care to maintain the required thickness for thermal conductivity.

Polyimide Foam

Polyimide foam has higher irradiation resistance than other organic insulation materials. The product evaluated was developed by IMI Tech. and fabricated by Stevenson and Lawyer Corp. Its formulation is now proprietary, but some information was obtained from literature and from telephone communication with IMI Tech. Although the aromatic polyimides fall in the class of thermoplastics, their high glass transition temperatures, insolubility, and intractable nature preclude the use of blowing agents in their cured state. The chief advantage of polyimide foams over other conventional foams are their thermal stability (relatively zero coefficient of thermal expansion), nonflammability, high glass transition temperatures, and higher resistance to irradiation damage. Actual experimental data in support of the last advantage have not been obtained for this material in the foam composition.

During the curing cycle of the polyimide foam at approximately 550°F, the volatile agents are cured out of the foam. The foam that is produced has an open cell structure. Therefore, air and water vapor could be absorbed into the foam, causing a problem in the cryostat during cooldown. Raw material cost is about 10 times that of Cryo-Lite.

CONCLUSIONS OF INSULATION STUDY

On the basis of data obtained thus far, most organic materials (polymers normally used for thermal insulation application) may not survive the irradiation levels estimated for the cryostat location. However, these conclusions are founded solely on mechanical strength properties, which may not be significant in this application. Materials normally used as insulators in magnet design are less appropriate for thermal insulation because they exhibit much higher densities and thermal conductivity values. Since the materials selected for evaluation do not possess the mechanical properties required for magnet design application, few experimental data have been published on irradiation effects at cryogenic temperatures.

Table III presents the relative cost of the required amount of a given insulation for the cryostat. Special precautions and additional hardware may be required for a given insulation material. These special features have been identified but not developed. Their actual cost and installation may dramatically change the overall cost of the thermal shield system.

Table III. Relative cost of candidate materials, not including installation cost (thickness required, 9 in.)

Material	Cost per unit	Quantity required	Total cost
Perlite	\$1.12/ft^3	3375 ft^3	\$3,780
Polystyrene foam	\$0.90/lb	8500 lb	\$7,650
Polyurethane foam	\$0.50/ft^2 (1 in. thick)	40,500 ft^2	20,250
Cryo-Lite	\$0.66/ft^2 (1 in. thick)	40,500 ft^2	\$26,700
Polyimide foam	\$7.00/ft^2 (1 in. thick)	40,500 ft^2	\$283,500
Q-fiber felt	\$13.20/ft^2 (1 in. thick)	40,500 ft^2	\$534,600

Since inorganic materials tend to be more radiation resistant than the organic materials evaluated thus far, Oak Ridge National Laboratory (ORNL) will propose Cryo-Lite as the baseline insulation. ORNL will also test an organic material, such as polyurethane foam.

SUMMARY

The preliminary design of the CIT cryostat is in progress at ORNL. A sandwich structure is envisioned with thermal insulation between stainless steel walls. Studies have been conducted to identify radiation-resistant insulation materials and to determine the structural shape requirements.

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