Application of High-Performance Aerogel Insulating Materials (Analysis & Test Results)

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I. Introduction

The NCSX stellarator core design is built around a 3-period, highly shaped plasma with an assembly of four magnet systems, the TF coils (TF), the Modular Coils (MC), the PF Coils (PF), and the Trim Coils, that surrounds an all welded Vacuum Vessel (VV). The VV features approximately 100 ports for heating, pumping, diagnostics, and maintenance access. The entire system is surrounded by a cryostat to permit operation of the coils at liquid nitrogen temperature. The VV and coils are assembled in 120° segments. The VV segments must be placed inside the MC by sliding the coils over each end of the vessel subassembly. Installation of the port extensions is done after this operation. They are slipped through access holes in the MC onto port stubs and welded on from inside. **Figures 1 & 2** illustrate the assembly of the MC over a VV section and installation of TF and port extensions to complete a sector of the VV.

Figure 1. MC being slipped over VV

II. Overview

The VV is designed to be baked to 350°C and operate at 20-80°C. Its exterior surface is surrounded by thermal insulation to isolate it from the MC, which operate at cryogenic temperature (77-80 K). The VV is maintained at temperature by helium gas circulated through tracing lines attached to the vessel

Figure 2. Assembled sector with port extensions welded on.

exterior. During bake out, the conductive heat loss through the insulation to the cryogenic system is significant. Heat losses drop during normal operation, but still impart a heavy load on the cryogenic system. The close proximity of the MC to the VV and the clearances required to maneuver the VV into the MC, at assembly, determine the space allotted for insulation. The conceptual design used 5 cm thick insulation batts of mineral/ceramic fiber attached to the VV surface with fasteners. In concept, the insulation thickness could be increased where space allows substantially reducing the heat loss, but this would be difficult in practice as there is only limited access to the VV after assembly. Foams based on polyimide or polyurethane polymers were ruled out because of their operating temperature limits. The attachment process was foreseen to be labor intensive, requiring custom fit and special treatment of seams to prevent gaps, either by lapping layers or stitching the interfaces. There was also concern about reliability. There was the risk that seams could open up or tears occur during assembly. A development program ensued to find a viable alternative, that is, a pourable insulation in the form of pellets or granules, which could be added after assembly and fill all available spaces, thus greatly reducing the cryogenic system and VV thermal requirements as well as simplifying installation. Preliminary analysis of thermal performance during bake out, using insulation back fill, showed a decrease in Cryostat LN2 load by

two thirds and VV heating by half, a significant improvement in performance. This was indicative that a pourable insulation concept would be worth pursuing and it became the new baseline.

III. Insulation Candidate Materials

A. Perlite

A form of heat expanded mica, frequently used as a pourable insulation in aerospace and the cryogenic industry. It has a low thermal conductivity, fairly low density, high temperature operation, and very inexpensive. On the down side, it absorbs and holds moisture and has a tendency to settle and compact. Relative motion between the VV and MC during bake out is ~1.5 cm, which could work the material and compact it. There is a risk that this could load up the MC during thermal cycling, resulting in damage. Thermal performance is inferior to Aerogel.

B. Glass Beads

Hollow micro-sphere glass bead powders have been evaluated and rejected for several reasons: cost, inferior thermal performance to the other choices, extreme dust generation, and indications that the material will load up during VV motion. A bar immersed in the powder and moved laterally through the material packs material ahead of the bar and it shows no tendency to move aside.

C. Mineral/insulation pellets

A pelletized version of the original mineral fiber insulation slated for the VV is available. It is probably a viable material but would require testing to quantify its compaction and moisture retention characteristics. Its thermal performance is inferior to Aerogel.

D. Aerogel

The material chosen as baseline for both the pourable insulation and the flexible batt insulation is silica aerogel. The batt is Pyrogel®, a product of Aspen Aerogel Inc and the pourable insulation is Nanogel®, a granular product produced by Cabot Corp., under license to Aspen Aerogel Inc. Aerogel is amorphous silica which forms a new family of high performance ultra-low density insulations. It has already found applications in aerospace, cryogenics, industrial building insulation, and in extreme weather garments for skiers, arctic workers, and mountain climbers. Aerogel was acknowledged in the Guinness Book of Records as being the lightest material in the world (1 Kg/m³). Some of the material characteristics for Nanogel are shown in **Table 1**. Additional data may be referenced in Cabot literature.

Table 1 Nanogel characteristics

Particle size	5 µm to 5 mm
Bulk Density	~100 kg/m ³ (5 mm) ~ 30 kg/m ³ (5 µm)
Surface area	600 to 800 m ² /g
Porosity	>90%
Thermal conductivity	0.018 W/m-K

IV. Nanogel Overview

Nanogel is available in two forms. The first is pellets, opacified to reduce IR radiation transmission through the material. The pellets are brown, quasi-spherical, averaging approximately 1 mm in diameter. The second is translucent irregular granules which average 3-4 mm in size. Both products shed dust, that of the granular product being nearly invisible to the naked eye in small quantities. Both products pour freely with some static cling of the dust to surfaces, particularly nonconductors, but this is not anticipated to be problem. Once a mono-layer of dust is deposited, it seems to shed further deposits.

V. Pyrogel Overview

The specific material chosen for the batt insulation is Pyrogel 6671. It has an operating temperature range from -269 C to 650 C. Its thermal properties down to zero degrees Centigrade are shown in **Table 2**. Performance at cryogenic temperatures may be referenced in research by NASA.¹ Pyrogel is very compliant and somewhat compressible, compacting to approximately 60% of its height. Recovery is close to 90%. The cost per volume of Pyrogel and Nanogel is high but still competitive with some of the other high tech ceramic cloth insulators. The material is easy to cut with scissors or utility knife, but does tend to dull them quickly. The material is available in 6 mm thick roll stock and can be jelly rolled around 5 cm diameter ducts without breaking or fraying.

VI. Thermal Performance

Heat loss from the original baseline configuration is shown in **Figure 3**. The heat loss from the new configuration is shown in **Figure 4**.

Material Properties Assumed:

Insulation blanket thermal conductivity 0.0002 w/cm-K

Pellet insulation thermal conductivity 0.0002 w/cm-K

The space between the VV, MC, and structural shell are assumed to be backfilled with pellet insulation. The port extensions, cryostat wall, and port covers are assumed to be covered with blanket insulation. With the Aerogel insulation, the VV tracing heating load to the vessel wall, at 350 bake out, reduces from 16.5 kW to 8.2 kW. The MC liquid nitrogen system cooling load reduces from 11.3 kW to 3.1 kW. During idle [pre-shot] operation, the VV heat load drops from 4.6 kW to 1.02 kW. The MC liquid nitrogen system cooling load reduces from 4.5 kW to 0.9 kW. The gaseous nitrogen cooling load is essentially unchanged since the major heat

Table 2. Aerogel thermal performance

contributors are in leak through the Cryostat and losses from the ports. The port insulation material is changed but the thickness is reduced so the net loss is unchanged.

VII. Design

Five cm of gap is provided between the port extensions and the MC shell for installation of port blankets and to accommodate thermal movement. This gap must be sealed by flexible boots to prevent leakage of the Nanogel. A G10 fiberglass retainer ring and a Gor-tex[®] cord, serving as an o-ring, form a loose seal to the MC shell. The retainer ring also mounts the Nomex[®] cloth boot. Samples of Nomex fabric and Gor-tex cord have been immersed under liquid nitrogen to check their performance at 77 K. They retain a large degree of flexibility and show no tendency for fatigue cracking. The port blanket insulation is covered in Nomex cloth as described later under Health Issues, then jelly-rolled around the pipes to obtain the required thickness. Stainless steel wire twists are sufficient to retain the material.

VIII. Fire Safety

Nanogel is a silated product, that is, it has methyl groups attached to the silica to render it hydrophobic. Above ~400 C the Methyl groups break down and come off as flammable gases, primarily carbon monoxide and methane. The “as delivered” product is not acceptable for contact with the 350 C VV, but Cabot Corp is developing a modified product for oxygen service, that is treated to remove the volatile materials. Tests conducted at ORNL confirm the viability of this alternative. The tests consist of forcing >1000° F air through Nanogel samples to drive off the volatiles. A blue flame is evident in a darkened room above the material,

^a Gor-tex is a registered trademark for W.L. Gore and Associates, Inc. expanded polytetrafluoroethylene (ePTFE).
^b Nomex is a registered trademark for Dupont Aramid fiber.

which eventually extinguishes. The treated material appears to be physically unchanged, there is no color change and no

Figure 3 Original insulation configuration. The diagram shows a representative section of VV, MC, and port extension. Heat losses are the total for the complete system.

Fig. 4. New insulation configuration

break down of the material, and no clumping or sticking. No tests have been performed to confirm whether the thermal

conductivity is affected. Cabot has also performed the out gassing (calcining) on samples and claims that the product performance is essentially un-altered, although it is no longer hydrophobic.² The amount of moisture uptake is believed to be very small but the material may have to be stored under nitrogen as a precaution.

IX. Health Issues

Aerogel is not a crystalline product and is not classified as a carcinogen or health hazard, only as a dust nuisance. The use of dust masks or respirators and goggles are recommended. Contact with the material has been found to have a drying effect and an unpleasant sensation on the skin. Rubber gloves are highly recommended. Dust is anticipated to become an issue, therefore, the design of the port blankets includes an outer jacket of fabric sewn around the edges to contain the dust. The port boots at the MC penetrations utilize the same fabric. The material is a tight weave Aramid fiber product suggested by a fabric supplier.³ Prototype bags filled with Nanogel have confirmed that no dust migrates through the weave. Testing in an oven at 350 C for 4 hours, under nitrogen, show no degradation of the fabric. The same test using air atmosphere, disintegrate the fabric in less than an hour. This is acceptable since the NCSX Cryostat is filled with dry nitrogen.

X. Testing Program

A. Flow tests

A labyrinth (ant farm) constructed with a transparent window to observe flow of Nanogel through narrow passages and turns is shown in **Figure 5**. The material flows freely through 0.6 cm deep passages, but has to be encouraged to turn corners; it piles up in a shallow slump angle and blocks flow. Both vibration and introduction of air flow are effective in restart of the flow. No efforts have been successful to persuade material vertically up into blind end passages.

B. Compaction and settling

Nanogel shows no indication of settling or compaction during vibration or handling. Testing has shown it is resilient under load, the material compresses and rebounds elastically. This resilience is sufficient to absorb the thermal movement between the VV and MC shell without stressing of the MC coils. It is friable, however, and is expected to undergo some breakdown over time, therefore, topping off of the insulation may be necessary. The level will be monitored in transparent standpipes, and filled as required. A procedure for installation of the granular insulation has not been developed and there are some uncertainties remaining. It is not clear how to fill the annulus around the VV and MC without voids or how to confirm the fill. It is clear from testing that simple filling from the top, even from

several points is not sufficient. Installation will probably require several methods, among which could be:

Figure 5. Labyrinth (ant farm) flow test fixture.

XI. Concerns

- Air entrained filling from bottom ports. This causes the material to fluidize and mobilizes it.
- Vibration of the VV to settle the material.
- Slight toroidal rotation of the VV, back and forth, to settle the material and break up bridging.
- Confirming the presence of insulation at each port. This involves loosening the boot ties and inspection of the port annulus

As a contingency, the most vulnerable regions (primarily at the top and bottom) of the MC have been provided with sufficient blanket insulation to assure survival even if voids should occur in the granular insulation.

References:

1. NASA report YA-F2-T, J.E. Fesmire, S.D. Augustynowicz, and S. Rouanet, *Aerogel Beads as Cryogenic Thermal Insulation System*.
2. E-mail and telephone conversations with Cabot Corp.
3. Warwick Mills Inc.
301 Turnpike Rd.
New Ipswich, NH. 03071
Weave pattern - 2X1 Oxford weave
Weight Nominal - 5.8 Oz/sq. yd
Style - T9-1231