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List of Acronyms

ºC	Degree Celsius
ºF	Degree Fahrenheit
$/m	Dollars per meter
µm	Micrometer
AEP	American Electric Power
CO_2	Carbon Dioxide
CUI	Corrosion Under Insulation
DOE	Department of Energy
kg/m^3	Kilogram per square meter
lbs/ft^3	Pounds per cubic foot
m	Meter
mm	Millimeter
MM	Millions
MMBtu/m/yr	Millions of British Thermal Units per meter per year
MMBtu/yr	Millions of British Thermal Units per year
MMT/yr	Millions of Tons per Year
MW	Mega Watts of Electricity
nm	Nanometer
PCF	Per cubic foot
pH	logarithm of the reciprocal of hydrogen-ion concentration in gram atoms per liter
ROI	Return on Investment
SEM	Scanning electron microscope
TBtu	Trillions of British Thermal Units
TBtu/yr	Trillions of British Thermal Units per Year
TIC	Total installed cost
W/m	Watts per meter
wt%	Percent of weight

1. Executive summary

Under this program, Aspen Aerogels has developed an industrial insulation called Pyrogel HT, which is 4-5 times more thermally efficient than current non-aerogel technology. Derived from nanoporous silica aerogels, Pyrogel HT was specifically developed to address a high temperature capability gap not currently met with Aspen Aerogels' flagship product, Pyrogel XT. Pyrogel XT, which was originally developed on a separate DOE contract (DE-FG36-06GO16056), was primarily optimized for use in industrial steam processing systems, where application temperatures typically do not exceed 400ºC. The bill of materials for Pyrogel XT (additives, sol gel chemistry, reinforcement type and weight) was judiciously chosen to simultaneously meet thermal performance goals and material durability within this specific temperature range. At the time, further improvements in thermal performance above 400ºC could not be reasonably achieved for Pyrogel XT without significantly affecting other key material properties using the current technology.

During this effort, Aspen Aerogels has significantly increased the state-of-the-art with respect to aerogel chemistries intended for use at high temperature. Significant progress was made in identifying and characterizing more efficient infrared opacifier additives that are capable of imparting thermal performance benefits at high temperatures. A comprehensive evaluation of new fiber reinforcements and an optimization of baseline sol-gel chemistry have resulted in improved thermal performance at 400ºC and above. These improvements were achieved without drastically affecting other key material properties. At the same time, the durability and handling of the aerogel insulation has significantly improved via post-production application of non-combustible dust-mitigation coatings. This technology has been manufactured in the laboratory, resulting with an insulation that exhibited a 40% reduction in thermal conductivity at elevated temperatures relative to Pyrogel XT. The performance of this technology has far surpassed all expectations and will close the high temperature capability gap that is currently restricting Pyrogel XT.

Through several installations of Aspen Aerogels' Pyrogel XT product, NextEra Energy Inc. has externally validated superior insulation performance and total installed cost; information essential for estimating the techno-economic performance of Pyrogel HT.

This program has developed a new aerogel-based high temperature insulation, Pyrogel HT, which not only provides better efficiency and durability, but also the lowest installed cost per unit performance, enabling plant managers to achieve greater levels of energy savings for each dollar of capital spent. Although Pyrogel HT can be applied to a broad range of high-temperature industrial applications (e.g., glass melting, metal casting, delayed coking, steam cracking, flue-gas treatment, ore smelting), its initial deployment is focused on the US power generation market. Cumulative sales of Pyrogel HT into domestic power plants should reach $125MM through 2030, eventually reaching about 10% of the total insulation market share in that space. Global energy savings would be expected to scale similarly. Over the same period, these sales would reduce domestic energy consumption by more than 65 TBtu. Upon branching out into all industrial processes in the 400°C -650°C regime, Pyrogel HT would reach annual sales levels of $150MM, with two-thirds of that being exported.

2. Introduction

The purpose of this program was to develop and commercialize improved aerogel insulation for high-temperature applications which reduces waste in a multitude of energy-intensive industries. These savings are realized through reduced installation costs, improved energy performance, and enhanced durability. This program supports the DOE Energy Efficiency and Renewable Energy (EERE) Industrial Technologies Program (ITP) mission to improve energy efficiency and environmental performance to make U.S industry lead the world in energy efficiency and productivity. Commercialization of the innovation developed on this program will support the ITP goal to drive a 25% reduction in industrial energy intensity.

This project builds upon the knowledge base gained during the development of Aspen's most successful insulation product, Pyrogel XT. First launched in April of 2008, Pyrogel XT was developed to address the market for insulating steam distributions systems, particularly within the refining and petrochemical business. Much of this development work was performed under contract with the DoE's Industrial Technology Program entitled "Aerogel-Based Insulation for Industrial Steam Distribution Systems" (Contract No. DE-FG36-06GO16056). As a result of that highly successful program, Aspen has sold over 4MM square feet of Pyrogel XT within the first 15 months since its introduction, and has saved an estimated 0.163 TBtu in the US alone.[1]

While Pyrogel XT will continue to grow and be a mainstay of the Aspen product line for many years to come, it cannot fully satisfy all the needs of the industrial insulation market. Because Pyrogel XT was optimized for performance in the range of 100°C-400°C, (200°F-750°F) the regime in which low- to medium-pressure steam systems operate, it does not adequately address the needs of higher temperature applications. This is illustrated in Figure 1 which shows the thermal conductivity of Pyrogel XT versus the target performance of Pyrogel HT, the material developed on this program. These curves suggest that a significant improvement in thermal performance is necessary for industrial aerogel insulation intended for use at temperatures exceeding 400ºC.

Because Pyrogel XT is optimized for a different segment of the industrial insulation market, it is Aspen Aerogels' intent to move forward with a two-product offering: Pyrogel XT for low- to medium temperatures, and Pyrogel HT for high temperatures. In this way, Aspen can deliver the greatest energy savings at the lowest possible cost. But achieving this new performance target required a delicate balance between opacification, hydrophobicity, and dust loading. The intent of this effort was to address each of these issues with the goal of producing a durable inexpensive aerogel insulation intended for energy intensive high-temperature applications.

The improved insulation material, Pyrogel HT, is expected to reduce industrial energy consumption in four ways. First, its resistance to thermal and mechanical degradation will ensure that energy efficiency does not degrade over time like that of existing products. Second, by offering the lowest installed cost per unit performance, it will enable plant managers to achieve greater levels of thermal efficiency for each dollar of capital spent. Third, by being so much thinner than existing materials, it can be used to upgrade the efficiency of older facilities where space constraints frequently prohibit increased insulation thickness. Finally, Pyrogel HT's flexible form factor and thin profile enable its use as a low-cost, in situ upgrade by simply wrapping it around existing insulation systems.

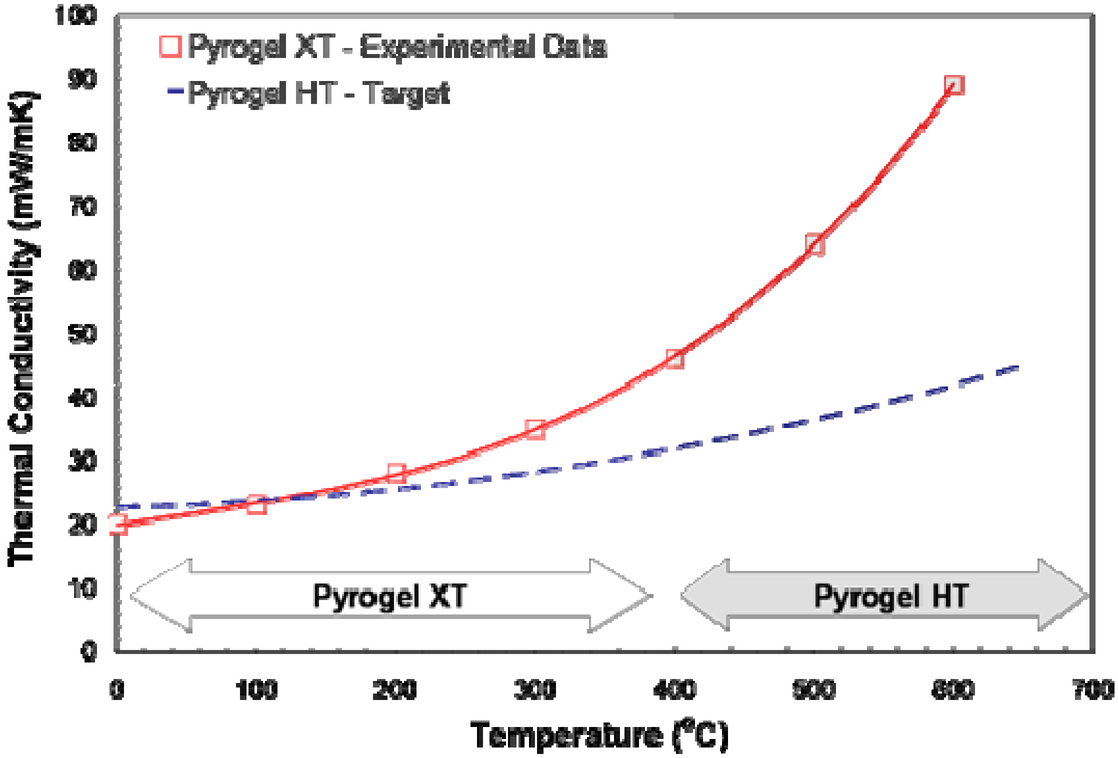


Figure 1. Thermal conductivity vs. temperature of Pyrogel XT and target for Pyrogel HT.

3. Background

High-temperature applications pose a particular challenge for manufacturers of industrial insulation because they exceed the survival temperature of most organic materials. For mineral wool, the leading product in the high-temperature space with 65% global market share, this can lead to performance loss via binder decomposition. When mineral wool is produced, the individual filaments are consolidated into discrete boards or lengths of pipe cover with an organic resin, or "binder". In the presence of oxygen, this binder begins to decompose at temperatures above 250°C (482°F), leaving behind an annular volume of unconsolidated fiber (Figure 2).

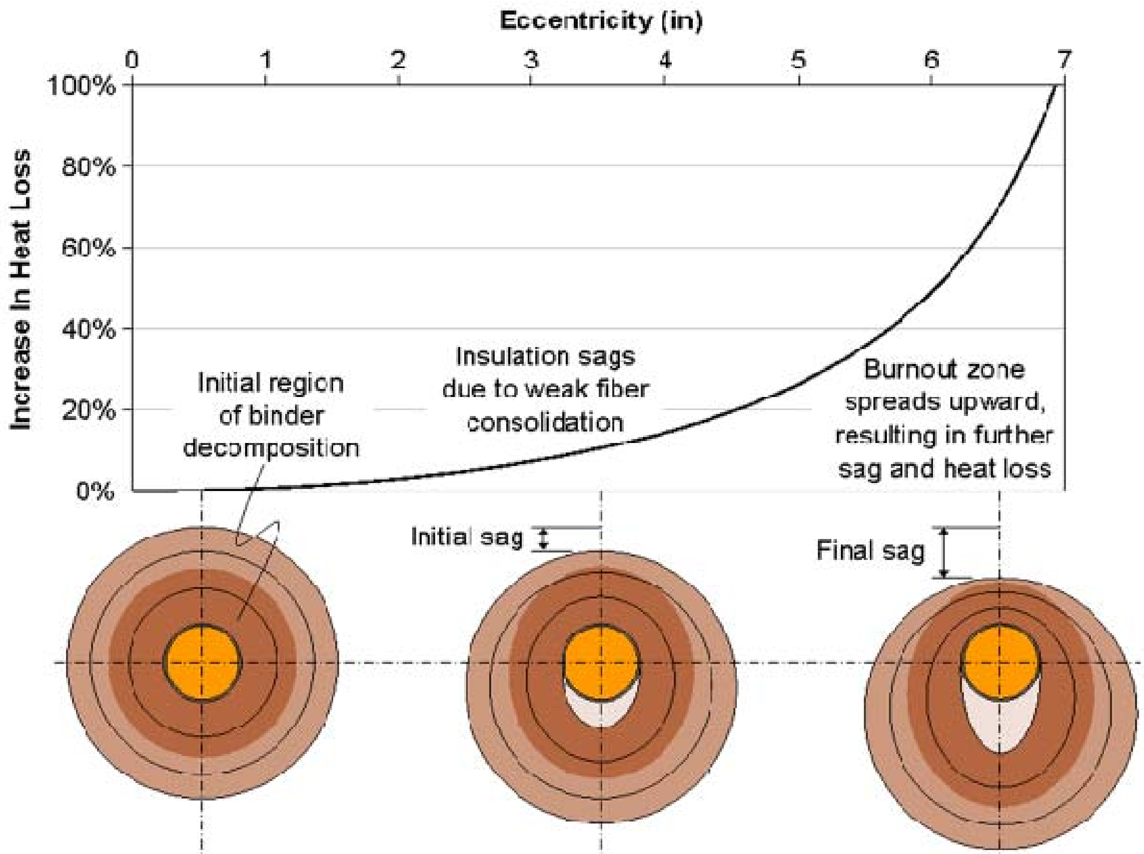


Figure 2: Binder burnout and its attendant loss of thermal performance.

With time and vibration, that fiber begins to dislocate and compress, causing the insulation to sag downward under its own weight. Sag becomes self-reinforcing as the reduced thickness leads to reduced thermal resistance at the top of the pipe, leaking heat into the outer layers and propagating the burnout zone upward. The result is a loss of insulation concentricity, a reduction of thermal performance, and an increase in surface temperatures, potentially leading to unsafe working conditions near the pipe. Over a typical 20-year service life, the rate of heat loss can increase by a factor of 2-3. In contrast to mineral wool, Pyrogel HT has no organic binders to burnout, relying instead on needled-glass fiber to maintain its physical integrity.

Calcium silicate, is cementitious by nature and also has no organic binder. It is, however, friable, expensive, and 5-10 times heavier than mineral wool, and so is only typically used in areas where mechanical damage is likely, such as near high-traffic areas. Both materials will readily absorb liquid water and ambient humidity, which can quadruple their effective thermal conductivity. Water-absorbent materials can also lead to corrosion under insulation (CUI) during shutdowns when the equipment drops back down to ambient temperature. CUI can be extraordinarily expensive to deal with, since it often goes undetected until catastrophic loss of containment occurs.

3.1. Aerogel Background

Pyrogel HT will address the shortcomings in the high-temperature insulation market by leveraging silica-based aerogel technology. Invented in the 1930's, aerogels are remarkable for having the world's lowest thermal conductivity. With a highly porous, open-celled molecular structure, silica-based aerogels are non-flammable, non-toxic, and survivable at temperatures above 650°C, or 1200°F. Often called "frozen smoke" in the popular literature, aerogels can be manufactured as powder, granules, monoliths (Figure 3a), or in the case of Aspen's product line, as fiber-reinforced flexible blankets (Figure 3 b&c). Aerogels can also be doped with various ingredients, providing broad adjustability of the chemical and physical properties, in particular high temperature thermal performance. This compositional flexibility distinguishes silica aerogels from the other single- or dual-component industrial insulation materials mentioned above.

Figure 3: Aerogel: a) monolithic form, b) flexible blanket form, and c) on construction site.

3.1.1. Thermal Properties of Aerogels at High Temperatures

The overall thermal conductivity of an aerogel material is the sum of three components: conductivity by the solid phase, gas phase and radiation. The solid phase thermal conductivity for aerogels is density dependent and is approximated by $k_s \propto \rho^{\alpha}$ (with α = 1.5), for densities between 70-230 kg/m^3. The high porosity of an aerogel endows it with very low solid-phase thermal conductivities. Gas conductivity is essentially negligible for aerogel materials owing to its very small sized pores. These pores are considerably smaller than the mean free path of air, so gas conduction via molecular collisions is essentially minimized.

The radiative component of thermal conductivity is directly proportional to T^3 (temperature) and inversely proportional to the infrared (IR) extinction coefficient $E = e \cdot \rho$. The specific extinction, e, is a temperature and wavelength dependent variable that can be determined via IR optical measurements or by calculating the scattering and absorption cross section by Mie theory[2]. Owing to a low extinction coefficient at wavelengths less than 8 μm, the radiative component of thermal conductivity for pure silica aerogels increases rapidly at high temperatures (i.e. >300°C). In general, pure silica aerogels are transparent to IR radiation and will exhibit a steep rise in thermal conductivity as a function of temperature. To overcome this disadvantage, aerogels are typically "opacified" with stable metal oxides that effectively scatter IR radiation at wavelengths below 8 μm (radiation of a theoretical blackbody at temperatures >100°C). The main functions of these additives are to impede radiant heat transfer by scattering radiation via reflection, refraction and diffraction of the incident radiation.

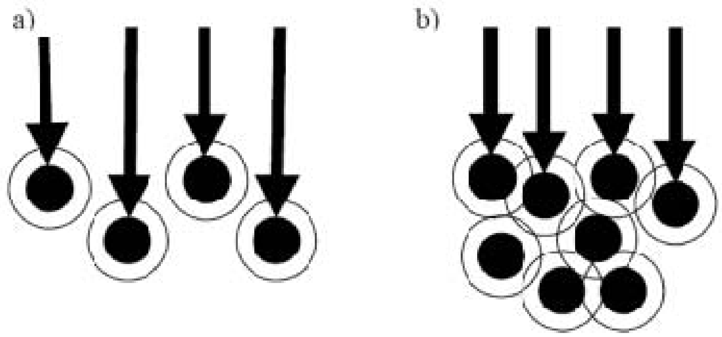


Figure 4: Schematic: poor scattering efficiency and overlap of scattering cross sections.

The opacity of a given material generally increases as a function of pigment concentration; i.e. more radiation is reflected, refracted or diffracted as the population of scattering centers increases. However, it has been shown that the opacity actually decreases at high levels due to pigment crowding and the overlap of scattering cross-sections. Aspen's production process combines well-dispersed suspensions of these opacifying metal oxide particles with a silica sol within a fiber matrix prior to transforming into a gel. The phenomenon of optical crowding (Figure 4) can also be induced at low pigment volume concentrations if the opacifying agents form large aggregates via flocculation. Preventing this flocculation process has been a significant challenge within Aspen's current aerogel production process, and can limit the overall thermal performance of a material at high temperatures. Additionally, the presence of large aggregates significantly complicates any manufacturing process and imposes an unnecessary limit on the maximum amount of opacifier per unit volume of insulation. Optimization of opacifier loading and delivery was of particular focus during this program.

3.1.2. Water Repellency and Non-Combustibility of Aerogel Insulation

Pyrogel XT was purposefully imparted with thermally robust and effective water repellent in order to prevent water absorption for applications in the steam distribution market. The nature of most of these applications renders them quite susceptible to equipment failure due to accelerated corrosion under insulation (CUI). It has been shown that insulation materials that readily wick and absorb moisture can significantly accelerate CUI failures leading to costly equipment shutdowns and repairs for the customer.

Aspen Aerogels has imposed stringent specifications for water uptake for Pyrogel XT in order to provide the customer with a robust insulation solution that provides unsurpassed protection against CUI. This level of water repellency is typically assessed according the methods outlined in ASTM C1511, which essentially affords a measure of water absorption after submerging the material in liquid water for 15 minutes. As evidenced by the data shown in Table 1, Pyrogel XT exhibits water repellency superior to that of all other competitive insulation when tested under these conditions.

Table 1: Water repellency per ASTM C1511 of Pyrogel XT in comparison to competitors.

	Average Water Uptake per ASTM C1511 (wt%)
Pyrogel XT	5
Mineral Wool	1100
Calcium Silicate	350
Perlite	8

An unfortunate consequence of imposing stringent guidelines for water repellency in Pyrogel XT is that a minimum level of water repellent additive must be incorporated during the aerogel manufacturing process. Therefore, the aerogel component of Pyrogel XT will always contain a minimum quantity of organic species (i.e. water repellent) that will readily oxidize or burn-out during higher temperature applications. Taken alone, the aerogel component of Pyrogel XT unfortunately contains enough organic content to render it combustible according to the Euroclass reaction-to-fire classification. However, Pyrogel XT is a composite that was specifically reinforced with a moderately dense (6 lbs/ft^3) non-combustible fiber reinforcement. The use of this fiberglass non-woven material effectively dilutes the fuel content of the parent aerogel and allows the material to achieve a non-combustible classification (i.e. Euroclass A2). Although this strategy provides the customer with a non-reactive thermal insulation, suitable for use at high temperatures, it also significantly dilutes the overall opacifier concentration for the material. It can also been shown that the use of dense fiber reinforcements in aerogel composites increases heat transfer via solid conduction pathways, leading to an increase in thermal conductivity at lower temperatures. It is evident that the stringent guidelines imposed for water repellency for Pyrogel XT combined with an unwavering commitment to provide a safe insulation material, effectively limit the thermal performance of this composite across its entire temperature range.

One of the main goals of this project was to explore the feasibility of adopting less stringent water repellency criteria for industrial aerogel insulation in order to provide greater flexibility in optimizing both the fiber reinforcement and aerogel formulation. Removing the impediment of achieving non-combustibility (via dilution with higher weight fiber reinforcements) will allow for the exploration of a wider variety of fiber reinforcements, possibly resulting in greater increases in opacifier concentration and subsequent improved high temperature thermal performance for the material. One of main focuses during this effort was to determine the optimal fiber chemistry, weight and diameter for the reinforcement in Pyrogel HT after a complete optimization of hydrophobe content.

3.1.3. Aerogel Insulation and Dust Mitigation

Increases in opacifier content, although highly effective in improving thermal performance, typically result in materials that exhibit a significant degree of dust evolution upon handling or installation. This unfortunate attribute results from the fact that the additives are not an integral part of silicate aerogel backbone. Materials containing increased opacifier content exhibit reduced cohesiveness, leading to the observed dusting behavior. This behavior is more than just an annoyance to the insulation contractor, as excessive loss of aerogel material from the composite can reduce material thermal performance significantly. An intriguing solution to contain the dust is to surface coat the aerogel composite after production to impart a smooth elastomeric film on both sides of the material. Aspen Aerogels has successfully implemented this strategy to mitigate the dust evolution from two of its other commercial insulation products (Figure 5). These aerogel products are coated at our East Providence production facility and are currently sold into the marketplace. The coating that is utilized possesses a significant amount of organic content and is unfortunately not suitable for use for high temperature products due to increased flammability and combustibility.

Figure 5: Dust evolution after handling Spaceloft 6250 uncoated (left) and coated (right).

An alternative solution to this problem arises out of the technology developed for asbestos abatement and containment. One of the last steps in the removal of asbestos insulation typically involves the application of lock-down coating or encapsulant on piping and equipment to prevent hazardous particles from becoming airborne. The effectiveness of these coatings to suppress dust is attributed to the formation of an elastomeric film. A large variety of these coatings have been specifically formulated to be meet certain non-combustibility criteria and have been rated for use on equipment operating at elevated temperatures[3]. These coatings, which are aqueous based and inexpensive, are ideal to suppress dust in high temperature aerogel insulation. During this effort, we took advantage of a large knowledge base of spray coatings and pre-existing equipment and infrastructure to explore the feasibility of this approach. Successful dust suppression will ultimately accelerate the adoption of the energy-saving technology developed on this program and will also serve to sustain high temperature thermal performance after extreme handling and installation.

4. Results and Discussion

The overall program objective was to develop an aerogel-based industrial insulation, named Pyrogel HT, for use between 400°C and 650°C (750°F and 1200°F). Targeted initially at the needs of the thermal power generation market, Pyrogel HT has proven to be more efficient than incumbent materials, including Pyrogel XT, and will reduce thermal losses from piping and equipment.

The specific objectives of the program were:

1. Identification of Industry Specific System Requirements: The testing/measurement requirements for operational performance and workability of Pyrogel were identified and are listed in Table 2.
2. Laboratory-Scale Optimization: A three-pronged laboratory scale optimization of aerogel formulation was conducted. This exercise included a determination of optimal sol formula, a comprehensive evaluation of candidate infrared opacifiers and a selection of the ideal fiber reinforcement (type, weight and fiber diameter).
3. Plant-Scale Performance Validation: Aspen Aerogels has successfully scaled the laboratory optimized Pyrogel HT formulation at the pilot-line scale via the production of aerogel insulation rolls measuring 10’ x 3’ (Figure 16). A comprehensive performance validation of these materials was conducted after application of an appropriate dust coating. The Pyrogel HT material produced at scale was shown to be capable of meeting the performance goals outlined in Table 2.
4. Draft Technical Data Sheet: Based on the performance validation of pilot-scale production rolls, a two page technical data sheet for Pyrogel HT has been written and is presented in Figure 20.

The progress towards meeting all of these objectives is detailed below, broken down by specific task.

4.1. Identification of Industry Specific System Requirements

The development of materials for use in high temperature applications requires a detailed knowledge of the conditions that they are exposed to as well as the testing requirements desired for material specification by the installer or end user. During this effort, Aspen has worked with its industrial partner, Florida Power and Light, to establish design goals and material requirements for Pyrogel HT. Investigations into the use of aerogel based insulation blankets for this particular market identified the following testing/measurement requirements for operational performance and workability (Table 2). The end result of this effort ultimately resulted in a preliminary set of design goals that served to guide the laboratory scale optimization of the formulation for Pyrogel HT.

Table 2. Property/Specification Targets for Pyrogel HT.

Test Spec	Description	Target
ASTM E84	Flame Spread and Smoke	FSI < 25, SDI < 450 (Class A)
ASTM C177	Thermal conductivity	≤45 mW/m-K at 500°C
ASTM C356	Thermal Shrinkage	<2.5%
ASTM C871	Chemical Analysis	Pass according to requirements of ASTM C795
ASTM C692	Stress Corrosion Cracking	Pass according to requirements of ASTM C795
ISO 1182	Non-combustibility	A2 Rating
ASTM C1511	Hydrophobicity	< 30 wt%

4.2. Laboratory-Scale Optimization of Pyrogel HT

Optimization of Sol and Hydrophobe Content. Work during this program was initially focused on determining the minimum levels of water repellency necessary for the proposed application. In particular, a number of Pyrogel HT prototype formulations were prepared with various levels of hydrophobe agent and were evaluated for heat of combustion and hydrophobicity (i.e. water uptake). Shown in Figure 6 are the heat of combustion and water uptake values as a function of relative hydrophobe content for a series of Pyrogel HT prototypes. This data clearly suggests that mild reductions in total fuel content can be achieved by reducing the relative hydrophobe content in Aspen's baseline product chemistry. This improvement is unfortunately concurrent with a significant increase in water uptake to levels at or above 20 wt%. The increased water uptake for these materials also resulted in a mild degradation of thermal conductivity (+15%) presumably from poor supercritical CO_2 extraction efficiencies. It was determined that ideal sol formulation for Pyrogel HT will involve only a slight reduction in hydrophobe content. This reduction will ensure that the Pyrogel HT material will meet the specifications for heat of combustion for Euroclass A2 reaction-to-fire classification (<717 cal/gram).

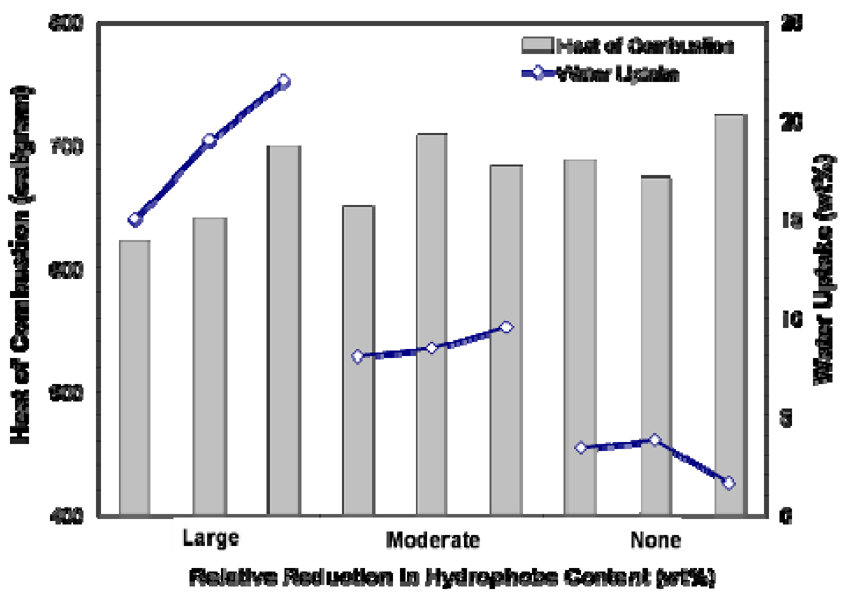


Figure 6. Heat of combustion, water uptake vs. hydrophobe content for Pyrogel HT.

Fiber Reinforcement Type and Weight. Work during this effort has focused primarily on the optimization and qualification of high temperature battings as possible reinforcements for the proposed Pyrogel HT material. Cost constraints limited the composition of these reinforcements mainly to E-glass based fibers, high temperature fibers such as alumina, silica or aluminosilicate are presently cost prohibitive for mass-scale production of aerogel composites. This work was focused mainly on the effects of fiber volume fraction (i.e. bulk fiber density) and fiber diameter on high temperature thermal performance. Thermal performance evaluation solely on needlepunched non-wovens has indicated that radiative thermal conductivity, the main mode of heat transfer at high temperature, is directly proportional to fiber diameter and indirectly proportional bulk fiber density[4]. Particular attention during this effort was paid to the use of non-combustible fiber reinforcements with bulk densities in excess of 6 pounds per cubic foot (PCF) and the use of fiberglass reinforcements with fiber diameters of less than 9 microns.

Shown in Figure 7 are the thermal conductivity curves for high temperature aerogel composites reinforced with fiberglass reinforcements with various bulk densities ranging from 6.0 to 10 PCF. Two distinct conclusions were made based on these measurements: (1) the thermal conductivity of aerogel composites appear to be directly proportional to fiber densities at temperatures below 200ºC and (2) the divergent slopes of the TC curves for 6.0 and 6.5 PCF composites suggests that a "crossover" in thermal performance could occur at temperatures exceeding 300ºC. The latter point is consistent with the literature[4] which suggests that radiative thermal conductivity, the main mode of heat transfer at high temperatures, is directly proportional to fiber density. The former point results from the fact that at lower temperatures the contributions from convective and conductive heat transfer to total thermal conductivity is significant. Increased fiber density naturally increases conductive heat transfer through the composite by providing for more pathways for heat transfer. As the temperature of the application increases, the contribution of solid conduction to total thermal conductivity decreases significantly.

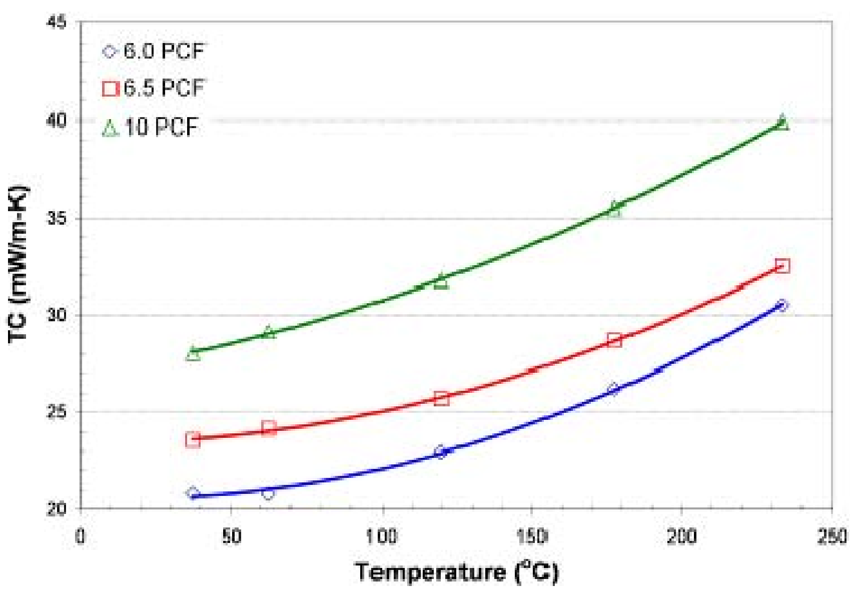


Figure 7. Aerogel thermal conductivity versus temperature for varied fiber densities.

During this program, we explored the effects of fiber diameter on the thermal conductivity of fiber reinforced aerogel composites. Shown in Figure 8 are scanning electron microscope images of the reinforcement used in Pyrogel XT compared to those studied for possible use in Pyrogel HT. It is clear from these images that the diameter of the fibers used for Pyrogel XT is significantly increased relative to the fiber reinforcements intended for Pyrogel HT. According to the literature, this effective decrease in average fiber diameter should lead to improved thermal performance for the Pyrogel HT materials.

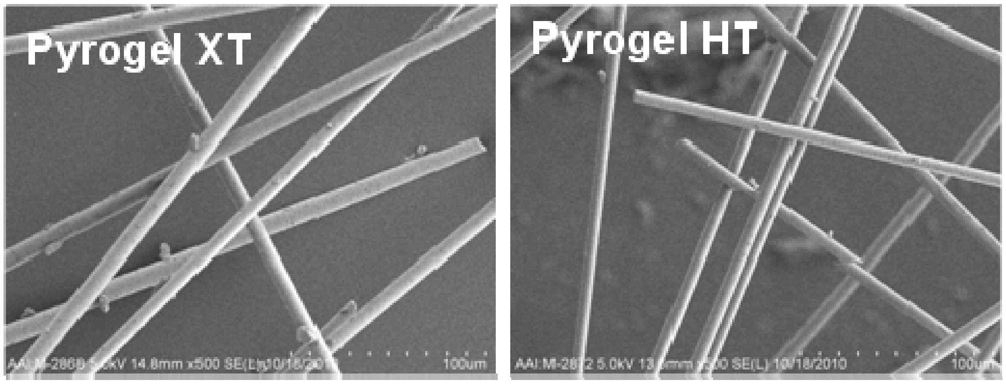


Figure 8. SEM micrographs of fiber reinforcement in Pyrogel XT (left) Pyrogel HT (right).

Specifically, the thermal conductivity as a function of temperature was determined for equivalent material prototypes prepared with 6 PCF fiber reinforcements possessing fiber diameters of 6 and 9 microns (Figure 9). In lieu of waiting for the completion of down-selection of opacifier material, these materials were prepared using the current formulation of Pyrogel XT at an equivalent aerogel target density and thickness. For all intents and purposes, both materials are equivalent except for a difference in the fiber diameter of the non-woven reinforcement. The data shown in Figure 9 clearly show that the use of lower diameter fiberglass resulted in significant thermal conductivity improvements at both low and high temperatures. In fact, the percent improvement in thermal conductivity appeared to increase as a function of temperature, consistent with the theory that the increased surface area of lower diameter fibers is more effective in scattering infrared radiation[4]. At the temperatures typically encountered in power processing applications (400 ºC -650ºC), it is evident that one can improve thermal performance by 15-25% solely by using a lower diameter fiber glass as reinforcement.

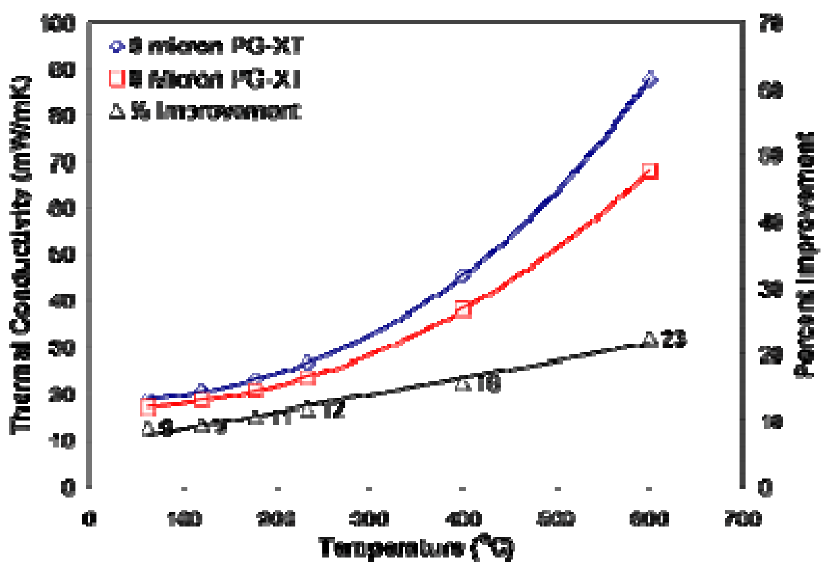


Figure 9. Pyrogel XT thermal conductivity versus temperature for 6 & 9 micron fiber.

Opacifier Type and Content. During this project, Aspen Aerogels examined the feasibility of using three distinct sources of infrared opacifiers in Pyrogel HT. For reporting purposes, these three chemically distinct materials are denoted as Candidate I, II and III. The selected materials are commercially available in median particle sizes ideal for scattering infrared radiation (2-8 microns). It is expected that the use of these materials at an optimized loading in Pyrogel HT will result in a significant reduction in thermal conductivity values relative to Pyrogel XT at temperatures exceeding 400ºC.

The first step in selecting the correct opacifier chemistry involved the execution of a comprehensive manufacturing feasibility study. The primary goal of this study was to determine the extent of particle agglomeration exhibited by the candidate opacifiers when subject to the pH changes encountered during the production of aerogel materials. Table 3 lists the candidate opacifiers, their respective refractive index and median particle diameters studied during this effort. Confirmation of respective particle sizes via laser diffraction and scanning electron microscopy was also conducted for Candidate opacifiers I, II and II during this project. The conclusion from this work was that all three opacifier materials are largely appropriate for use in the manufacture of high temperature aerogel insulation.

Also listed in Table 3 is the necessity of pigment surface coating to keep them well dispersed in alcohol during aerogel manufacture. Work during this program has indicated that opacifier materials possessing isoelectronic points within the range of pH values utilized during aerogel manufacture (pH 2-10) can result in severe particle agglomeration and flocculation. This destabilization effect, which diminishes manufacturability and results in substandard aerogel material, can be avoided by surface coating the opacifier particles with a microscopic layer of organosilane. During this effort, we have determined that Candidate opacifiers II and III will need to be surface coated to prevent particle agglomeration and to enable manufacturing and scale-up.

Table 3. Opacifiers studied for potential use in Pyrogel HT.

Identifier	Refractive Index	Median Particle Diameter	Pigment Coating Necessary?
Candidate I	2.6	4.2 um	No
Candidate II	2.7	2.8 um	Yes
Candidate III	2.9	3.5 um	Yes
Candidate IV	2.9	5.5 um	No
PG-XT Opacifier	2.9	3.6 um	Yes

One of the major goals during this project was to perform a down-select on the opacifier of choice for use in Pyrogel HT. As such, we executed a fairly comprehensive thermal performance evaluation for all Candidate opacifiers at all feasible concentrations. Illustrated in Figure 10 are the thermal conductivity curves for Pyrogel HT prototypes prepared with all Candidate opacifiers at a fixed concentration of 15 wt%. It is clear from these results, that the opacifiers studied during this program are equal to or better than those used in Pyrogel XT with respect to thermal performance. For instance, Candidate II opacifiers exhibit a 15-20% improvement in thermal performance relative to those observed for Pyrogel XT. We have also found that this performance improvement holds well for all loadings up to 20 wt%, suggesting that the Candidate II opacifiers are the opacifier material of choice for use in Pyrogel HT.

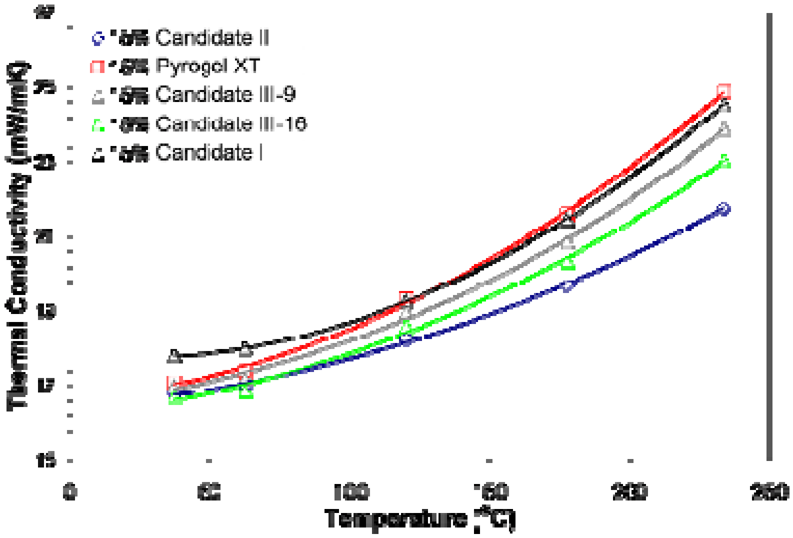


Figure 10. Pyrogel HT thermal conductivity versus temperature for varied opacifier types.

Figure 11 shows the thermal performance curves for the best performers within each Candidate type. These results suggest that each type of opacifier is capable of meeting the thermal performance targets for this program. However, Candidate II opacifiers appeared to be more effective on a per weight basis, necessitating only 15 wt% to meet the thermal performance targets. The use of lower opacifier concentrations is particularly attractive as it lowers product costs, simplifies the production process and results in a less friable and more durable product. For that reason, we elected to down select to Candidate II opacifiers for use in Pyrogel HT. It is important to note that the thermal performance curves in Figure 10 and Figure 11 were determined on prototypes reinforced with fiberglass non-wovens possessing an average fiber diameter of 9 microns. As described above, it was expected that the use of lower fiber diameter reinforcements will result in further decreases in thermal conductivity, imparting Pyrogel HT with unsurpassed thermal performance. During this program, we ultimately evaluated the performance of materials containing Candidate II opacifiers prepared with lower fiber diameter reinforcements (see Pilot Scale Validation).

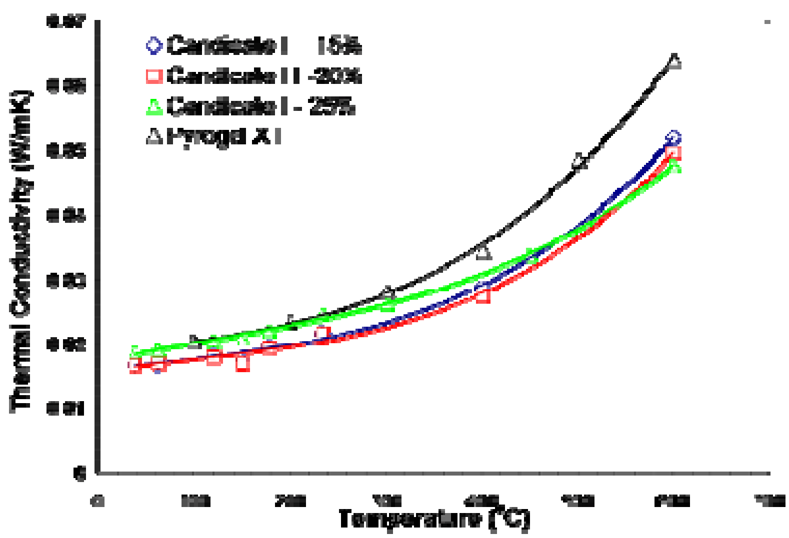


Figure 11. Pyrogel HT thermal conductivity versus temperature for top opacifiers.

Dust Mitigation via Coating. One of the goals of this program was to significantly increase the handling and durability of the proposed aerogel insulation by applying low levels of non-combustible encapsulants to the material after production. The main goal of this effort is to determine the effects of coating on overall dust evolution, thermal conductivity, corrosivity, non-combustibility, thickness and density at a variety of coat weights.

During this program, Aspen Aerogels coated a number of manufactured Pyrogel XT (10mm) materials at various coat weights using dilute Serpiflex (W.R. Grace) as a coating material. Serpiflex is a low-cost polyacrylate emulsion with high filler content and is typically used in asbestos lockdown applications. Because many lockdown applications typically involve in-service equipment, the dried coating is developed specifically to be inflammable and non-combustible. It is well suited in dust mitigation applications for friable insulation materials such as Pyrogel HT. Various samples were coated on both sides using direct application methods to target the following coat weights (per side): 10, 20, 50, 80, 125 g/m^2 (Figure 12, left). At all coat weights except for 125 g/m^2, the resulting change in thickness is negligible and near zero (Figure 12, right).

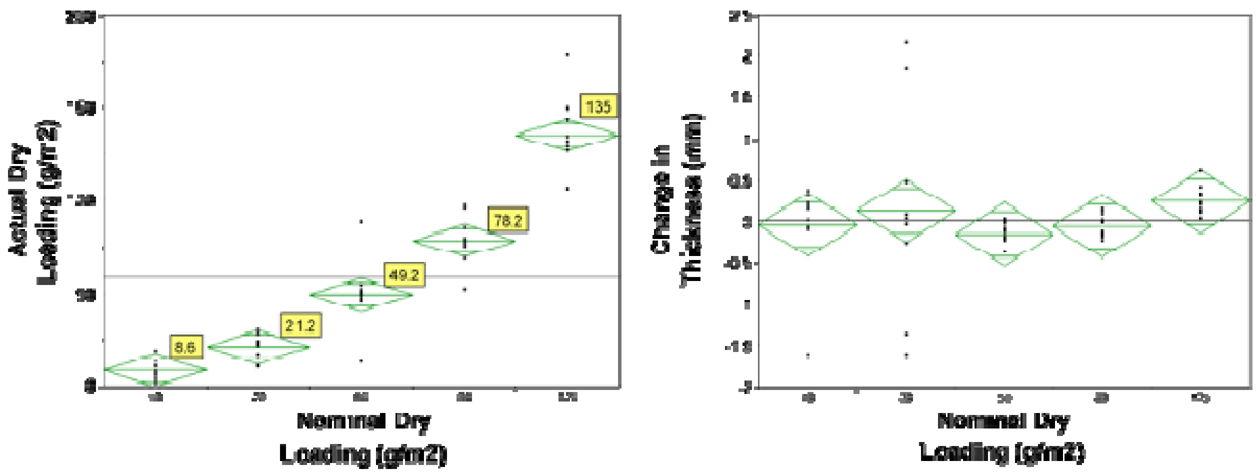


Figure 12. Coat weight versus nominal loading (left) and change in thickness (mm)

Although dried Serpiflex coatings are designed to be inflammable and non-combustible, they do contain a substantial quantity of organic content. Heat of combustion testing (ISO1716) indicated that these dried coatings exhibit a fuel content of ~2350 cal/gram. In order to maintain Euroclass A2 reaction-to-fire classification for the proposed insulation material it was vital to achieve significant dust reductions at a minimum coat weight. Excess coat weights are likely to result in an aerogel composite that exceeds the Euroclass A2 specification of 717 cal/gram as measured by ISO1716 test methods. During this program, we have utilized a standardized measurement protocol aimed at affording a precise and quantifiable measure of dust evolution for aerogel blankets. This protocol and the associated test apparatus were developed internally at Aspen Aerogels. The key to this test method is the measurement of dust content within a contained volume upon application of flexural stresses. Flexure was chosen as the pertubation method of choice as it closely resembles the typical handling of the proposed material in the field (i.e. cylindrical pipe or boiler applications). Measurement of dust concentration was conducted over the course of 10 flexure cycles using a laser-photometer based aerosol monitor. Outcomes were taken as the average of dust concentration (mg/m^3) over the course of ten flexure cycles.

Dust concentrations for highly friable blankets typically fall off precipitously after ten flexure cycles, rendering further measurement superfluous. Shown in Figure 13 are the as-determined dust loads as a function of nominal coat weight for Pyrogel XT samples coated with Serpiflex. The data indicated that as-manufactured Pyrogel XT exhibits a highly variable and large quantity of dust upon flexure. Interestingly the data also suggested that minimal coat weights as low as 10 g/m^2/gram (per side) are highly effective and result in a near 10-fold reduction in dust concentration in comparison to uncoated materials. The improvements in dust evolution at coat weights in excess of 10 g/m^2 were essentially negligible and would likely come at the cost of reaction-to-fire (i.e. non-combustibility) performance.

As discussed above, excessive coat weights are likely to impact the non-combustibilty of the aerogel composite. We have conducted ISO1716 (bomb calorimetry) testing of the coated aerogel composites to determine the impacts of coat weight on heat of combustion As shown in Figure 14, it is clear that nominal coat weights of greater than 50 g/m^2 (per side) will render these materials noncompliant with the specifications outlined in EN13501 for Euroclass A2 classification (HoC < 717 cal/gram). Fortunately, the dust evolution tests outlined above indicated that coat weights as low as 10 g/m^2 (per side) are necessary to achieve a significant dust reduction. It is highly likely that coated Pyrogel HT composites will exhibit reduced dust evolution and still maintain Euroclass A2 compliance.

Coated samples were also subject to thermal conductivity testing at 37.5ºC via ASTM C518 methods (heat flow meter). The data illustrated in Figure 15 indicate that at all coat weights a mild to moderate degradation of thermal properties is observed. At the minimum coat weight of 10 g/m^2, an increase thermal conductivity of nearly 1 mW/mK was observed. Although this increase is likely to become negligible at higher temperatures, this data coupled with the lack of change in thickness suggests that a microscopic and sacrificial layer of aerogel is destroyed and/or degraded upon coating application.

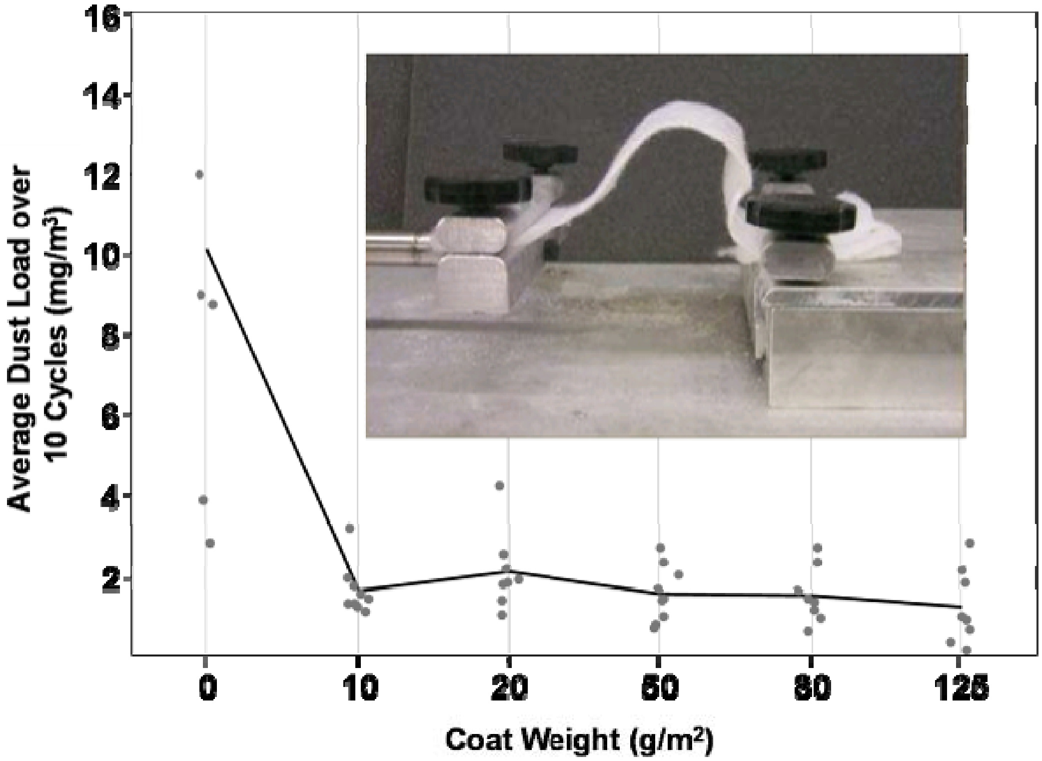


Figure 13. Dust load versus coat weight for Pyrogel XT samples. Inset: Test apparatus.

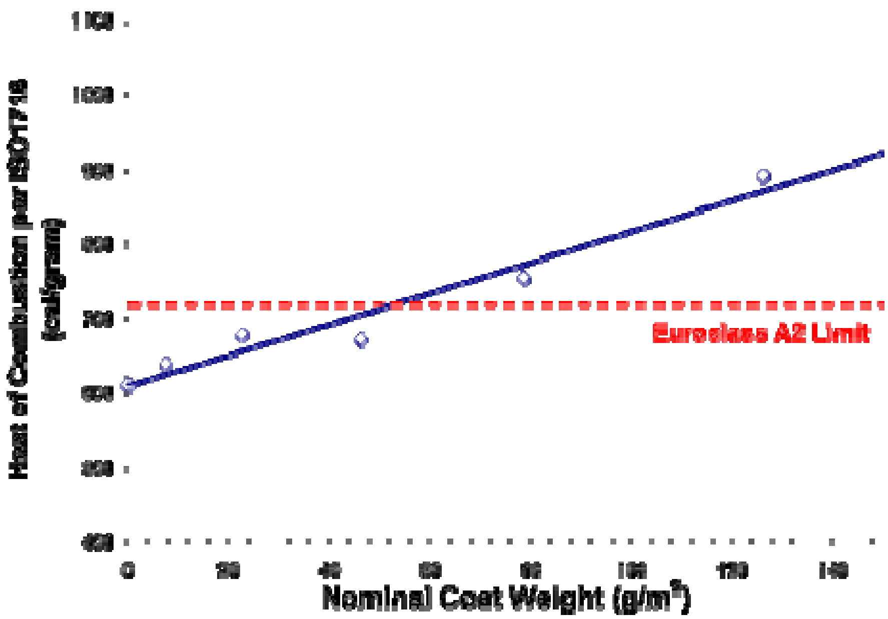


Figure 14. Heat of combustion versus coat weight for Serpiflex coated aerogel samples.

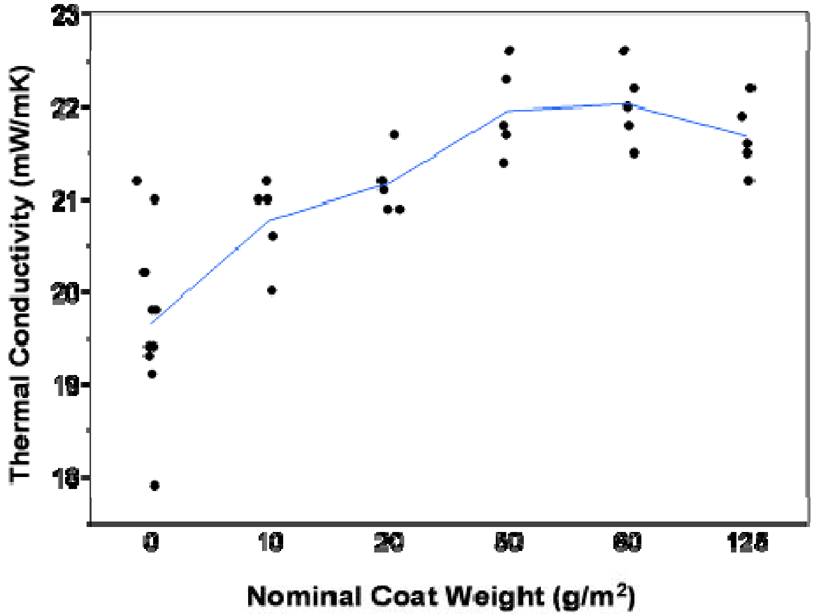


Figure 15. Thermal conductivity versus coat weight for Serpiflex coated aerogel.

4.3. Pilot-Scale Performance Validation

Pilot-Plant Scale Validation of Optimized Product Formulation. The above outlines a successful effort in identifying the correct sol formulation, opacifer type, opacifier content, batting type and batting density for Pyrogel HT in order to meet the performance criteria listed in Table 2. Shown in Table 4 are the key attributes of this design. During this effort we completed a design verification aimed at validating the performance of this optimized product. We have successfully scaled the Pyrogel HT formulation at the pilot-line scale via the production of aerogel insulation rolls measuring 10' x 3' (Figure 16). The performance validation of these materials was conducted with material produced at scale after application of an appropriate dust coating as described above. The following is a summary of test results from this performance validation, indicating that this project has been largely successful in developing Pyrogel HT materials capable of meeting the performance goals outlined in Table 2.

Table 4. Product design for Pyrogel HT.

Product Attribute	Value	Comment
Fiber Type	Fiberglass	Necessary to meet reaction-to-fire classification of A2
Hydrophobe Content	Moderate	Slight reduction relative to Pyrogel XT.
Opacifier Type	Candidate II	Highly effective at low concentrations.
Opacifier Content	15 wt%	Content sufficient to meet thermal performance.
Corrosion Mitigant	Same as Pyrogel XT	Meet corrosion criteria outlined in ASTM C795.

Figure 16. Pilot-line scale production of the Pyrogel HT insulation.

Thermal Conductivity via ASTM C518. Thermal conductivity values for the Pyrogel HT roll were determined according to a transient step-heating methods developed by Thermophysical Research Laboratories (TPRL). The accuracy of was confirmed by performing identical measurements using calibrated steady-state measurements (ASTM C518) at lower temperatures. The data shown in Figure 17 clearly indicate that the Pyrogel HT prototypes developed during this project outperform the current Pyrogel XT incumbent. These prototypes exhibited a thermal conductivity value of ~39 mW/mK at 500ºC, surpassing the goals for thermal performance outlined in Table 2, and represents a near 40% improvement relative to Pyrogel XT. This vast improvement in thermal performance, embodied in a low-dust and highly durable industrial insulation, that will undoubtedly allow for a significant reduction in energy expenditures for energy-intensive high temperature applications such as power generation.

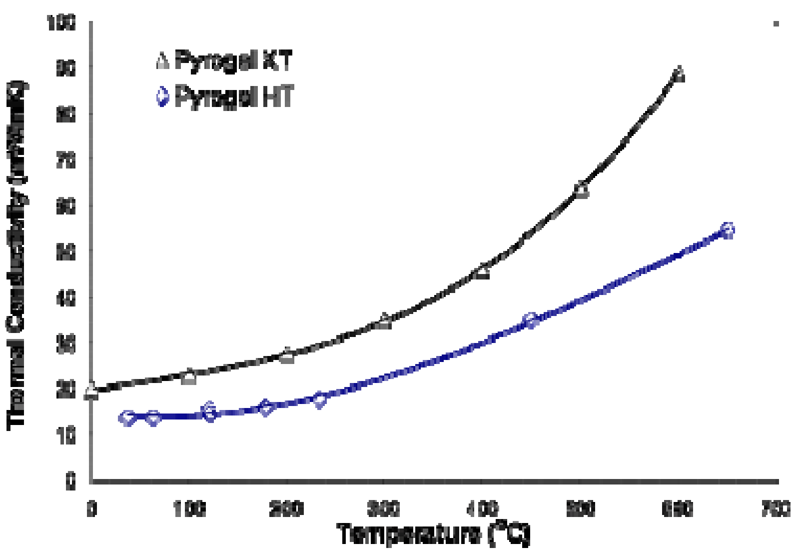


Figure 17. Thermal conductivity profiles for Pyrogel XT & HT.

Thermal Shrinkage via ASTM C356. The average linear shrinkage under soaking heat at 650 ºC was determined according to the test methods outlined in ASTM C356. The data illustrated in Figure 18 indicate that the Pyrogel HT roll produced during this project exhibited a slightly elevated thermal shrinkage in comparison to Pyrogel XT. Although there is no pass/fail criteria in ASTM C356, it is an accepted industry standard for thermal insulation to exhibit no more than 2.5% linear shrinkage while in use. The elevated shrinkage exhibited by Pyrogel HT could be a result of using fiber reinforcement with diminished tensile strength. Although work during this project was largely successfully in determining the optimal fiber diameter and weight for fiber reinforcements in Pyrogel HT, much work remains in producing a durable non-woven mat for use as reinforcement. It can be shown that the mechanical strength of these non-wovens is highly dependent on the extent of fiber entanglement. For fiberglass non-wovens, this entanglement is typically derived from a traditional needle-punch process, with variables such as needle density, needle type and needle punch frequency affecting the mechanical nature of the reinforcement. Improvements in the strength of Pyrogel HT could likely be achieved via a further engagement of batting vendors to improve the strength of fiber reinforcements.

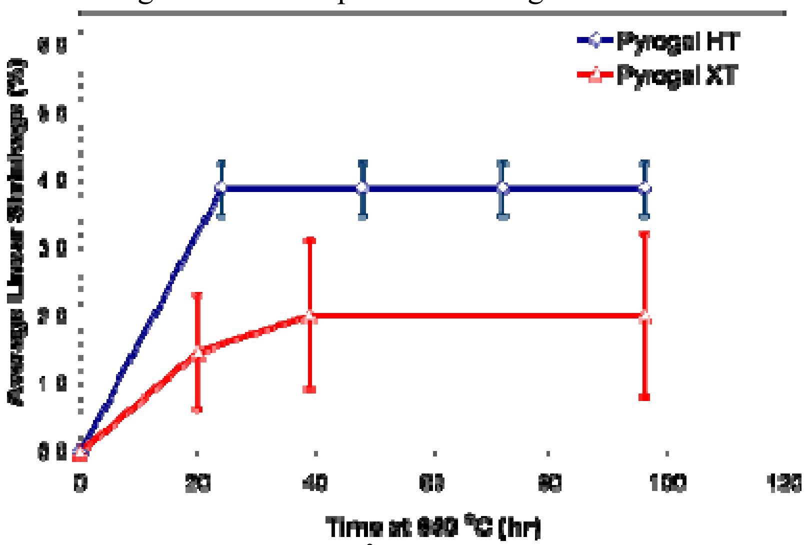


Figure 18. Average linear shrinkage at 650°C of Pyrogel HT in comparison to Pyrogel XT.

Tensile Strength via ASTM D5034. The average tensile strength of the Pyrogel HT prototypes was determined for a single ply of 10 mm material according to the methods outlined in ASTM D 5034, Standard Test Method for Breaking Strength and Elongation of Textile Fabrics. The average tensile strength for Pyrogel HT was determined to be 340 N in the machine direction and 210 N in the cross direction. Although these values are indicative of a fairly durable insulation material, they do represent a ~35% reduction in tensile strength relative to Pyrogel XT. This reduction in strength can likely be improved with further optimization of the fiber reinforcement as described above.

Compressive Strength via ASTM C165. The compressive resistance of Pyrogel HT was acquired according to the methods outlined in ASTM C 165. Specifically, the compressive stress at 10% and 25% strain for a single ply of Pyrogel HT was determined to be 29 kPa and 116 kPa, respectively. These values are slightly lower than that exhibited for Pyrogel XT, indicating that improvements in the mechanical strength of the fiber reinforcement is necessary prior to full scale commercialization of Pyrogel HT (see above).

Corrosivity via ASTM C871. In the event that liquid water penetrates an insulation material, it is important that that material maintain an aqueous chemistry within a specific pH range. Insulation materials with adventitious chloride anions and low pH values can significantly accelerate corrosion rates. To determine the quantity of extractable anions, Pyrogel HT was tested according to methods outlined in ASTM C871. Regions of unacceptable and acceptable anion quantities are described by the Karnes curve shown in Figure 19. The extractable ion results for Pyrogel HT indicate that this material falls within the acceptable region of the curve, indicating that this material will likely not contribute to corrosion under insulation (CUI). The extractable pH values for Pyrogel HT were determined to be 8.8, a value that is sufficiently alkaline to significantly retard the rate of corrosion.

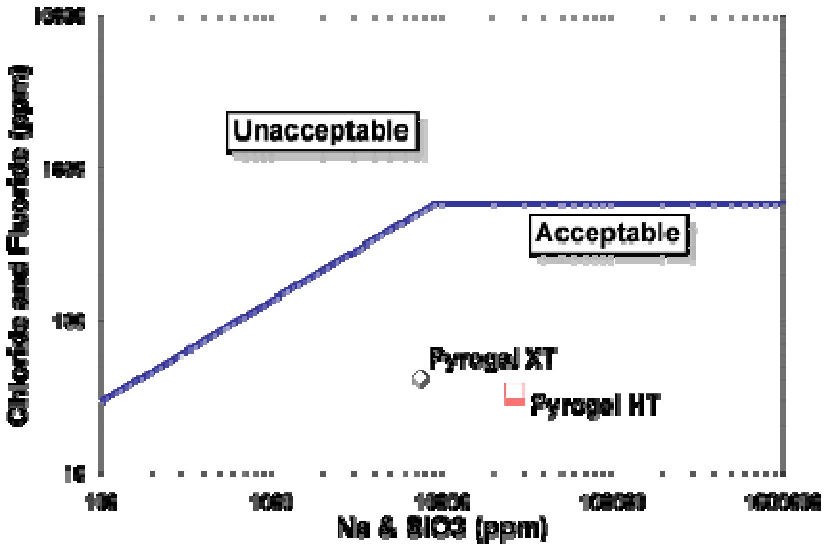


Figure 19. Extractable ion results (ASTM C871) for Pyrogel HT compared to Pyrogel XT.

Hydrophobcity via ASTM C1511. Corrosion is an electrolytic process that will not take place in the absence of moisture. It is highly desired for any industrial insulation material to be water repellent (hydrophobicity) at a wide range of application temperatures. The water retention of Pyrogel HT was determined according to the methods outlined in ASTM C1511. Specifically, the change in weight was determined for multiple samples after complete submersion in 6” of deionized water. Coated and uncoated Pyrogel HT samples exhibited water uptakes of 1.1 and 2.0 wt%, respectively. This value is comparable to those observed for Pyrogel XT and indicates that the material developed during this program is largely hydrophobic. These results compare well with that observed for Pyrogel XT, which exhibits a 3-4 wt% uptake when tested to the same standard.

Water Vapor Sorption via ASTM C1104. The amount of water absorbed upon exposure to high humidity conditions was determined via the methods outlined in ASTM C 1104. Specifically, Pyrogel HT exhibited an average weight gain of 4.2 wt% upon exposure to 95% RH at 49°C for 96 hours. Pyrogel HT easily meets the requirements for maximum water vapor uptake as outlined in ASTM C 547, the Standard Specification for Mineral Fiber Pipe Insulation (<5.0 wt%).

Non-combustibility via ISO1182/ASTM E136. The non-combustibility of conventional insulation materials such as mineral wool, perlite and calcium silicate is typically determined by observing their behavior when subjected to a heated vertical tube furnace at 750°C. This test method typically involves the determination of non-combustibility assessed according to certain criteria for mass loss, sample temperature rise, furnace temperature rise and duration of flaming. Samples of Pyrogel HT were tested according to methods outlined in ISO1182. The results indicated in Table 5 clearly indicate that Pyrogel HT exhibits reaction-to-fire behavior consistent with a Euroclass A2 classification. This particular classification is rated as non-combustible and is consistent with a material that will not exhibit excessive heat release and/or flame spread during a fire event.

Table 5. ISO1182 results for Pyrogel HT in comparison to those observed for Pyrogel XT.

Insulation (type)	**Sample Temperature Rise** (°C)	**Duration of Flaming** (seconds)	**Mass Loss** (wt%)
Pyrogel HT	35	0	4.8
Pyrogel XT	32	0	4.0
Euroclass A2 - P/F	<50	<20	<50

4.4. Preparation of Preliminary Technical Data Sheet

The above test results clearly indicate that the prototype Pyrogel HT materials produced at the pilot line scale meet the specific performance objectives for this program. Based upon these test results, Aspen Aerogels has drafted a preliminary technical data sheet for Pyrogel HT. The purpose of this exercise was to have a prepared concise list of material properties to accompany any developmental samples submitted to our industrial partner (Florida Power and Light) or any other potentially interested party.

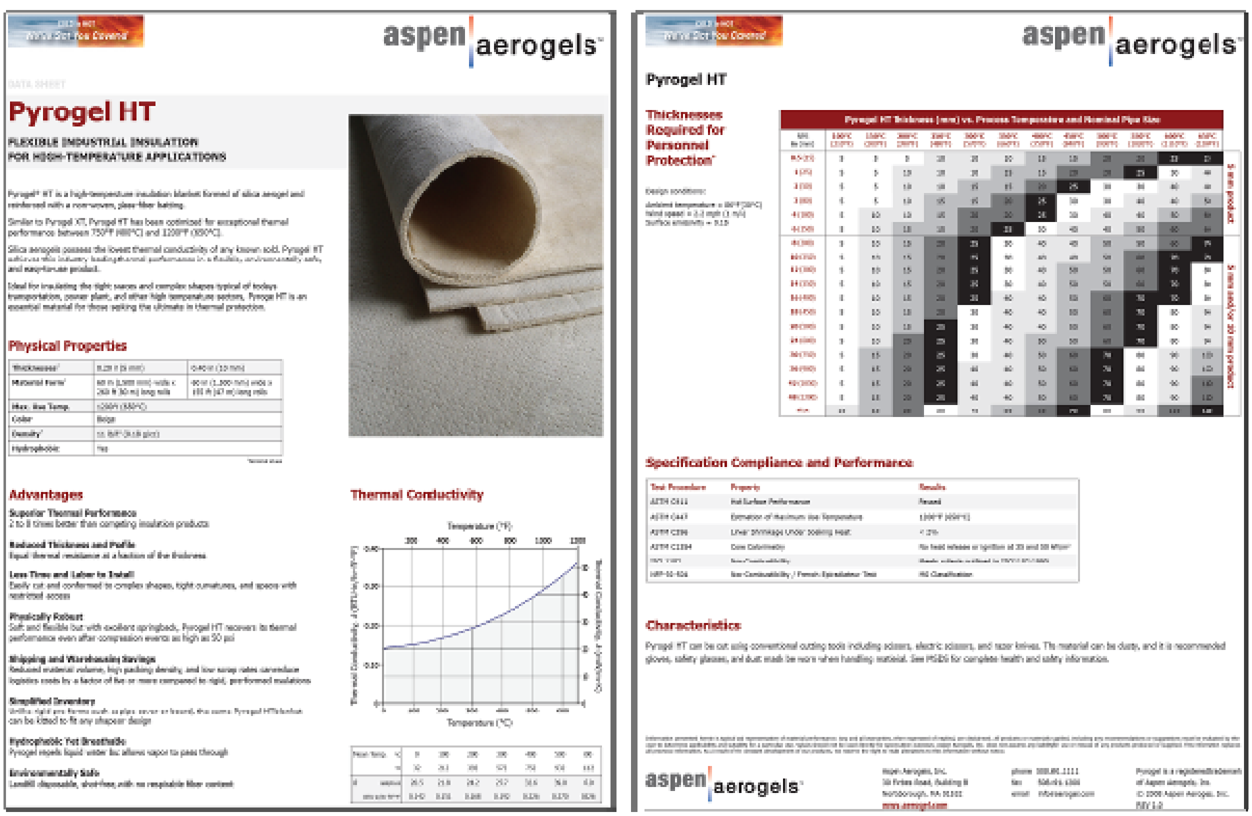
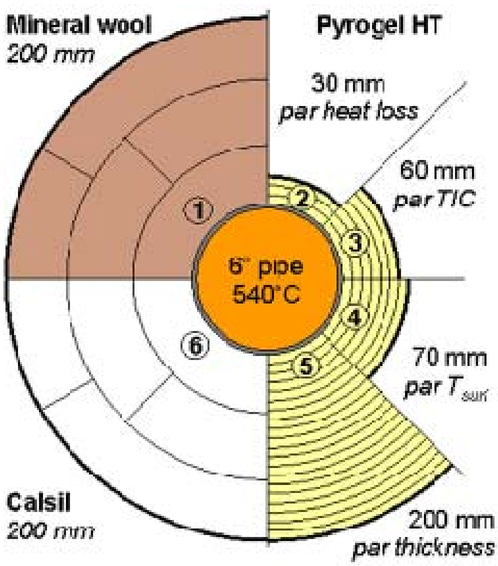


Figure 20: Pyrogel HT technical data sheet

5. Benefits Assessment

Any energy-saving technique or device must define a baseline level of energy usage against which its effects are to be measured. For Pyrogel HT, that baseline is mineral wool pipe cover. As shown in Figure 21, a typical power plant application would be the insulation of a 150 mm (6") high-pressure steam pipe operating at 540°C (1000°F). Modern insulation design standards would use around 200 mm (8") of mineral wool for an indoor application, or 200 mm of calcium silicate outdoors. The expected start-of-life heat loss for each of these systems (Q'_o) is shown in the table in Figure 21.



#	Insulation Material	Thk (mm)	T_{surf} (°C)	TIC ($/m)	Q'_o (W/m)	Q'_{AVG} (W/m)	Savings (MMBtu/m/yr)
1	Min. Wool	200	49.6	$430	238	476	-
2	Pyrogel HT	30	75.6	$212	235	187	7.2
3	Pyrogel HT	60	51.4	$433	137	137	10.1
4	Pyrogel HT	70	47.6	$510	122	122	10.2
5	Pyrogel HT	200	31.5	$1,677	62	62	12.4
6	Calsil	200	49.3	$580	234	468	-

Figure 21: Six insulation systems designed to different sets of requirements.

Also shown in Figure 21 are four different Pyrogel HT designs, each providing equivalence against one particular performance metric: 2) energy efficiency, 3) total installed cost (TIC), 4) touch temperature or 5) thickness. While any of these can come into play depending on specific customer requirements, experience has shown that designing on the basis of equivalent TIC is most representative of the market's aggregate behavior. First, it captures the prevailing sentiment that all facility managers want energy efficiency – so long as it doesn't cost them anything. Second, it is a good numerical "average" of the four possible design scenarios, and so is broadly representative of total savings. Taking this as the baseline performance comparison, expected energy savings can be quantified. This has been done for three distinct types of market opportunity: construction of new plants, retrofitting existing plants, and in situ repairs of degraded insulation systems. Each is described below.

5.1. Energy Savings in New-Build Facilities

On new construction, Pyrogel HT offers an automatic efficiency improvement over mineral wool because it offers greater performance for each dollar of capital spent (42% more thermally efficient for the case illustrated in Figure 21). Further, this advantage grows over time as the mineral wool's performance begins to degrade. Averaging over the lifetime of the insulation, the heat loss from the mineral (Q'$_{AVG}$ in Figure 21) can be assumed to be twice that of the initial design value, giving 60 mm of Pyrogel HT a 71% better lifetime thermal efficiency vs. 200 mm of mineral wool pipe cover with equivalent installation costs.

This same type of analysis has been applied to the entire inventory of piping in a typical new facility. In this case, that is Navasota Energy's 550 MW combined-cycle, gas-fired facility near Madisonville, TX.[5] Here, the plant-wide reduction in energy usage across all pipe sizes and process temperatures averages out to be 56%, for savings of 4400 MMBtu/yr. Because the installation of Pyrogel HT can be done for the same up-front cost as the less efficient mineral wool (about $800/sqm of pipe surface area), the delta-investment is zero and the ROI is infinite.

On a macro-level, the US has added new thermal generation capacity at the rate of about 2.2% annually, or 16 GW/yr. As each new plant brings another opportunity to upgrade designs to Pyrogel HT, the total scope for incremental energy savings is 8.0 MMBtu/year for each new megawatt of generation capacity designed around Pyrogel HT. Assuming a 12-year ramp to 65% market penetration, and accounting for the fact that energy savings compound year-over-year as more of the installed base is upgraded to higher efficiency materials, the savings are estimated to be 0.24 TBtu/yr by 2020 and 1.0 TBtu/yr by 2030.

5.2. Energy Savings from Retrofitting Old Facilities

The US installed base of power generation units (excluding non-fired energy sources like wind, geothermal, nuclear, and hydroelectric) has a median age of 33 years. Within this existing infrastructure lives a lot of damaged insulation that, on average, only gets upgraded once every 20 years (5% turnover rate). On the aforementioned 550 MW plant, the cost of removing the existing material and replacing it with Pyrogel HT should run about $170K, or $425/MW of generation capacity. Assuming $5/MMBtu energy costs, the resultant plant-level savings should be $22K/yr (averaging a 56% reduction in piping heat loss), producing an ROI of 13% and a payback of just under 8 years.

Rolling this up to the macro level, the potential scope for energy savings from plant retrofits is 5.9 TBtu/yr. Assuming a 10-year ramp to 50% market penetration, and accounting for compounded savings, Pyrogel HT should be reducing US energy consumption by 2.2 TBtu/yr in 2020 and 3.7 TBtu/yr in 2030.

5.3. Energy Savings from In Situ Repairs

In situ repair is an attractive option for many plant managers because it is effective, inexpensive, and does not require the line to be taken out of service to be worked on. For example, the case illustrated in Figure 22 would see an immediate savings of 35% by adding a single, 10 mm layer of Pyrogel HT. For $5/MMBtu energy, the annual savings would be $37 per meter of pipe insulated, while the installation cost would be $41/m. This equates to an ROI of 91%, or a simple payback of only 13 months.

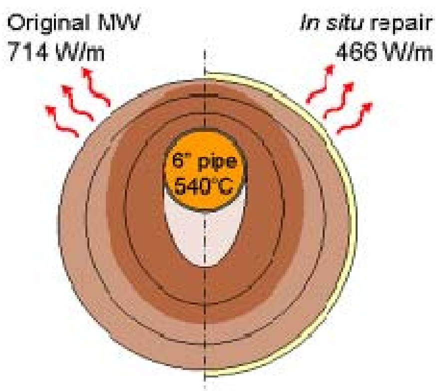


Figure 22: In situ repair with a single-ply overwrap of Pyrogel HT.

On the macro-scale, in situ insulation repairs could be saving nearly 1.2 TBtu/yr within the first 10 years. In situ repair with Pyrogel HT would be one of the fastest energy savings measures to gain traction because the economics are so attractive and the disruption so minimal.

5.4. Total Energy Savings and Economics

The complete rollup of expected energy savings is described in Figure 23. On the left is the expected progression of market share among power generation facilities on a per-GW basis. On the right is the expected rollout of annual energy savings for each of the three opportunities discussed above. In total, Pyrogel HT offers potential savings of nearly 5.9 TBtu/yr within just the power-generation market segment.

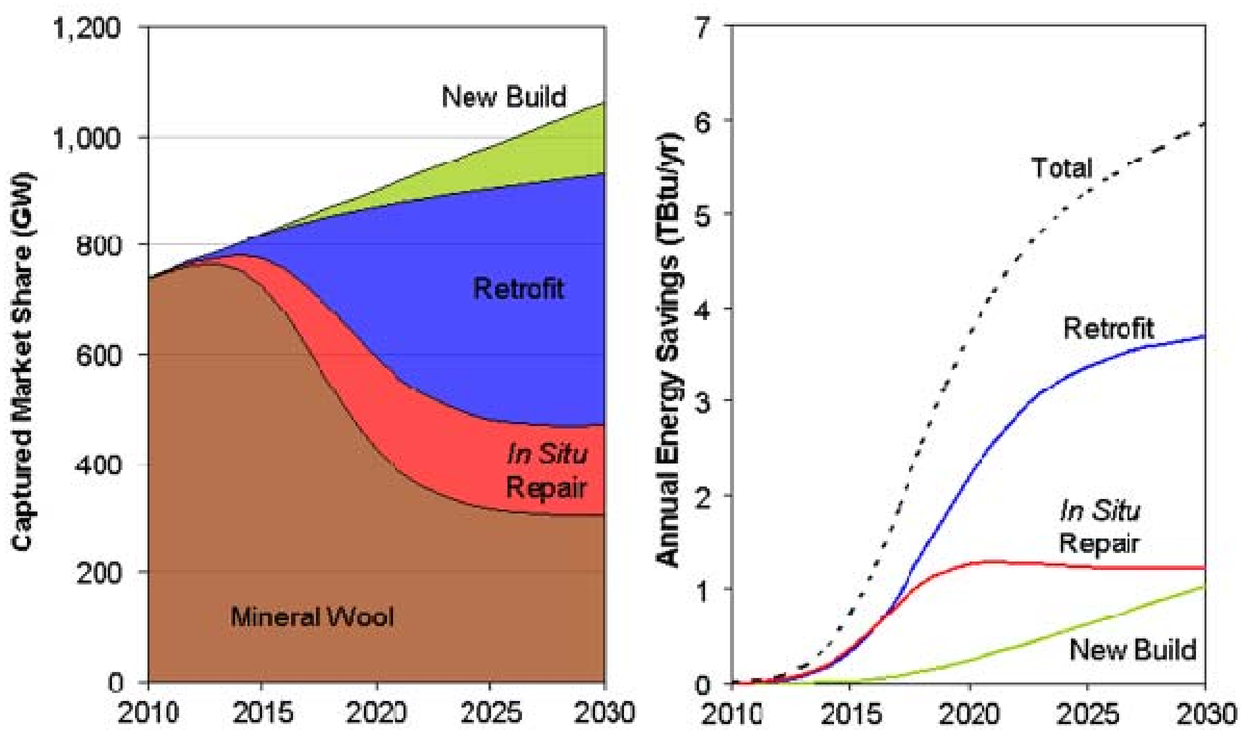


Figure 23: Anticipated energy savings in the power generation industry.

Cumulative sales of Pyrogel HT into domestic power plants should reach $125MM through 2030, eventually reaching about 10% of the total insulation market share in that space. Global energy savings would be expected to scale similarly. Over the same period, these sales would reduce domestic energy consumption by more than 65 TBtu. Upon branching out into all industrial processes in the 400°C -650°C regime, Pyrogel HT would reach annual sales levels of $150MM, with two-thirds of that being exported.

Table 6: Expected savings within just the US power industry.

Industrial Application (type)	**Energy Savings** (%)	**Typical ROI**[1] **(%)**	**Energy Savings by 2030 (TBtu/yr)**	**CO_2 Savings by 2030 (MMT/yr)**	**Pyrogel HT Sales Volume**[2] **($MM/yr)**
New Build	56	∞	1.0	0.10	1.8
Retrofits	56	13	3.7	0.37	4.3
In Situ Repair	35	91	1.2	0.12	1.4
Total	65	-	5.9	0.59	7.5

1. *ROI includes not just the cost of Pyrogel HT, but also the installation labor and accessory materials*
2. *Average sales volume from 2015 to 2030*

6. Commercialization

Commercialization of the innovation developed on this program has supported the ITP goal to drive a 25% reduction in industrial energy intensity. The project is aligned to the goals of ITP's Materials for energy systems portfolio – development and deployment of better insulation materials.

Pyrogel HT addresses a capability gap in insulation materials for temperatures between 400°C -650°C (750°F-1200°F). This range covers some of the most energy-intensive processes in industry today, including glass melting, metal casting, delayed coking, steam cracking, flue-gas treatment, ore smelting, and power generation, which is the first target market. Pyrogel HT provides a thinner, lighter, and more durable insulation. It is also quicker to install and cost less than current market leaders; mineral wool and calcium silicate. This combination of faster, better, and cheaper will enable a rapid market penetration and a fast rollout of the anticipated energy savings.

Aspen Aerogels has a world-class manufacturing facility that can produce small batches of developmental products in the most realistic environment possible: the actual manufacturing plant and process equipment used for full-scale manufacturing. In future efforts, this facility would be used to produce enough material for performance testing of the new insulation technology. The insulation would be installed on specific equipment in power plant utilities. The scope of work will include a representative quantity of piping (e.g., 50m) and associated elbows, flanges, valves, and support shoes, as well as the associated jacketing and accessory materials. Installation will be performed by a professional insulation contractor who will monitor labor productivity and document the total installed costs of each system. In-service insulation performance will be monitored over the course of the effort with thermocouples and infrared surveys. Periodic core sampling may be done to assess any long-term degradation of either material. Facility managers from Florida Power and Light will be surveyed to understand any operability, maintenance, or other in-service issues with either material. This data will be consolidated to provide relevant comparison of safety, reliability, and total cost of ownership of Pyrogel HT vs. mineral wool pipe cover. Using these updated figures, Pyrogel HT's macro-benefits will be reassessed, including domestic energy savings, CO_2 reduction, and increased exports. Upon successful completion and demonstration of the new insulation at full scale, the life cycle economic benefits will be attractive for utilities to save energy and reduce costs with Pyrogel HT.

Aspen Aerogels has a proven track record of working with the Department of Energy to develop and successfully commercialize insulation products. Developed under a similar program, Pyrogel XT has, within the first 15 months since its launch, resulted in over $10MM is sales while reducing domestic energy consumption by 0.163 TBtu. Pyrogel HT will build upon the success of Pyrogel XT by pushing the aerogel performance envelope to encompass applications between 400°C and 650°C.

7. Accomplishments

The overall project objective was to develop an aerogel-based industrial insulation for use between 400°C and 650°C (750°F and 1200°F), targeted initially at the needs of the thermal power generation market.

A new insulation formulation, Pyrogel HT, has been developed for low thermal conductivity between 400°C and 650°C. The thermal conductivity was improved by choosing an optimal opacifier to inhibit radiation heat transfer at higher temperatures; the opacifier loading was optimized for maximum effectiveness; and the batting fiber diameter was chosen to minimize conduction through the batting. A coating was also developed to ameliorate dust during handling and installation. Pyrogel HT exhibits a 40% reduction in thermal conductivity at 600°C as compared to Pyrogel XT.

8. Conclusions

This program has developed a new aerogel-based high temperature insulation, Pyrogel HT, which not only provides better efficiency and durability, but also the lowest installed cost per unit performance, enabling plant managers to achieve greater levels of energy savings for each dollar of capital spent. Although Pyrogel HT can be applied to a broad range of high-temperature industrial applications (e.g., glass melting, metal casting, delayed coking, steam cracking, flue-gas treatment, ore smelting), its initial deployment is focused on the US power generation market. Cumulative sales of Pyrogel HT into domestic power plants should reach $125MM through 2030, eventually reaching about 10% of the total insulation market share in that space. Global energy savings would be expected to scale similarly. Over the same period, these sales would reduce domestic energy consumption by more than 65 TBtu. Upon branching out into all industrial processes in the 400°C-650°C regime, Pyrogel HT would reach annual sales levels of $150MM, with two-thirds of that being exported.

9. Recommendations

Although significant progress has been made in identifying the correct aerogel chemistry, opacifier and batting type to obtain desired thermal performance, significant work remains in order to complete the development and full-scale commercialization of Pyrogel HT. The following work remains in order to fully support the commercialization and product launch of Pyrogel HT:

- Working with batting vendors to improve mechanical properties and cost of the fiber reinforcement.
- Optimization of opacifier grit size (i.e. particle size) in order to simultaneously meet thermal performance and non-combustibility goals.
- Working with toll-processors to effectively surface-treat opacifiers at a large scale.
- Further optimization of aerogel formulation to minimize organic content and to decrease the intensity of any material exotherms experienced in the field.
- Modification of batting and/or formulation to achieve a suitable fire rating when tested to UL1709.

To develop the product, a significant amount of work will involve a process development and process optimization in an effort to continue to lower overall production costs. Feasibility studies involving the combination of key unit processes (casting, aging, extraction) will be explored in detail. Materials will be produced for developing a low cost-high performance insulation that radically changes the industrial insulation marketplace. Performance trials will be conducted at industrial facilities owned by both American Electric Power and Florida Power Light. These demonstration projects will involve detailed temperature measurements in order to validate the projected energy savings stated in the Benefits Assessment.

10. References

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