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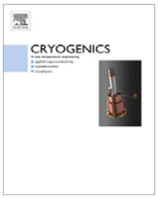

Spray-on foam insulations for launch vehicle cryogenic tanks

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ABSTRACT

Spray-on foam insulation (SOFI) has been developed for use on the cryogenic tanks of space launch vehicles beginning in the 1960s with the Apollo program. The use of SOFI was further developed for the Space Shuttle program. The External Tank (ET) of the Space Shuttle, consisting of a forward liquid oxygen tank in line with an aft liquid hydrogen tank, requires thermal insulation over its outer surface to prevent ice formation and avoid in-flight damage to the ceramic tile thermal protection system on the adjacent Orbiter. The insulation also provides system control and stability throughout the lengthy process of cooldown, loading, and replenishing the tank. There are two main types of SOFI used on the ET: acreage (with the rind) and closeout (machined surface). The thermal performance of the seemingly simple SOFI system is a complex array of many variables starting with the large temperature difference of 200–260 K through the typical 25-mm thickness. Environmental factors include air temperature and humidity, wind speed, solar exposure, and aging or weathering history. Additional factors include manufacturing details, launch processing operations, and number of cryogenic thermal cycles. The study of the cryogenic thermal performance of SOFI under large temperature differentials is the subject of this article. The amount of moisture taken into the foam during the cold soak phase, termed Cryogenic Moisture Uptake, must also be considered. The heat leakage rates through these foams were measured under representative conditions using laboratory standard liquid nitrogen boiloff apparatus. Test articles included baseline, aged, and weathered specimens. Testing was performed over the entire pressure range from high vacuum to ambient pressure. Values for apparent thermal conductivity and heat flux were calculated and compared with prior data. As the prior data of record was obtained for small temperature differentials on non-weathered foams, analysis of the different methods is provided. Recent advancements and applications of SOFI systems on future launch vehicles and spacecraft are also addressed.

1. Background

Spray-on foam insulation (SOFI) materials were first developed in the 1960s and included applications for the Saturn V moon rockets and subsequently the Space Shuttle [1,2]. From a volumetric viewpoint, all space launch vehicles consist primarily of large tanks to contain the propellants. For example, the Space Shuttle's External Tank (ET) is comprised of a forward liquid oxygen (90 K) tank of 141,000 gallons capacity and an aft liquid hydrogen (20 K) tank of 383,000 gallons capacity (see Fig. 1). These cryogenic propellant tanks and feed-lines must be thermally insulated to prevent or minimize, according to specific requirements, the condensation of air or the formation of ice and otherwise provide sufficient isolation from the ambient environment. The thermal insulation system is designed to meet three conjoined areas of requirements: safety, control, and flight performance. Safety aspects include the prevention of excessive ice formation or liquid air condensate that could present a debris hazard or an enhanced flammability problem. Control during pre-launch loading operations is of course vital for successful cooldown, tanking, stabilization, and replenishment within the time constraints of the mission. The insulation system provides the added benefit of reducing the continuous boiloff losses of the cryogenic propellants. Flight performance requirements include thermal protection of the vehicle tanks from radiant heating or aerodynamic effects.

Other cryogenic tank insulation materials used in the past include rigid foams and cork. For some vehicles, the liquid oxygen tanks have been left bare; the insulation in this case is layers of frost from the humid air surrounding the vehicle on the launch pad. Cryogenic propellant loading operations can take from several hours up to around 12 h. Provision must also be made for unloading the vehicle due to a scrub and repeat loading at some later date. This thermal cycling is an important design parameter for the mechanical behavior of the insulation and must be carefully considered to avoid adverse consequences such as cracking or delamination from the tank wall.

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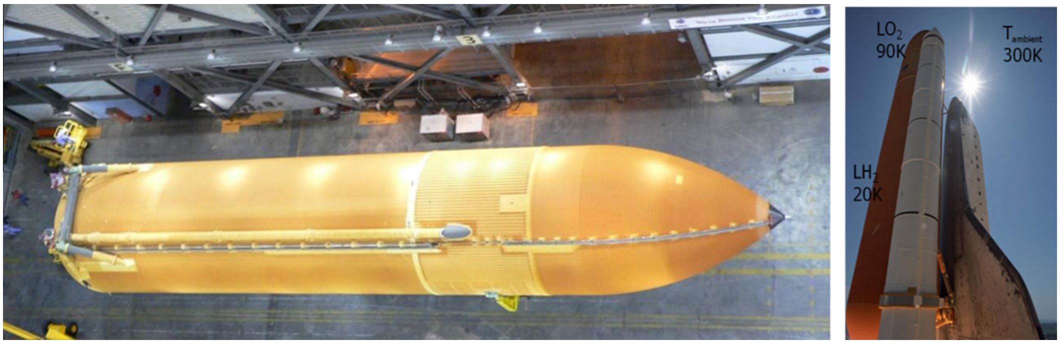

Fig. 1. A view of the Space Shuttle External Tank in the Vehicle Assembly Building (left) and in flight (right).

The objective of the tank insulation system is to reduce heat flux to acceptable levels while providing consistent performance at the least total system mass. Apparent thermal conductivity [*k*-value, mW/m-K] is the overall measure of the thermal performance per unit thickness of insulation material. The variations of apparent thermal conductivity (*k*-value) with cold vacuum pressure for different cryogenic insulation materials are shown in Fig. 2 [3–5]. The boundary conditions are approximately 293 K and 77 K and the residual gas is nitrogen. There are two main regions of interest for space launch and exploration applications: ambient pressure (non-vacuum) and high vacuum. Although the non-vacuum application is of primary interest, SOFI applications for in-space cryogenic storage are also of interest. In such cases where the cryogenic tanks are loaded on the launch pad, a composite system of materials that offers both non-vacuum and high-vacuum performance must be devised. Fig. 2 illustrates the extreme thermal performance difference between these two cases. Even though aerogel blankets may be twice as good as SOFI at the ambient pressure, the performance of a typical multilayer insulation (MLI) system is 100 times better [6]. However, MLI is not practical for use in an open ambient, humid-air environment while the aerogel blanket is fully hydrophobic and well-suited for such exposures [7]. Therefore, the proper design and selection of insulation materials depends strongly on the environmental parameters.

2. Introduction

The well-developed, modern spray-on foam insulation (SOFI) materials have an extraordinary combination of mechanical and thermal properties in addition to being light in weight. SOFI systems are generally produced from two-part mixtures of polyisocyanurate or polyurethane materials. The chemistries of the raw materials, catalysts, and reactions must be well understood to minimize physical and mechanical anomalies that can occur during the spray and curing processes [8]. The operating environment of a launch vehicle is a complex combination of thermal extremes, moisture, aerodynamic heating, aerodynamic and acoustic loads, mechanical loads, and a host of other inter-related factors. The cryogenic tank's thin layer of foam insulation is therefore subject to a number of potential structural problems. These problems may include substrate debonding, delamination between knit lines (intermediate layers), fragmentation or crushing, strength failure, aero-shear failure, fatigue, and foam loss due to rapid expansion of entrapped gases during heating [9]. However, the main

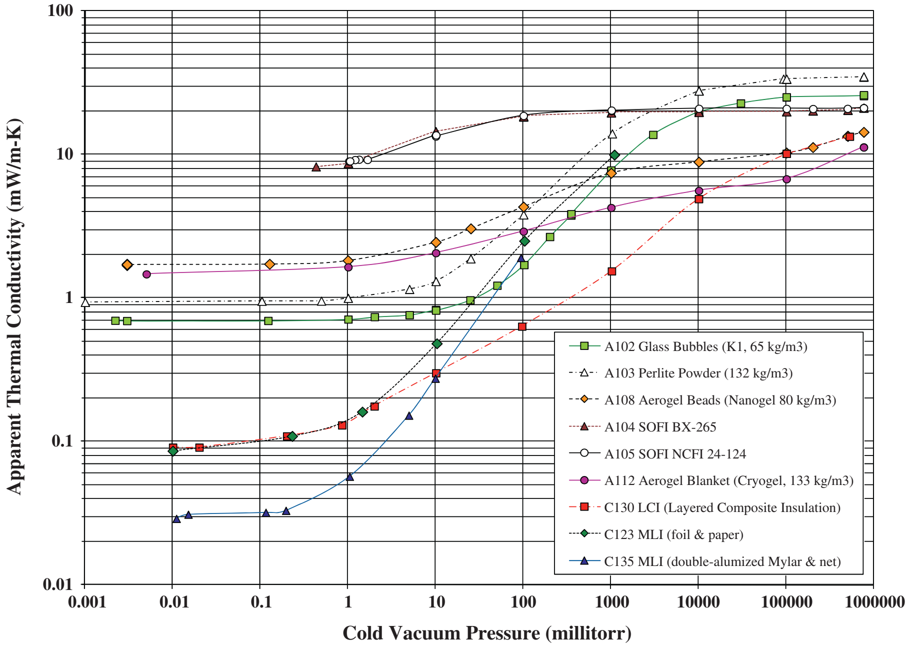

Fig. 2. Variation of apparent thermal conductivity (*k*-value) with cold vacuum pressure for different cryogenic insulation materials at the boundary conditions of approximately 293 K and 77 K (the residual gas is nitrogen).