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Thermal Protection Study of Cryogenic Tank Cars

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16. Abstract

This study was concerned with the thermal protection capability of insulation systems used on tank cars which are utilized in the transportation of hazardous materials at cryogenic temperatures. The heat sources in question are fires which the tank car may encounter if involved in a railroad accident. It was found that the most common insulation used is evacuated perlite powder. A number of thermal tests were conducted on perlite and several on a type of superinsulation. Two representative environments, described in Title 49 of the Code of Federal Regulations, Part 179.400 (as of November 83), were simulated in the test series. The perlite was tested without an imposed vacuum and the temperature behind the test specimen did not exceed 157 °C (314 °F) as measured by thermocouples which were protected by perlite throughout the test. Due to a bulge formation in the panel as a consequence of the extreme heat, the perlite level dropped and exposed the top thermocouples which measured very high temperatures. The superinsulation failed in the most severe environment, but performed better in the other. Evacuation improved the results for both types of insulation. Recommendations are presented for a continuation of the work with the goal being to achieve more definitive results.

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INTRODUCTION

The Ballistic Research Laboratory was under contract to the Federal Railroad Administration to study insulation systems. The objective was to study typical insulation systems used in the construction of tank cars that are capable of transporting materials at cryogenic temperatures. The study was narrowed to the evaluation of appropriate insulation systems with respect to their thermal response to typical environments which can exist in railroad accidents.

The literature was searched for information concerning characteristics of materials which are used in insulation systems for the storage and transportation of cryogenic materials. It appears that the most common insulation material used in the construction of tank cars is perlite powder, therefore this material was tested. In addition, several tests were perform on a type of superinsulation. It was decided that the insulation system of the tank car designed to transport liquid hydrogen would be a good choice to simulate because liquid hydrogen is transported at -127 °C (-423 °F) which is the lower part of the cryogenic temperature region.

Insulation panels, simulating the sandwich structure of the liquid hydrogen tank car, were tested in representative fire environments as defined in Reference 1. A torch fire facility, developed for this kind of thermal testing, was utilized in providing the appropriate environments. Temperature data obtained are presented with conclusions concerning the test results. Recommendations for work needed to reach applicable evaluation procedures are presented in the final section.

TYPES OF INSULATION

An excellent review of the insulations used in the storage and transportation of cryogenic materials is presented in Reference 2. The text in this section is in the main taken from that source. As pointed out in Reference 2, the type of insulation choosen for a particular use must depend on a number of practical considerations such as economy, convenience, weight, bulk, and ruggedness. These considerations are important in the railroad industry.

There are three mechanisms which control the level of heat transfer through insulations. One is thermal radiation which transports heat most effectively through a vacuum. The rate of heat lost by radiation is directly proportional to the emissivity of the surface and the fourth power of the surface temperature. Therefore, the greater the emissivity of a reflecting surface in an insulation and the lower the surface temperature, the better is the efficiency of the system. Another mechanism is the conduction of heat through the gas which has permeated the insulation. Conduction decreases in proportion to decreases in the gas density, therefore, losses through the residual gas are proportional to pressure (within limits). A third mechanism is conduction through solid material where heat losses are proportional to the conductivity of the insulating material and the area of contact between the insulation and support structures.

The types of insulation systems can be categorized with respect to the level of evacuation. Insulations used in nonevacuated systems include polyurethane foams, polystyrene foams, fiberglass phenolic honeycomb sandwich, corkboard, and balsa wood. Polyurethane foams are made in densities from 23.9 Kg/cu meter (1.5 lb/cu ft) to 318 Kg/cu meter (20 lb/cu ft) and range in cell configuration from a flexible or open cell to a rigid or closed cell. Polyurethane can be foamed in place using an appropriate nonomer (an unpolyerized form of a chemical compound) foaming agent as a catalyst. Closed-cell foams are relatively impervious to gas diffusion, but an airtight barrier on the surface of the foam is beneficial for preventing air condensation at the cold surface. Such a barrier has the added advantage of providing a partial vacuum in the insulation due to cryopumping action.

Polystyrene is a low-density, rigid closed-cell, foam. Polystyrene foam is usually received in bulk form from the manufacturer and machined to the desired shape. However, a process using granules of polystyrene and a blowing agent at a temperature of from 110 °C (230 °F) to 132 °C (270 °F) allows the substance to be foamed in place. Fiberglass phenolic honeycomb sandwichs with laminated fiberglass outer skins are not as effective, but have a superior load-carrying capacity. Therefore, an overall savings might be realized using the latter because a thinner tank skin can be used.

Corkboard and balsa wood have been found to be effective as an insulation, but their surface must be sealed to prevent air condensation; otherwise, their thermal conductivity values rise approximately 50%. The temperature maximums these insulations can safely be subjected to were found to be 593 °C (1,100 °F) for composition corkboard, 371 °C (700 °F) for balsa wood, and 232 °C (450 °F) for foamed corkboard. The surface of these materials become charred and blackened after exposure to these temperatures.

Examples of evacuated insulation systems include isocyanate and urethane foams, expanded perlite and santocel. Isocyanate and urethane foams have been evacuated from 1 to 50 microns pressure. Evacuation can reduce their thermal conductivity from one half to one third of their nonevacuated values. Styrene foams under evacuated conditions provides moderate improvement. Glass and silica foams shows no improvement. The isocyanate, urethane, and styrene foams can support a one-atmosphere load. However, the time necessary to evacuate is extremely long and high

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Ref. 1. Title 49, Code of Federal Regulations (CFR), Part 179 105-4 (as of November 1983)

Ref. 2 "Liquid Hydrogen Technology", Report No. AE62-0774, General Dynamics Astronautics, San Diego, California, September 1962 pumping rates must be continued to maintain the vacuum. For example, to achieve and maintain a 50-micron vacuum in styrofoam, a pumping speed of 5 cubic meters per minute per cubic meter (8.55 cu yd/minute/cu yd) was required and 40 hours were needed to obtain that evacuation value.

When a space containing a gas, say air, is filled with a low-density powder, the apparent thermal conductivity remains nearly equivalent to the thermal conductivity of the gas. However, there is a substantial reduction in the apparent thermal conductivity when the gas pressure is reduced to a value such that the molecular mean free path becomes comparable to the interstitial distances. That pressure is on the order of 1 to 0.1 mm of mercury (1.934×10^{-2} to 1.934×10^{-3} psi). Below 10^{-3} mm of mercury (1.934×10^{-5} psi), the rate of heat transfer is essentially independent of pressure. The mechanisms for heat transfer then are thermal radiation across the evacuated space and conduction through the powder. Heat transfer can be reduced further by a factor of approximately four by mixing with the basic powder a metal opacifier in the approximate weight ratio of one to one. An example of a metal opacifier is an aluminum powder. Such a configuration is relatively opaque to thermal radiation provided homogeneity is maintained to prevent a conductive short circuit. As a metal opacifier, no significant difference has been found between aluminum, silver, nickel and copper powders. Evacuated powder insulations have been used where their thermal effectiveness remained for many years without the need for a repeat of the evacuation process.

Perlite and Santocel are primary examples of materials which have been used as the basic substance in powder evaculated systems. Perlite is a low-density, low-cost powder that has been used successfully in insulating liquid hydrogen storage tanks. Santocel is a low density powder consisting of silica aerogel. It is a desiccant that can quickly remove water vapor from air.

The production and maintenance of a high vacuum takes precise manufacturing techniques and high-vacuum pumping equipment. Outgassing from the containing surfaces and diffusion of gases through the metal walls tends to destroy the vacuum. However, so called "getters" are often used which absorb residual gases. Liquid hydrogen temperatures helps to maintain the vacuum through a cryopumping action. Overall, it appears that high-vacuum transfer lines are too expensive and hard to maintain in the field. As an alternative, a condensable gas system has proven to be feasible. For example, the space between the inner and outer line can be filled with carbon dioxide which at liquid hydrogen temperatures solidifies and forms a vacuum in the insulating space. Such a system has been maintenance free for years after the initial installation.

Laminar insulations, referred to as superinsulations, derive their high impedance to heat flux from the effects of multiple radiation barriers. However, high vacuum is essential for this type of system since thermal conduction through the gas must be reduced to a minimum. The radiation barriers consist of foils of highly reflective metals separated by a nonconductor of thermal heat. Aluminum foil is normally used for the radiation shields. Aluminized Mylar has been tried due to its higher strength, but was found to have about twice the thermal conductivity value as aluminum. Materials in use as spacers include glasswool, fiberglass, paper, and nylon netting.

The most common insulation used in the construction of cryogenic tank cars is the perlite powder with gas evacuation. (Reference 3) The two basic designs of tank car insulation systems are those where the perlite is on the inside of the main tank car shell with an inner floating shell which holds the lading, and those where the perlite is on the outside of the primary shell protected by a steel jacket. In addition to the perlite insulation systems, there are in existence tank cars whose insulation systems were constructed using the superinsulation concept. The main thrust of this study concerns these two types of insulation.

THE LIQUID HYDROGEN CRYOGENIC TANK CAR

The design specifications for the cryogenic tank car used to transport liquid hydrogen are presented in Reference 4. The same car is used to transport liquid methane (-162 °C or -260 °F) and liquid ethylene (-102 °C or -152 °F). Some of the pertinent specifications of this tank car as given in Reference 4 are as follows:

"The material used in the shell, heads, and appurtenances shall be suitable for use at - 253 °C (-423 °F) and be compatible with the lading and the usual cleaning compounds recommended for this service. Chromium-nickel steel plate made to ASTM Specification A-240-61T, Type 304 is an approved material, and when used it shall be in the annealed condition prior to fabrication, forming, or fusion-welding. The minimum ultimate tensile strength shall be as given in ASTM Specification A-240, Type 304."

"The annular space between the two shells shall contain an approved insulating system so installed as to insure against excessive settling and the creation of voids in the insulation when the car is in service. The material shall not burn or spark when touched with a glowing platium wire in an atmosphere of air or lading. The insulation shall be such that the total heat transfer from the atmosphere at ambient temperature to the hydrogen at atmospheric pressure will not vaporize more than

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Ref. 3. F. A. Vassalo, et al, "Review of Proposed Specifications Relating to the Shipment of Ethylene in Tank Cars at Cryogenic Temperatures," PB-241380, Calspan Corporation, Buffalo, New York 14221, September 1974

Ref. 4. Title 49, Code of Federal Regulations (CFR), Part 179.400 (as of November 1983).

2.36 kg (5.2 lbs) of liquefied hydrogen per hour when the car is stationary."

"The distance between the outside wall of the inner container and the inside wall of the outside shell shall not be less than 5.08 cm (2 in)."

Other requirements are as follows:

DOD Specification - 113A60W
Material - Stainless Steel
Bursting Pressure - 168.8 kg/sq cm (240 psi)
Minimum Thickness
    of Shell Head - 0.476 cm (3/16 in)
Test Pressure - 42.26 kg/sq cm (60 psi)

"The safety relief devices consist of 2.54 (1 in) relief valve and 5.08 cm (2 in) diameter rupture disk; sized based on calculations conducted by the Phillips Petroleum Company on uninsulated vessels. Heat input rates were based on the following formula:

$$Q = 36{,}000\ A^{0.8}\ F\ (\text{BTU/hr}).$$

The area (A) was raised to the 0.8 power to account for the wetted surface of the tank car shell. The relief valve was sized to release pressure based on a loss of vacuum and the rupture disk was sized on the basis of the tank car exposure to an external fire and a loss of vacuum."

THE TORCH FIRE FACILITY & TEST SETUP

The torch fire facility was designed to produce a large hydrocarbon fuel flame for impingment on the surface of a test specimen to evaluate its insulating qualities. The flame's characteristics corresponded to the requirements cited in Reference 1. For that reason, the facility was qualified as an approved device for testing insulation systems for railroad tank cars.

The torch's basic structure was two 10.2 cm (4 in) diameter pipes leading vertically from a propane supply tank and then horizontally to the torch nozzle. These can be seen in Figure 1. One of the pipes was used to transport propane vapor while the other was used to transport liquid propane. Each pipe had a compressed air actuated valve which was used to regulate the amount of propane passing through. Prior to reaching the nozzle the two pipes joined, thus, a mixture of liquid and vapor propane flowed through the nozzle. These valves were regulated by the torch operator remotely from inside an instrumentation and control trailer. In a test the propane valve was opened about 27 % and the liquid valve was closed completely. Those values of valve settings produced the desired flame characteristics.

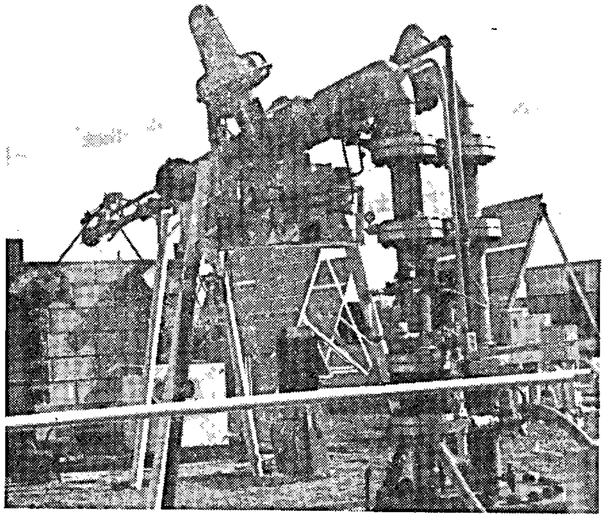

Figure 1: The Torch Fire Device

The configuration of the insulation test assembly holder and the supporting cart were as as shown in Figure 2 and 3. The cart was located on a track so that the distance between the torch nozzle and the front surface of the test specimen could be changed to fit the need of a specific test. That distance is referred to as the TN/SS Distance. The holder, which supported the test specimen assembly, was mounted on top of a cart. Around the holder, shown in Figures 2 and 3, was a shield designed to prevent flames from reaching around the rear enclosure. It was not required in this case because the enclosure was filled with insulation. The shield therefore was removed. The holder, though not of a design which had been used in previous test programs, was utilized because of its availability.

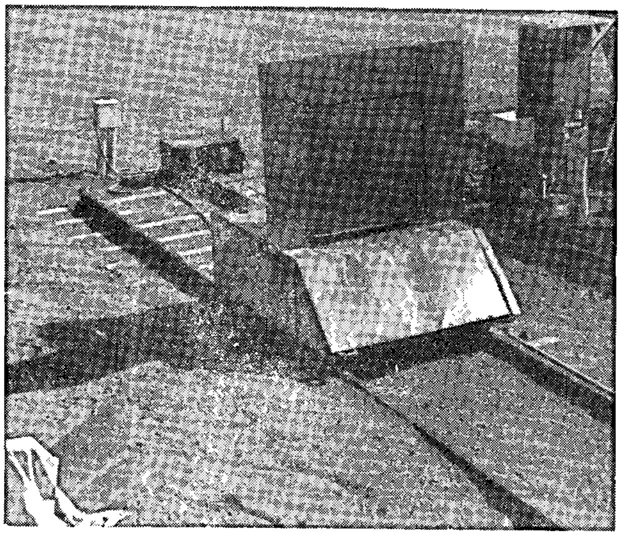

Figure 2: A Front View of the Holder

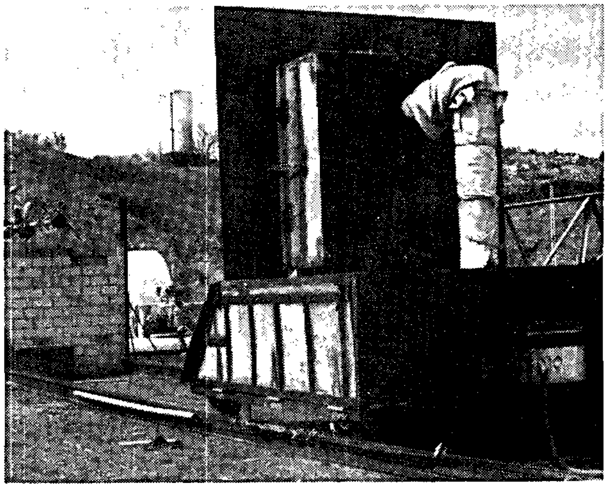

Figure 3: A Rear View of the Holder

The test program was intended to be in the category of exploring general phenomenon, but, it was desirable to at least crudely simulate a section of the hydrogen tank car. It was found that the thickness values of the inner and outer shells of the hydrogen tank car are 0.508 cm (0.2 in) and 1.11 cm (0.44 in), respectively. Therefore, these same thickness values were used for the back and the front plates of the test panels, respectively. The inner shell of the hydrogen tank car is made of stainless steel or an aluminum alloy, but both the front and back plates were made of propane tank car quality steel. It was not considered worth the expenditure in time and money to obtain the actual materials which, if used, would not have made any important difference to these exploratory tests.

The test panels had to be closed systems because the perlite material, being a light weight powder, required containment. In addition, the superinsulation consisted of a thin layer of a kind of fiberglass backed by aluminum foil and since a large number of layers were to be compressed into 5.08 cm (2 in), a closed panel type construction was the most convenient to apply. A most important factor was that the closed system allowed the imposition of a vacuum which was to be attempted in several tests.

The construction of a panel started with the welding together 5.08 cm (2 in) steel channel to form a rectangle 120.4 cm (47.4 in) square. The exterior of the channel was lined with a thermal insulation cloth to help shield against heat transport through the sides. On the exterior of the channel were welded side panels. The final outside dimensions were 121.9 cm (4 ft) square and 6.35 cm (2.5 in) thick.

The remainder of the panel construction consisted of welding on the channel the front and back plates. To prevent either plate from collapsing inward, spacers were installed on the inner surface of the back plate. The spacers were 4.45 cm (1.75 in) long and 2.86 cm (1.18 in) thick. While used in the perlite panels, spacers were discarded in the construction of the superinsulation panels because these would have obstructed the procedure of installing the insulation. The welding on of the front plate completed the construction of the panel. This panel construction constituted the basic design which was varied for special requirements of specific tests. These special features will be discussed as needed.

The test specimens were mounted on the front of the holder by setting them on a narrow ledge and achieving a tight fit against the holder's front surface with bolts.

DOT PERFORMANCE STANDARDS

The Department of Transportation (DOT) Performance Standards are based on data generated in an extensive research program concerning the thermal protection of the propane tank car. Therefore, these standards are only partially applicable when evaluating the thermal qualities of an insulation system for the cryogenic tank car. In the exploratory tests conducted in this program, the performance standards were only used in terms of providing an appropriate environment. The tests were not intended to generate results for insulation system approval, but the data to be obtained were for providing insight into the qualities of the insulation systems in question. The performance standards taken from Reference 1 are presented below.

Prior to actually testing an insulation system a pool fire calibration is required to verify that the torch fire facility is operating with sufficient efficiency such that it can be used to create an appropriate pool fire environment. A pool fire environment is a representative environment that a surface area of a tank car is exposed to while the tank car is engulfed in the flames of a pool fire. Such a pool fire would be a typical one which might occur at the site of a wrecked railroad train.

The DOT regulations defines the procedure for the performance of a pool fire calibration test as follows: "A pool fire environment shall be simulated in the following manner: (i) The source of the simulated pool fire shall be a hydrocarbon fuel. The flame temperature from the simulated pool fire shall be at 1,600 °F, plus or minus 100 °F, throughout the duration of the test. (ii) An uninsulated square steel plate (bare plate) with thermal properties equivalent to tank car steel shall be used. The plate dimensions shall be not less than one foot by one foot by nominal 5/8-inch thick. The plate shall be instrumented with not less than nine thermocouples to record the thermal response of the plate. The thermocouples shall be attached to the surface not exposed to the simulated pool fire, and shall be divided into nine equal squares with a thermocouple placed in the center of each square. (iii) The pool fire simulator shall be constructed in a manner that results in total flame engulfment of the front surface of the bare plate. The apex of the flame shall be directed at the center of the plate. (iv) The steel plate holder shall be constructed in such a manner that the only heat transfer to the back side of the plate is by heat conduction through the plate and not by other heat paths. (v) Before the plate is exposed to the simulated pool fire, none of the temperatures shall be in excess of 100 °F, nor less that 32 °F. (vi) A minimum of two thermocouple devices shall indicate 800 °F after not less than 12 minutes nor, more than 14 minutes of simulated pool fire exposure."

A torch fire calibration test is required for the same reason as the pool fire calibration test except that the verification is to ascertain that an acceptable torch fire environment can be created. A torch fire environment is a simulation of the environment a tank car is exposed to when it has impinging on its outer surface a propane torch caused by a punctured propane tank car located nearby.

The required procedure for performing a torch fire calibration test is as follows: "A torch fire environment shall be simulated in the following manner: (i) The source of the simulated torch shall be a hydrocarbon fuel. The flame temperature from the simulated torch shall be 2,200 °F, plus or minus 100 °F, throughout the duration of the test. Torch velocities shall be 40 miles per hour plus or minus 10 miles per hour throughout the duration of the test. (ii) An uninsulated square steel plate with thermal properties equivalent to tank car steel shall be used. The plate dimensions shall be not less than four feet by four feet by nominal 5/8-inch thick. The plate shall be instrumented with not less than nine thermocouples to record the thermal response of the plate. The thermocouples shall be attached to the surface not exposed to the simulated torch and shall be divided into nine equal squares with a thermocouple placed in the center of each square. (iii) The steel-plate holder shall be constructed in such a manner that the only heat transfer to the back side of the plate is by heat conduction through the plate and not by other heat paths. The apex of the flame shall be directed at the center of the plate. (iv) Before exposure to the simulated torch, none of the temperature recording devices shall indicate a plate temperature in excess of 100 °F or less than 32 °F. (v) A minimum of two thermocouples shall indicate 800 °F in a time of 4.0 minutes, plus or minus 0.5 minutes of torch simulation exposure."

Whenever a successful calibration test is run, the same distance between the torch nozzle and the front surface of the bare plate must be used in the following test of an insulation system. The importance of that distance is easy to understand, since naturally, the greater its value, the cooler is the flame at the front surface of the bare plate. For convenience in discussing the tests, this distance is referred to as the TN/SS Distance, where TN and SS implies torch nozzle and specimen surface, respectively.

The procedure for submitting an insulation system to the pool fire environment according to Reference 1 is as follows: "(i) The thermal insulation system shall cover one side of a steel plate identical to that used to simulate a pool fire. (ii) The uninsulated side of the steel plate shall be instrumented with not less than nine thermocouples placed as described above to record the thermal response of the steel plate. (iii) Before exposure to the pool fire simulation, none of the thermocouples on the thermal insulation system's steel plate configuration shall indicate a plate temperature in excess of 100 °F nor less than 32 °F. (iv) The entire insulated surface of the thermal insulation system shall be exposed to the simulated pool fire. (v) The pool fire simulation test shall run for a minimum of 100 minutes. (vi) A minimum of three successful simulation pool fire tests shall be performed for each thermal insulation system in question."

The procedure for submitting an insulation system to the torch fire environment according to Reference 1 is as follows: "(i) The thermal insulation system shall cover one side of a steel plate identical to that used to simulate a torch fire as described above. (ii) The back of the steel plate shall be instrumented with not less than nine thermocouples placed as described above to record the thermal response of the steel plate. (iii) Before exposure to the simulated torch, none of the thermocouples on the thermal insulation system steel plate configuration shall indicate a plate temperature in excess of 100 °F nor less than 32 °F. (iv) The entire outside surface of the thermal insulation system shall be exposed to the simulated torch fire environment. (v) A torch simulation test shall be run for a minimum of 30 minutes. (vi) A minimum of two successful torch simulation tests shall be performed for each thermal insulation system."

In the regulations just cited, the word "successful" was used to indicate that an insulation system met the test criteria. As noted, a minimum of three successful pool fire tests and two successful torch fire tests are required in order for an insulation system to be judged an approved system. An assumption was that those tests to be used would be legitimate in that, from a physical standpoint, the regulations were met and nothing occurred during the tests which could be judged as a reason for concluding that the tests were unfair. The most frequent physical occurence leading to a substandard test was the wind which tended to blow the torch flame off center. In its review of each test, BRL provided all of the data generated and pointed out problem areas for the benefit of FRA.

The performance standards were applied in this test program only to the extent that the procedure for determining if a correct torch and pool fire environments were achieved. Therefore, a number of calibration tests were performed and the correct TN/SS Distance determined and verified.

DATA ACQUISITION

The Data Acquisition System consisted of several devices which recorded with redundancy in order to minimize the chance of losing data. The key device in the system was the Fluke Data Logger which accepted 28 channels of measurements. The device transformed the signals into units consistent with the parameters measured and passed the data to other devices. Besides obtaining a permanent record, data concerning the operation of the facility were displayed for monitoring purposes. That was important because adjustments during testing was required to maintain an appropriate flame environment. More important, such monitoring provided information which could have warned of developing circumstances that would have warrented aborting the test for safety reasons.

Definitions of the 28 channels are listed in Table 1. In those cases where locations of measuring devices were defined by indicating right or left, the observer was assumed to be facing the rear of the holder. The temperature signals were immediately converted from millivolts to degrees Fahrenheit, tabulated, and stored. The first nine channels provided the temperatures on the back plate. These were the most important set of data since they served as the basis for evaluating the insulation systems in question. The same nine channels were used to acquire temperatures on the back of the bare plate in calibration tests. The positions of the nine thermocouples were in accordance with the regulations presented in Reference 1. That is, in the center of each of nine equal size squares was attached a thermocouple. Viewing the back plate from the rear of holder, the signal for Channel Number 1 and the signal for Channel Number 9 were measured by thermocouples located in the centers of the top-left square and the bottom-right square, respectively. The others were located in numerical order; proceeding from left to right and top to bottom. The nine thermocouples in question were referred to as the back plate thermocouples. The Number 10 Thermocouple measured the temperature at the back of the rear enclosure on the inside. It provided information on the amount of heat which was transported through the insulation in the rear enclosure or from the exterior of the back side of the rear enclosure. The remaining channels listed in Table 1 were utilized as indicated.

While the data from all active channels were available, only the back plate (or bare plate in the calibration tests) temperatures were considered for this report. The Number 10 Thermocouple, being protected by the insulation in the rear enclosure, measured near ambient in all of the tests. Therefore, those measurements were not included in the plots.

TABLE 1: FLUKE DATA LOGGER CHANNELS

Channel Number	Parameter & Location	
1	Temp. - Back Plate,	Top Left Square
2	Temp. - Back Plate,	Top Center Square
3	Temp. - Back Plate,	Top Right Square
4	Temp. - Back Plate,	Center Left Square
5	Temp. - Back Plate,	Center Center Square
6	Temp. - Back Plate,	Center Right Square
7	Temp. - Back Plate,	Bottom Left Square
8	Temp. - Back Plate,	Bottom Center Square
9	Temp. - Back Plate,	Bottom Right Square
10	Temp. - Back of Rear Enclosure	
11	Temp. - Propane,	Supply Tank
12	Temp. - Torch Orifice,	
13	Temp. - Propane,	Storage Tank
14	Pressure, Torch Orifice	
15	Pressure, Manway #1,	Supply Tank
16	Pressure, Manway #2,	Supply Tank
17	Pressure, Propane,	Storage Tank
18	Percent Open,	Liquid Torch Valve
19	Percent Open,	Vapor Torch Valve
20	Level, Propane,	Supply Tank
21	Level, Propane,	Storage Tank
22	Pressure, Differential	
23	Not used	
24	Temp. - Center of Rear Enclosure	
25	Temp. - Left Edge & Middle of Holder	
26	Temp. - Back of Rear Enclosure	
27	Temp. - Right Edge & Middle of Holder	
28	Wind Speed	
29	Wind Direction	

CALIBRATION TESTS

The results from a successful torch fire calibration test are presented in Figure 4 (TF-12-08-83-CRY-D). The TN/SS Distance choosen was 3.66 meters (12 feet) which was based on previous tests. The initial plate temperatures were in the neighborhood of 32.2 °C (90 °F). As can be observed in Figure 4, at least two thermocouples measured 427 °C (800 °F) in the time interval between 3.5 and 4.5 minutes as required in the regulation, therefore the test was judged as being successful. This test therefore verified that the TN/SS Distance used was correct, and the same distance was used in the torch fire tests on the insulations. The Number 1 Thermocouple measured much lower values than the others. It was speculated that the device did not have a good contact with the surface of the back plate. Before each test, all of the thermocouples were checked by reading out data. Such a check however was not fully effective because the values measured were ambient which does not detect a poor connection. However, any thermocouple which measured suspicious values in a test was, prior to the next test, repaired.

The problem of poor connections was resolved by adopting a method different from cementing the thermocouples. At the location where a thermocouple was to be attached, a nut with a hole in its side and adjacent to the plate surface was tack welded to the surface. The thermocouple was placed in the hole and a bolt screwed into the nut to press the thermocouple against the plate's surface. A small bit of insulation was placed between the bolt and the thermocouple to minimize damaging the thermocouple. Once applied, the procedure worked well for the remainder of the program.

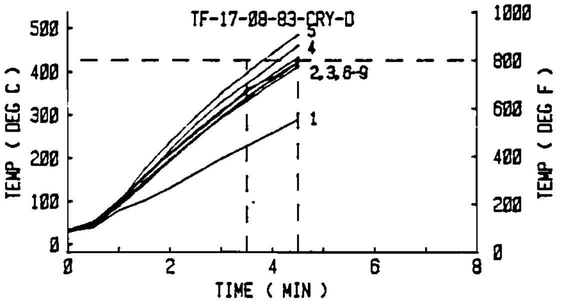

Figure 4: A Torch Fire Calibration Test

Wind effects were the major reason for failures in performing pool fire calibration tests. In a pool fire test, the flame barely reaches the front surface of the plate when a test is successful. For that reason a slight wind can blow the flame off target by a significant amount. The results from a successful pool fire calibration test are presented in Figure 5 (TF-30-11-83-CRY-B). The irregular variations in the slopes rather than a smooth incline were caused by the effects of the wind on the flame. But regardless, the test was deemed a success because a minimum of two thermocouples measured 427 °C (800 °F) in the required period between 12 and 14 minutes. The TN/ SS Distance was 6.6 meters (21.5 ft) and that value was used in the pool fire tests of the insulation systems.

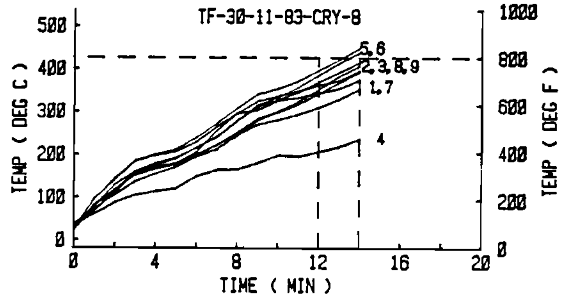

Figure 5: A Pool Fire Calibration Test

TORCH FIRE TESTS ON PERLITE INSULATION

Since the perlite was in powder form and transported to the test site in bulk, it had to be poured by hand in small amounts into the test panel. Two holes were made in the "top" of the panel for that purpose. It was not possible to handle the perlite without face masks because a suffocating dust cloud formed immediately; a fact which hindered considerably the loading operation. It was known that perlite settles, so the heavy panel was lifted and banged against the wrecker to induce settling. Afterwhich, any empty space which had developed was refilled. The procedure helped, but the fact that the densities of the perlite in the panels were not determined remained. It is conceivable that fair estimates could have been achieved by weighing the perlite prior to the filling operations, but that was not done. Consequently, the results constitute only qualitative values and the data's use should be limited to general applications. However, the information could serve as a basis for planning a precise test program.

Temperatures for the first test of a panel filled with perlite powder and without a vacuum are presented in Figure 6 (TF-18-83-CRY-A). The test was aborted at 22 minutes because Number 2 Thermocouple had measured temperatures above 538 °C (1000 °F). Thermocouples 1 and 3 measured lower values, but far exceeded those measured by Thermocouples 4 to 9. It seems apparent that the variations in temperature measurements between thermocouples were due to the level of exposure of each as the perlite fell toward the bottom of the panel.

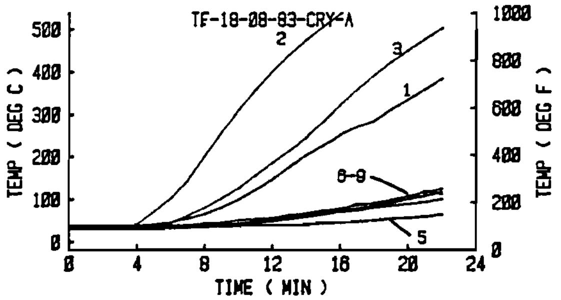

Figure 6: The First Torch Fire Test on Perlite with Nonevacuated Panel

There appears to be two contributing reasons for the behavior of the thermocouples as shown in Figure 6. The two holes in which the perlite was poured were located on the ends of the panel's top and at these two points the panel could be completely filled. However, it was impossible to fill the panel toward the center with the method employed. Therefore, Number 3 Thermocouple did not initially have as much perlite above its position. The perlite fell in the panel due a bulging process as the front plate expanded in response to the extreme heat. Since the front plate was welded at its edges, a bulge was the only physical possibility. Since the least amount of support for the front plate was the center, the apex of the bulge occurred there. For these reasons, the top center thermocouple, Number 2, received the greatest exposure and therefore measured the highest temperatures. Thermocouple Numbers 1 and 2 received the next greatest exposure and therefore measured lower temperatures. All of the other thermocouples were not exposed and, of these, the maximum values measured were in the neighborhood of 107 °C (225 °F). The data shows that perlite performed well even though the panel had not been evacuated of gas.

A second torch fire test was performed with the perlite panel (TF-10-08-83-CRY-B). The temperature data for that test are presented in Figure 7. The results are similar to the previous test and essentially indicate the same type of bulging and thermocouple response due to exposure.

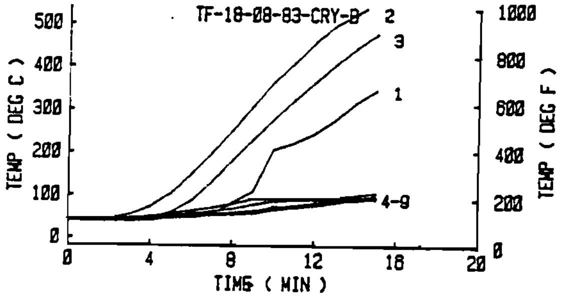

Figure 7: The Second Torch Fire Test on Perlite with Nonevacuated Panel

In order to perform a perlite test where the top three thermocouples would not be exposed due to the falling of perlite, the panel was modified. The change consisted of adding a 61 cm (2 ft) extention on top. This added source of perlite was expected to fall down such that Thermocouples 1, 2, and 3 would continue to be shielded. The top was left open entirely, therefore loading the perlite was an easier task than that experienced in filling the unmodified panel.

The results from the torch fire test of the perlite filled modified panel are presented in Figure 8 (TF-06-12-83-CRY-A). The test was continued to 30 minutes since no thermocouple had measured extreme temperatures. The bulging of the panel due to metal expansion was mainly in the middle as before. Since the reservoir of perlite was available in the extention, all of the thermocouples were shielded throughout the test and none of the temperature measurements exceeded 177 °C (350 °F). The bulge, which was greater near the middle, caused Thermocouple Numbers 1, 2, and 5 to be more protected with the thickest layer of perlite. The effect of this can be observed in Figure 8 by the lower temperatures measured by these thermocouples.

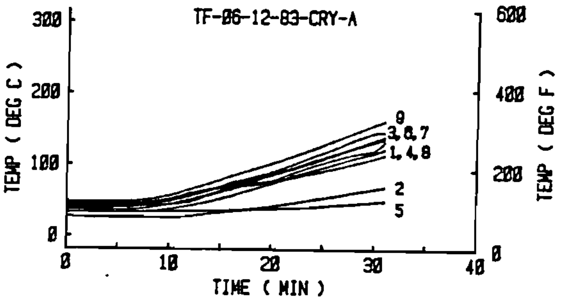

Figure 8: Torch Fire Test on Perlite with Modified Panel

POOL FIRE TESTS ON PERLITE

An unmodified panel of perlite, was tested in the pool fire environment for 100 minutes (TF-30-11-83-CRY-C). The temperatures are shown in Figure 9. After a short interval of about 5 minutes, the upper thermocouples (Numbers 1, 2, and 3) had begun losing thermal protection due to perlite falling into the bulge. The remaining thermocouple measurements gradually increased, thus indicating the maintenance of a protective layer of perlite. None of the temperatures from these protected thermocouples exceed 316 °C (600 °F) at the end of 100 minutes.

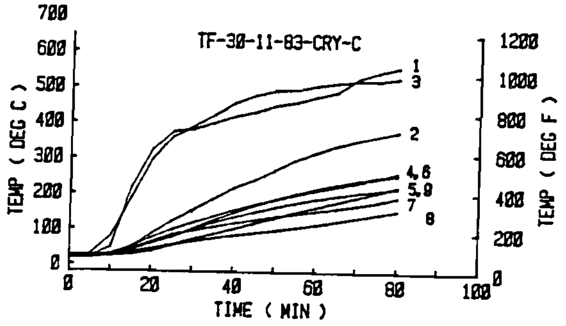

Figure 9: Pool Fire Test on Perlite with Nonevacuated Panel

TF-30-11-83-CRY-C was the only test conducted for the full 100 minutes as would have been required if an actual insulation evaluation program were in progress. But, based on the data and various factors concerning the test setup, it appeared that only qualitative conclusions concerning insulation characteristics could be realized and thus testing for more than 50 minutes would not be worthwhile for the following reasons. First of all, the densities of the perlite in the panels were not determined, as stated above. Another was that the panels were warping and cracks were forming between the panels and the holder box. It was obvious that some heat was reaching the outer thermocouples by that path. In addition, the flame was being affected by the wind, a factor which was detrimental to pool fire tests. It seemed that the best approach was to conserve the available time and resources to ensure that all variations of conditions under consideration could be tested. Then, if justified, devise ways to mitigate weaknesses in the procedures and initiate a realistic program that could yield definitive results.

One pool fire test was performed on a closed unmodified panel filled with perlite. The imposition of the vacuum was accomplished by vacuum pump attached to the panel via a 5.08 cm (2 in) pipe. While pumping the vacuum, the pump rested on the cart behind the holder. The equipment was too unsophisticated to impose the vacuum level usually achieved in tank car construction. A vacuum test was not performed in a torch fire environment because it was speculated that such a severe environment would quickly destroy the partial vacuum and that better procedures would be required.

Figure 10 presents the results from this test (TF-16-12-83-CRY-A). A vacuum of 1100 microns was achieved over 2.5 days of pumping. After five minutes into the test, the vacuum level had decreased until a value could not be discerned on the micron vacuum scale gauge. The top three thermocouples measured temperatures far above the values measured by the other thermocouples. This indicated that the perlite had fallen into the bulged region. However, the temperatures of these thermocouples averaged around 232 °C (450 °F) which was low compared to the temperatures measured by the same thermocouples in the nonevacuated test after 50 minnutes (TF-30-11-83- CRY-C). In the nonevacuated test, the values were in the neighborhood of 482 °C (900 °F). The vacuum apparently caused a substantial improvement over the unevacuated test. It appeared that the vacuum tended to reduce the level of bulging and that the thermocouples toward the top received more protection than in the unevacuated case.

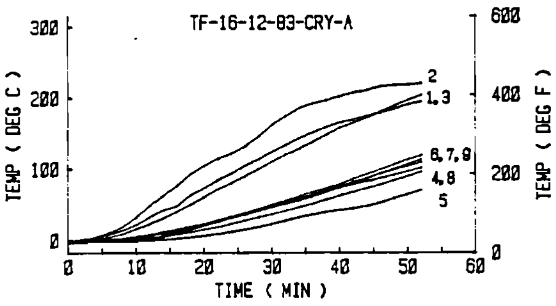

Figure 10: Pool Fire Test on Perlite With Evacuated Panel

Two pool fire tests were conducted on the modified version of the perlite panel. Both of these tests were terminated at 50 minutes for those reasons explained above. The results from the first are presented in Figure 11 (TF-02-12-83-CRY-A). Since the ambient temperature was below 0 °C (32 °F), the torch was used to raise the initial back plate values above freezing. The wind forced the flame laterally, therefore, Thermocouples 3, 6, and 9 started initially at higher temperatures and maintained higher values throughout the test. The extra perlite in the bulge which formed, provided additional thermal protection for Thermocouples 2 and 5.

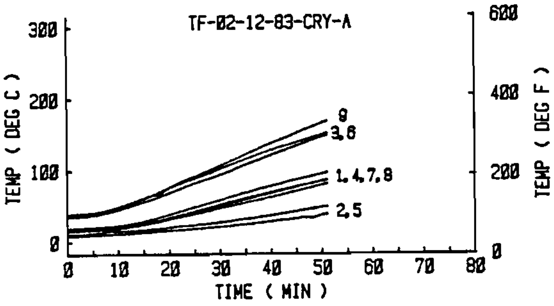

Figure 11: First Pool Fire Test on Perlite with Modified Panel

The second pool fire test of a modified panel with perlite was performed with a panel that had been used (TF-06-12-83-CRY-B). For that reason, the panel initially had a bulge with an apex height of 3.81 cm (1.5 inch) in the middle of the bottom section on which the thermocouples were attached. Thus, at the start of the test the center of the test panel contained 8.89 cm (3.5 in) thickness of perlite. The data for this test are presented in Figure 12. All of the thermocouples measured temperatures below 93 °C (200 °F). These low temperatures reflect the initial increased thickness of the perlite and the fact that the bulge did not increase to any significant degree during the test. Therefore, there was probably only a small shifting of the perlite. The wind was calm during the test and appeared to have little effect on the results.

Several conclusions can be made based on these tests. (1) Perlite, as an insulation, is effective even if not evacuated; (2) perlite, being a powder, will easily fall into a cavity, such as a bulge, if one should form; and (3) even a partial vacuum appeared to increase the thermal protection of a perlite system.

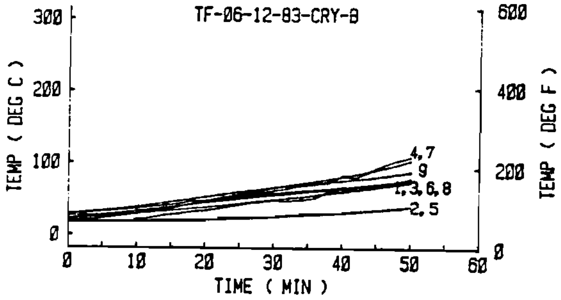

Figure 12: Second Pool Fire Test on Perlite with Modified Panel

TESTS ON SUPERINSULATION

The superinsulation used in the tests was purchased in rolls and consisted of a type of ceramic fiber backed by aluminum. The insulation was cut into 120 layers which were compressed in a 122 cm (48 in) square by 5.08 cm (2 in) thick panel. The layers were stacked on a panel on which the front plate had not been welded. The 120 layers of insulation formed a stack about 30 cm (12 in) high. Using the front plate, the stack was pressed by hand until C-clamps could be attached. With the C-clamps, the insulation was completely pressed in the 5.08 cm (2 in) thick panel. Then the front plate was welded to the edges of the panel. The final construction was similar to that used in the perlite tests, but no spacers were installed.

The superinsulation was first tested without a vacuum in a torch fire environment (TF-08-12-83-CRY-A). Figure 13 presents the data from that test. The insulation provided thermal protection for about 15 minutes and failure then set in rapidely. At 25 minutes the test was terminated because the back plate temperatures were in excess of 538 °C (1000 °F). A post examination of the panel showed that the insulaion had completely disintegrated. Clearly, such an insulation without a vacuum cannot stand the severity of a torch fire environment, a result that was not surprising.

The superinsulation panel was tested in a pool fire environment without a vacuum for 50 minutes (TF-07-12-83-CRY-A). Figure 14 presents the results from that test. The data shows that the insulation provided thermal protection for the duration of the test which was a suprising result. No thermocouples measured values above 260 °C (500 °F). A comparison of the various curves showed that the outside thermocouples measured higher values than the center ones (Numbers 2, 3, and 7). This correlated with an inspection which showed that the panel had warped. This caused cracks between the panel and and holder box which allowed heat from the flame to reach the outside thermocouples.

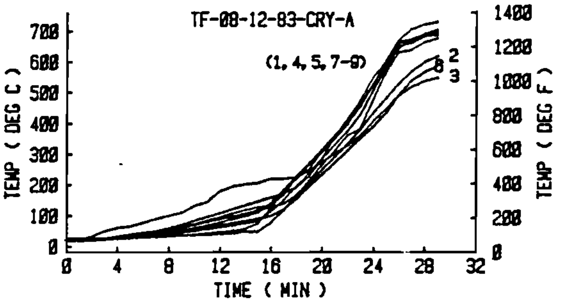

Figure 13: Torch Fire Test on Superinsulation with Nonevacuated Panel

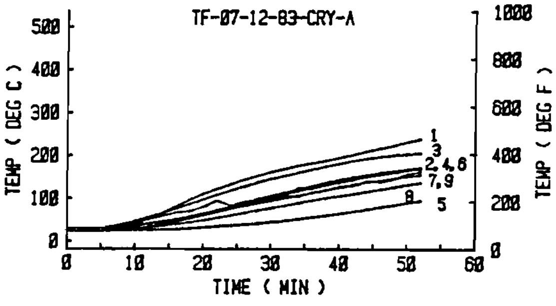

Figure 14: Pool Fire Test on Superinsulation with Nonevacuated Panel

A 500 micron vacuum was placed on a superinsulation panel which was tested for 50 minutes in a pool fire environment. The data are given in Figure 15 (TF-13-12-83-CRY-A). The vacuum of 1000 microns held for seven minutes, but then declined until the gauge scale read zero. The average of the final temperatures measured was approximately 121 °C (250 °F) which was about 56 °C (100 °F) below the previous test with no vacuum. Additional protection was provided by the vacuum presumably because the less dense gas transferred less heat by conduction. An inspection of the panel after the test showed that the panel had collapsed inward rather than outward as had occured in previous tests.

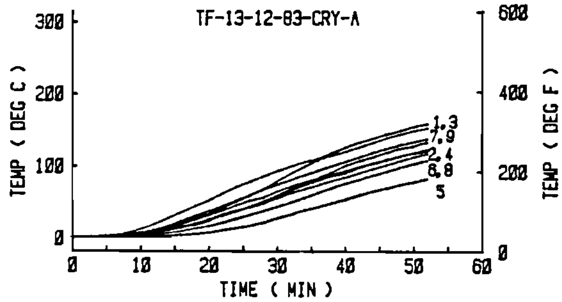

Figure 15: Pool Fire Test on Superinsulation With Evacuated Panel

In conclusion, superinsulation without a a vacuum is inadequate in its ability to survive a torch fire environment. Under a pool fire environment, the performance was better with the imposition of a vacuum. The test setup was inadequate in that crack development between the panel and holder box interface allowed heat transfer which led to erroneous results. Any future tests with superinsulation should be conducted with panels which have been constructed with precision and according to those standards imposed in the construction of thermal protection systems for tank cars.

RECOMMENDATIONS

This study indicates that perlite powder is the most common insulating material used in the fabrication of thermal insulation systems for tank cars used to transport materials at cryogenic temperatures. The test results showed that perlite is an effective insulation under the conditions of torch or pool fire environments. However, except for that qualitative conclusion, the temperatures measured are not in themselves applicable to the type of problem one would expect to have with the cryogenic tank car. In the case of a liquid gas, any amount of heat flux into the lading will immediately cause some liquid to be transformed into a gas which then increases the pressure. The higher pressure will be relieved by venting from the relief valve and at a certain pressure the rupture disks will yield. The primary unknown of importance is whether the pressure will be relieved at a rate which precludes a tank car explosion.

A theoretical study of cryogenic tank cars is needed. A comprehenive compilation of the materials used in the structure of the tank cars and their insulations should be made along with pertinate material characteristics. With that information, predictions of pressure buildup, pressure relief, and tank car ruptures should be made with available formulations. Utilizing these calculational results, the important parameters perhaps can be identified and a realistic test program devised. That is not to say that much of this has not been done, but the literature search did not reveal a source for this information.

A holder should be designed for the torch facility which will provide measurements of heat flux through an insulation system subjected to a fire environment. With such data, accurate estimates of venting requirements and tank pressures can be generated.

In view of the fact aluminum constitutes the material from which some tank cars are made, a number of torch fire tests should be conducted for the purpose of determining the thermal response of aluminum subjected to a fire environnment.

REFERENCES

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3. F. A. Vassalo, et al, "Review of Proposed Specifications Relating to the Shipment of Ethylene in Tank Cars at Cryogenic Temperatures," PB-241380, Calspan Corporation, Buffalo, New York 14221, September 1974

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