AEROGEL BLANKET INSULATION MATERIALS FOR CRYOGENIC APPLICATIONS

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ABSTRACT

Aerogel blanket materials for use in thermal insulation systems are now commercially available and implemented by industry. Prototype aerogel blanket materials were presented at the Cryogenic Engineering Conference in 1997 and by 2004 had progressed to full commercial production by Aspen Aerogels. Today, this new technology material is providing superior energy efficiencies and enabling new design approaches for more cost effective cryogenic systems. Aerogel processing technology and methods are continuing to improve, offering a tailor-able array of product formulations for many different thermal and environmental requirements. Many different varieties and combinations of aerogel blankets have been characterized using insulation test cryostats at the Cryogenics Test Laboratory of NASA Kennedy Space Center. Detailed thermal conductivity data for a select group of materials are presented for engineering use. Heat transfer evaluations for the entire vacuum pressure range, including ambient conditions, are given. Examples of current cryogenic applications of aerogel blanket insulation are also given.

KEYWORDS: Cryogenic tanks, thermal insulation, composite materials, aerogel, thermal conductivity, liquid nitrogen boil-off
PACS: 65.60.+a, Thermal properties of amorphous solids and glasses

SHORT HISTORY OF AEROGEL BLANKET DEVELOPMENT

Aerogel blanket development began in 1993 through a Small Business Innovation Research (SBIR) program between Aspen Systems, Inc. (Marlborough, MA) and NASA Kennedy Space Center (KSC, FL). The motivation was to enable new and improved thermal insulation systems for cryogenic and other high-performance, low-temperature needs. Production methods were developed starting with 75-mm diameter specimens and progressing to near one m^2 sizes by 1995. Continuing toward engineered applications, a field installation kit consisting of about 20 m^2 of 13-mm thick aerogel blankets was produced in 1996, a considerable large-size production for that time. This kit was used to accomplish a number of field demonstrations for cryogenic piping applications. Information such as UV stability, hydrophobicity, thermal cycling, and other long-term exposure effects were investigated over the next 5 years. The measure and understanding of oxygen compatibility and flammability limits were another crucial factor in the development process. Aspen Aerogels, Inc. (Northborough, MA) was formed in 2001 for the beginning of large-scale production. Initial commercialization was enabled by Aspen's development of more cost-efficient processing methods resulting in over 100-fold cost reduction. Chief among these were a semi-automated batch process and a supercritical drying step at reduced pressures and temperatures.

Aspen Aerogels' patented processing method consists of infiltrating a sol mixture into a fibrous web in an automated roll-to-roll manner. The sol is catalyzed to convert to a gel within the interstitial spaces of the web prior to subsequent processing steps [1-4]. The gelation step is followed by an aging step in a solution that improves strength and critical performance properties such as thermal conductivity and hydrophobicity. The final step in the process is to dry the wet-gel under supercritical CO_2 conditions. The use of supercritical carbon dioxide for removal of gel solvent from thick gel blanket composites for large scale processing has proven both safe and economical. There are several steps in the gel composite manufacturing process wherein the product properties can be altered to meet various target application requirements. For example, aerogel material properties can be modified through the use of new precursor materials and/or additives before sol gelation to improve compression resistance, enhance IR opacification and introduce anti-sintering properties. Additionally, the type of fiber batting selected for aerogel reinforcement can be optimized for performance and durability in the end-use application environment. Typically, the type of reinforcement used will be different if the insulation is going to be exposed to high temperatures *versus* cryogenic temperatures, with inorganic glass or ceramic fiber reinforcement favored at high temperatures.

Thermal performance of the aerogel blanket insulation materials under actual-use cryogenic conditions is important for the design, development, and implementation of new systems. Example systems include piping (both single-wall and double-wall), valves, joints, and tanks. Advantages of using the aerogel materials include superior thermal performance, weathering resistance, long life, and ease of application. Testing must be performed to meet requirements for both engineering and economics factors. Characterization of the materials under the appropriate boundary temperatures and environmental conditions as they will be used in the field is essential to implementation of aerogels over conventional insulation materials. Many different aerogel blanket materials have been tested at the Cryogenics Test Laboratory (CTL) of NASA KSC using a family of insulation test cryostats. Although the thermal conductivity data is important, factors such as mechanical and chemical, as well as end-use environment and cost are crucial.

MATERIALS AND SPECIFICATIONS

The performance data for Aspen Aerogels' flexible blankets are summarized in Table 1. These materials do not have corrosive effects on steel including stress corrosion cracking in austenitic stainless steel, and are fungi resistant. In addition, there are typically no outgassing issues with these aerogel products, many of which have passed strict specifications for space use [5]. Non-flammable, hydrophopic aerogel blankets have also been produced for cryogenic applications [6].

Many different aerogel blanket insulation materials and combinations have been tested at the CTL over the years of development. A select list of these materials and their installed densities are listed in Table 2. Aerogel blankets have been tested in different combinations with multilayer insulation (MLI) materials [7]. Further details are discussed in the literature [8-12]. Prior to testing, each material was typically heated above 340 K and evacuated to achieve an initial high vacuum level condition.

Table 1. Performance data for Aspen Aerogels' flexible aerogel blankets; NA = Not Applicable.

Type	Spaceloft	Cryogel	Pyrogel	Pyrogel XT
Maximum use temperature, °C	125	90	300	650
Minimum use temperature, °C	-201	-201	-201	-201
Mean Temperature °C	Apparent thermal conductivity, max mW/m-K			
-129	14.0	13.4	NA	NA
-73	15.0	15.0	NA	NA
-18	16.0	15.7	NA	NA
24	17.0	17.0	20.0	21.0
38	17.3	17.6	21.0	21.6
93	19.0	21.0	22.0	23.1
149	NA	27.0	24.1	25.3
204	NA	NA	27.6	28.8
260	NA	NA	31.0	31.7
316	NA	NA	NA	36.1
371	NA	NA	NA	43.3
Compressive resistance, min, @ 10% deformation, kPa	34.5	34.5	80.0	20.7
Linear shrinkage after exposure to maximum use temperature	<2.5%	< 2.5%	< 2.5%	< 2.5%
Water vapor sorption, max, weight %	5%	5%	5%	5%
Surface burning characteristics: Flame spread index, max Smoke developed, max	 25 50	NA	 25 50	 5 10
Exothermic temperature rise, max, with no facings, run at max recommended thickness	NA	NA	93° C	93° C
Water absorption after heat soak, maximum % increase by weight	NA	NA	NA	50%

Table 2. Test materials and installed thicknesses and densities.

Ref. No.	Test Apparatus	Material System	No. layers	Total Thickness mm	Installed Density g/cc
A111	C-100	Pyrogel	6	18.3	0.124
A112	C-100	Cryogel	2	22.6	0.134
A113	C-100	Cryogel + MLI	1+15	21.5	0.092
C105	C-1	Gray + MLI	1+10	29.5	0.079
C110	C-1	White	2	32.0	0.125
C138	C-1	Silingel	4	16.0	
F145	C-4	Silbond	5	38.4	0.069
F146	C-4	WaterGlass	6	33.2	0.101
F211	C-4	Cryogel Z	2	8.26	0.204

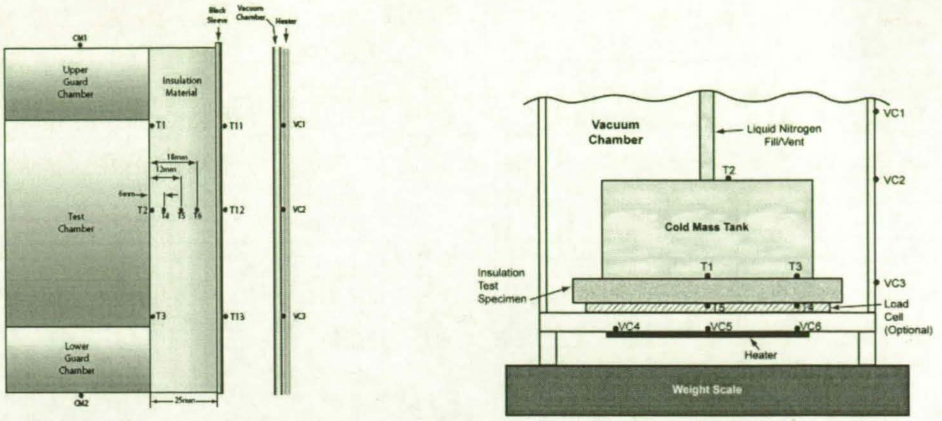
CRYOGENIC TEST METHODS AND APPARATUS

The Cryostat-100 test apparatus, and its predecessor, Cryostat-1, were the primary instruments used in testing. The system is a liquid nitrogen boil-off (evaporation) calorimeter which provides absolute data for the apparent thermal conductivity (k-value) of materials or systems. Mass flow of nitrogen gas under steady-state, energy-rate balanced conditions is the primary measurement. This new apparatus is capable of extremely stable boil-off rates over a very wide range of heat flux.

The cold mass cylindrical configuration is 167-mm by 1026-mm, including guarded ends. Test materials are held in place around the cold mass using circumferential wraps of wire or tape. Test temperatures are as follows: cold-boundary temperature (CBT) 78 K, warm-boundary temperature (WBT) 293 K, and temperature difference (ΔT) 216 K. Multiple temperature sensors are included for boundary and thickness layer temperatures as shown in Figure 1a.

Cryostat-4, Figure 1b, was used for smaller size test specimens. This instrument is a flat plate configuration and provides a comparative k-value measurement. Calibration is accomplished using in-house standard reference data from Cryostat-100. Further details of these test methods and apparatus can be found in the literature [13].

The test specimens are evacuated and heated to achieve a high vacuum level within the material prior to beginning a series of tests. After a suitable warm vacuum pressure (WVP) is obtained, typically 1 millitorr, tests are conducted over the full range of cold vacuum pressures (CVP). Most engineering applications fall into one of three levels of thermal performance as designated by the following CVP's: high vacuum (HV), below 1x10-4 torr; soft vacuum (SV), ~1 torr; and no vacuum (NV), 760 torr. A typical test series consists of a minimum of eight CVP's starting at HV and increasing to NV. Nitrogen is the residual gas for all tests.



(a) (b)

Figure 1. a) Cryostat-100 schematic showing location of temperature sensors. b) Cryostat-4 schematic showing location of temperature sensors and LN2 fill port.

CRYOGENIC TEST RESULTS

Over 90 tests of 9 different aerogel blanket systems were performed. Variation of k-value with CVP is presented in Figure 2 and Table 3. The k-values rise only moderately in the soft-vacuum range as the gas conduction that begins to dominate the heat transfer is suppressed by the nanoporous aerogel material. The two insulation systems including MLI blankets show improved performance in the high vacuum range where radiation heat transfer becomes a dominant factor. Temperature profiles throughout the thickness of the insulation systems were measured. Example temperature profiles for Cryogel and Pyrogel are presented in Figure 3.

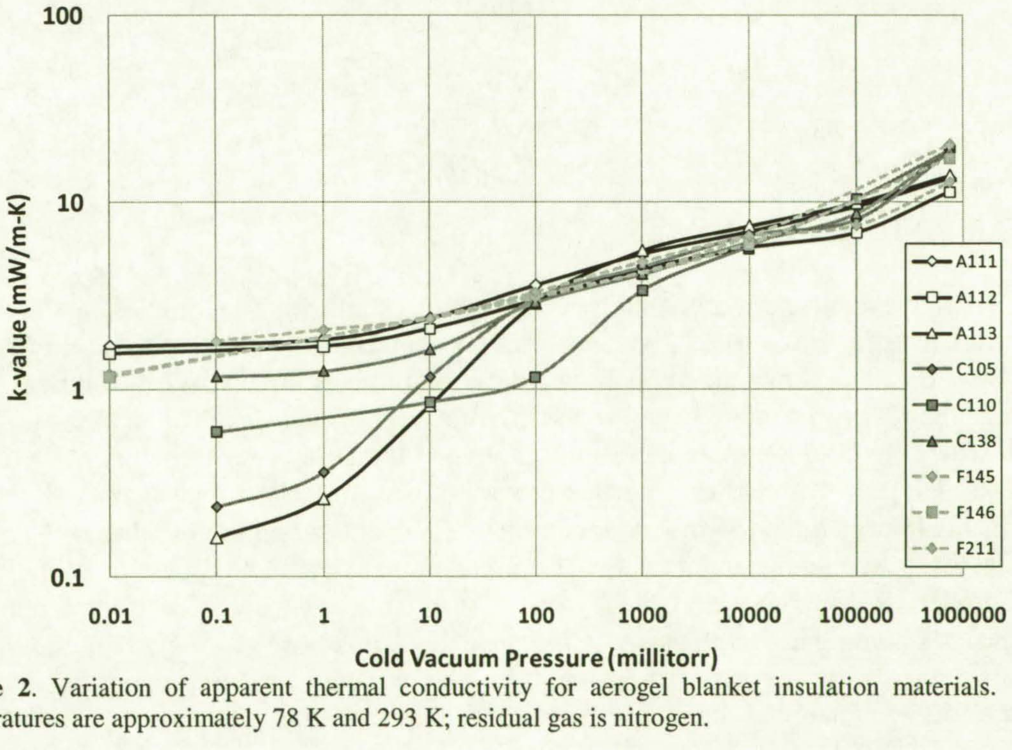


Figure 2. Variation of apparent thermal conductivity for aerogel blanket insulation materials. Boundary temperatures are approximately 78 K and 293 K; residual gas is nitrogen.

Table 3. Variation of apparent thermal conductivity for aerogel blanket insulation materials. Boundary temperatures are approximately 78 K and 293 K; residual gas is nitrogen.

CVP	**k-values (mW/m-K)**									
(millitorr)	**A111**	**A112**	**A113**	**C105**	**C110**	**C138**	**F145**	**F146**	**F152**	**F211**
0.01	1.70	1.55	-	-	-	-	1.21	1.17	1.99	-
0.1	-	-	0.16	0.24	0.60	1.17	-	-	-	1.81
1	1.85	1.70	0.26	0.36	-	1.25	-	-	2.10	2.08
10	2.40	2.11	0.82	1.16	0.86	1.63	-	-	3.18	2.39
100	3.60	2.99	2.88	3.06	1.16	2.91	3.11	3.18	5.10	3.30
1,000	5.26	4.35	5.49	4.49	3.36	4.12	-	-	9.08	4.79
10,000	6.92	5.68	7.43	6.63	5.80	6.09	6.56	5.99	12.09	6.53
100,000	9.42	6.82	9.88	8.05	10.33	8.67	-	-	13.88	7.51
760,000	13.34	11.28	13.81	18.44	18.91	19.30	20.30	17.13	18.70	12.74

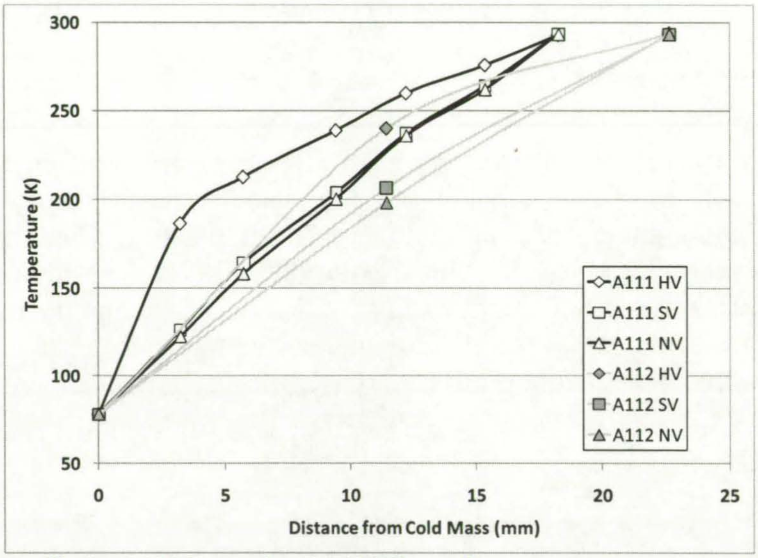


Figure 3. Temperature profile for A111 Pyrogel and A112 Cryogel.

ANALYSIS AND DISCUSSION

Complementary test methods are necessary for establishing a complete understanding of the heat transfer properties for a given material system and to establish credibility of the heat measurement results. Ambient temperature data for thermal conductivity (lambda) combined with cryogenic data for k-value can allow some first approximations of lambda as a function of temperature or extrapolation to another set of boundary temperatures of interest.

The measured temperature profiles provide a way to perform an estimated computation analysis of the intermediate thermal conductivity (λ), depending on the number of layers making up the total test specimen. Lambda values for ambient pressure and temperature conditions were obtained from ASTM C-518 and C-177 test instruments. The ambient temperature lambda values and the cryogenic λ-values for Cryogel and Pyrogel are presented in Figure 4. The ambient data are always a good starting point, but the cryogenic-vacuum variations usually have profound effects on changing the internal behavior of the material.

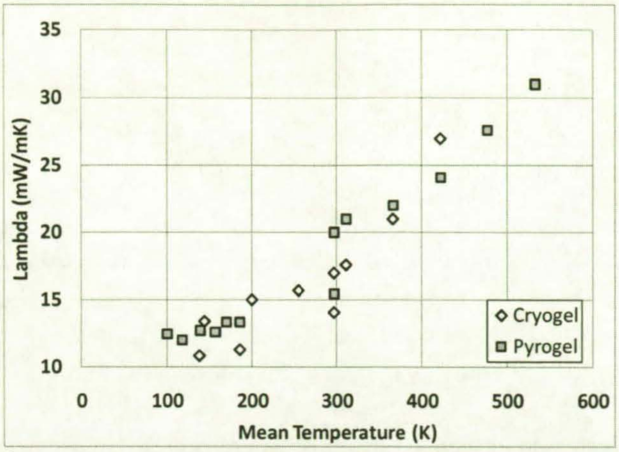


Figure 4. Lambda values and λ–values for Pyrogel and Cryogel at ambient pressure using several test instruments.

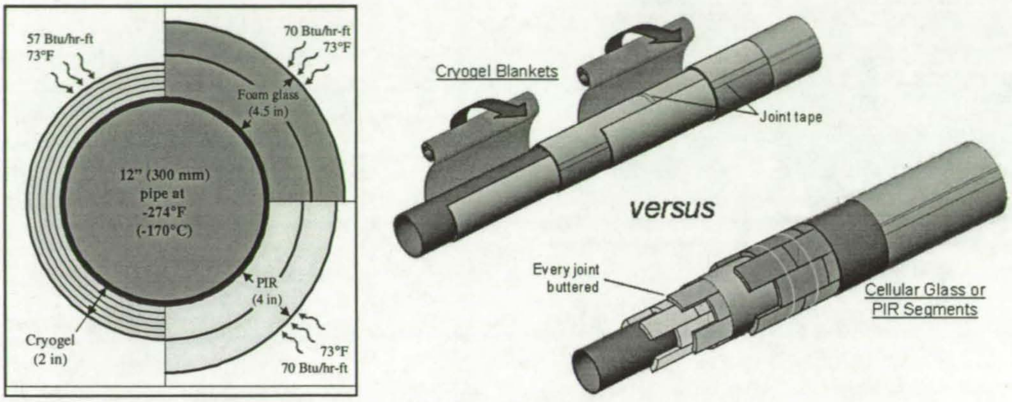
EXAMPLE APPLICATIONS

Example applications for aerogel blankets include the oil and gas processing industry (LNG, LPG, ethylene, etc.), offshore oil, refineries, petrochemical and gas processing, building and construction, appliances, outdoor gear and apparel, transportation, military, and aerospace. Aspen's low temperature product (Cryogel) is primarily used for ambient pressure environments, but can be used under soft vacuum and high vacuum conditions as well. Cryogel offers several benefits for insulating cryogenic pipes. These benefits include a decreased insulation thickness requirement in comparison to conventional insulations (Figure 5a), a simplified insulation system design (i.e. no contraction joints), and fast installation, even during operating conditions (Figure 5b). Cryogel is also useful for insulating difficult areas such as between flanged sections of vacuum-jacketed piping.

CONCLUSIONS

Cryogenic thermal performance testing of a wide variety of aerogel blanket materials was successfully completed. Different test methods and conditions are needed to characterize insulation materials for the full cryogenic-vacuum environments. These results are being applied to projects throughout the world for cost and energy efficiency improvements. These projects include cryogenics, oil & gas, building construction, refrigeration, general industry, and many other areas for a wide temperature range. The thermal performance benefits of aerogel blankets are clear. Developed over the last 15 years, this technology is being shown to enable new possibilities for long-life, low-maintenance thermal insulation systems in both industry and consumer products.

Near-term projections for aerogel blanket materials production are on the order of tens of thousands of square meters (tens of millions of square feet) per year. As aerogel-based solutions become the new standard for insulation problems, further refinement of these thermal conductivity data will likely be required to match the increased engineering knowledge-base. Further detailed studies and testing for standard data sets on thermal conductivity are continuing as engineering requirements are developed. Lightweight blankets optimized for the high vacuum environment of space or vacuum-jacketed equipment are now under development.



(a) (b)

Figure 5. (a) Cryogel has a decreased insulation thickness requirement in comparison to conventional insulations on cryogenic pipes. In this diagram, all three designs meet the same condensation control criteria. (b) Cryogel's simplified system design for cryogenic pipes.

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