PERFORMANCE OF ALUMINUM SCREEN
AND FOIL AS A THERMAL FUSE AND
INSULATION FOR ISOTOPE POWER PLANTS

R. S. Holcomb

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PERFORMANCE OF ALUMINUM SCREEN AND FOIL AS A THERMAL FUSE AND INSULATION FOR ISOTOPE POWER PLANTS

R. S. Holcomb

ABSTRACT

Fusible insulation composed of aluminum screen and a combination of screen and foil was evaluated as a combined thermal insulation and thermal fuse for the heat-block shield of the reference design power plants of the Isotope Kilowatt Program. The function of the thermal fuse is to prevent overheating of the isotope fuel capsules in the event of the loss of cooling of the heat block by the coolant for the power conversion system.

Thermal conductivity and meltdown tests were performed on test specimens of two sizes: 5 1/2 in. OD x 48 in. long and 17 in. OD x 48 in. long. Tests were run with maximum insulation temperatures from 500 to 1050°F in air and nitrogen at pressures from 0.012 mm Hg abs to 15.4 psia and in argon at 15.4 psia.

The best results were obtained with insulation composed of an aluminum foil interspersed at every eighth layer of screen. The thermal conductivity for this material was found to be 0.077 Btu/hr-ft-°F at a mean insulation temperature of 600°F in nitrogen at 1 psia or argon at 15.4 psia. The meltdown results yielded maximum average heat block surface temperatures of 1520°F with the heat block vertical and 1580°F with the heat block horizontal.

INTRODUCTION

Two basic design types of radioisotope electric power unit have been selected as reference designs for the Isotope Kilowatt Program. One of these is a direct conversion design that employs thermoelectric-heat pipe modules.¹ The other is a Rankine cycle system that employs a turbine-generator unit driven either by steam² or Dowtherm A vapor.³ Each of these designs employs a fluid to transport heat from the heat block-shield to the power conversion equipment. In the case of the thermoelectric unit, the fluid in the heat pipes is potassium. In the Rankine cycle systems the fluid is either water or Dowtherm A. A vertical section through the thermoelectric system is shown in Fig. 1.

Fig. 1. Reference design for the 2 kW(e) isotope power unit with thermoelectric converters.

One of the possible accidents that might befall one of these units is the loss of cooling of the heat block. This could occur because of flow stoppage or loss of fluid from a break in the system. In the event that loss of cooling did occur, the temperature of the heat block would rise because the heat loss through the thermal insulation is normally only about 10% of the full power output. This would lead to melting of the fuel cladding if conventional ceramic thermal insulation were used around the heat block. One method of coping with this problem would be to use insulation that would serve as a thermal fuse for the heat block by melting at a temperature sufficiently low that the fuel cladding would not exceed some safe temperature well below its melting point. The heat block would increase in temperature until the insulation began to melt, and then the temperatures would level off. The insulation would continue melting until it was reduced to a thickness such that it would transmit the full power heat load at the melting point of the insulation.

Evaluation of materials that might serve as thermal insulation at operating temperature, but would melt at somewhat higher temperatures was chosen as a primary task of the Isotope Kilowatt Program. The maximum allowable temperature of the fuel cladding for a loss-of-cooling accident was adopted as 2000°F.⁴ Allowances for temperature drops between the fuel and the heat block surface require that the insulation have a melting point in the range of 1200-1400°F. The normal operating condition for the insulation is a hot-face temperature of 800-1100°F. A survey of materials that might fulfill the requirements resulted in the selection of aluminum and glass as the two most promising candidates.

After a literature review of glass insulation, a cellular glass insulation product of the Pittsburgh-Corning Company marketed under the trade name of Foamglas was selected for preliminary evaluation. Samples were placed in a small furnace for a period of one hour at 1200°F and then removed for examination. The outer surface showed a change in color and a slight amount of sagging and fusion of the edges of the outer glass cells. These effects did not appear significant, however, and the material seemed to have remained in a condition to be quite effective as thermal insulation. The same samples were put back into the furnace for a period of one hour at 1300°F. Examination revealed some additional fusion on the edges of the

glass cells at the surface, but no gross melting or powdering had occurred. It was concluded that the glass had neither a low enough range of softening temperature nor was brittle enough to fracture and powder at 1200 to 1300°F, and therefore would not fulfill the requirements of the heat block thermal fuse and insulation.

The poor results from the glass insulation led to a concentration of attention on aluminum as the candidate material. The major concern with the use of aluminum is the low emissivity of both the solid and molten aluminum near the melting point. The values of emissivity commonly reported at these temperatures for aluminum are in the range of 0.1 to 0.15. Thermal analysis studies⁵ have shown that for a thermal fuse with a melting point of 1200°F, a surface emissivity for the material of at least 0.25 would be required in order to prevent the fuel cladding temperature from exceeding 2000°F. The most commonly used form of aluminum insulation, multilayer aluminum foil, did not appear to have a high enough emissivity to be satisfactory as a thermal fuse. However, an insulation matrix composed of a large number of layers of aluminum wire screen offered the possibility of providing both an effective insulation and a thermal fuse with the voids in the screen yielding a high enough surface emissivity to prevent overheating of the fuel cladding. Insulation composed of multi-layer stainless steel screens has been employed in gas-cooled reactors in France.⁶ The thermal conductivity for an aluminum screen matrix was estimated from experimental data obtained by the French to be about 0.042 Btu/hr-ft-°F at a mean insulation temperature of 400°F for a screen composed of 0.010-in. diameter wire on a mesh of 16 x 18 wires per inch. This particular geometry was selected for preliminary testing because the lowest value of thermal conductivity was thought to lie in the range of mesh size of 16 to 20 wires per inch.

DESCRIPTION OF TEST PROGRAM

Testing of the aluminum screen as a thermal fuse and insulation was conducted in three phases. The first phase was a preliminary test in a rather simple system to determine the feasibility of the use of the material for the application. The second phase was a series of tests to measure the

thermal conductivity and the meltdown performance on a small-scale specimen in a system where the ambient gas and system pressure could be varied. The third phase was a series of tests to measure the thermal conductivity of a 1/4-scale insulation specimen and the thermal response of a 1/4-scale heat block during meltdown of the aluminum screen in a system where the ambient gas and system pressure could be varied.

The preliminary test apparatus consisted of an electric cartridge heater inside a roll of aluminum screen with aluminum foil wrapped around the outside of the screen. Thermal conductivity tests were run for insulation hot face temperatures of 600 to 1050°F. A screen meltdown test was run to determine the heater surface temperature response. All of the tests were run at atmospheric conditions.

The small-scale tests were run inside a 6-in. diameter vacuum tank. The heat source was an electric cartridge heater. Three insulation specimens were tested: a 1-in.-thick specimen of aluminum alloy 5056 screen, a 2-in.-thick specimen of alloy 1100 screen, and a 2-in.-thick specimen of alloy 1100 screen interspersed with aluminum alloy 5052 foil. Thermal conductivity data were taken for all three specimens for a range of hot face temperatures of 500 to 1050°F and for gas pressures from 0.012 mm Hg abs to atmospheric pressure. Meltdown tests were run on the two specimens of 2-in. thickness.

The 1/4-scale system consisted of a 8-in. diameter 1023 carbon steel heat block inside an 18-in. OD vacuum tank. The heat was supplied by four electric cartridge heaters inside the heat block. The insulation specimen was made of alloy 1100 screen interspersed with aluminum alloy 5052 foil and was 3 1/4-in. thick. Thermal conductivity tests were performed for hot face temperatures of 500 to 1050°F for gas pressures of 0.1, 1, and 15.4 psia with nitrogen being the ambient gas and the heat block in the vertical position. A meltdown test was run at 0.1 psia. A second insulation specimen was installed and the tests were performed with argon at 15.4 psia. The tests were repeated using argon with the assembly lying in a horizontal position.

Preliminary Atmospheric Tests

Apparatus

The insulation test specimen was composed of a roll of screen 32-in. long with an ID of 1 1/2 in. and an OD of 3 1/2 in. The screen consisted of approximately 0.010-in. diameter wire on a mesh of 16 x 18 wires per inch. The screen was purchased through the General Services Administration and was bought under Federal Specification RR-W-365, Wire Fabric (Insect Screening). This specification calls for screen of type VII aluminum alloy wire and have a chemical composition within the limits shown in Table 1. Data from the Alcoa Aluminum Handbook⁷ indicate that the core of the wire was composed of alloy 5056 and the cladding of alloy 6253. A melting range of 1055-1180°F is given for the core material, but no melting range is given for the cladding material. The specification also calls for the screen to be coated with an aluminum pigmented paint.

Table 1. Composition of Aluminum Wire Screen Used
for Preliminary Test

Material	Core %	Cladding %
Magnesium	4.5 to 5.6	1.0 to 1.5
Silicon	0.3 maximum	45 to 65 of Mg.
Manganese	0.05 to 0.2	
Chromium	0.05 to 0.2	0.15 to 0.35
Zinc	0.1 maximum	1.6 to 2.4
Iron	0.4 maximum	0.5 maximum
Copper	0.1 maximum	0.1 maximum
Other Elements Each	0.05 maximum	0.05 maximum
Other Elements Total	0.15 maximum	0.15 maximum
Aluminum (by difference)	Remainder	Remainder

The heat source was an electric cartridge heater with a power rating of 5000 W. The heater had a stainless steel sheath with an OD of 5/8 in., an

overall length of 54 in., and a heated length of 42 in. The heater was centered inside the test specimen with lava spacers at both the bottom and the top.

Fibrous ceramic insulation was placed at the ends of the screen to minimize end heat losses and to prevent air circulation upward along the heater and out the top by natural convection. Aluminum foil was wrapped around the outside of the screen to eliminate natural convection currents through the screen. The bottom of the assembly was placed in a shallow stainless steel can to contain any molten aluminum that might flow from the screen.

Chromel-alumel thermocouples were located at axial positions of 19, 21, and 23 in. along the heated length on the heater surface, and at corresponding axial positions on the inner and outer surfaces of the screen specimen. The thermocouple emf was measured with a precision temperature indicator with the smallest scale division being 0.002 mV. A diagram showing the location and identification number of the thermocouples is shown in Fig. 2.

Electrical power was supplied to the heater from a variable transformer which had a range of output voltage from 0 to 270 V and a maximum power rating of 7.5 kva. The voltage across the heater was measured with a voltmeter that had full-scale ranges of 30, 75, 150, and 300 V. The current was measured with an ammeter connected to the secondary winding of a current transformer. The ratio of the primary to secondary current was 2:1. The ammeter had full-scale ranges of 2.5 and 5 A.

Procedure

Thermal conductivity tests were run for screen inner surface temperatures of 600 to 1050°F. Since the heat was removed by radiation and natural convection from the outside of the screen, the screen outer surface temperature increased as the power level was increased. The power input varied from 180 W to 530 W over this temperature range. For each temperature, the power input was set and held constant until the system appeared to be at thermal equilibrium. The thermocouple outputs, current, and voltage were then read and recorded. The power input was then increased and the procedure repeated at the next higher temperature.

ORNL-DWG 73-4085

Fig. 2. Schematic diagram of preliminary insulation test.

The meltdown test was run by first bringing the system to equilibrium at a screen surface temperature of about 1050°F. The power input was then increased to the value corresponding to the heat flux that would exist on the full-scale heat block insulation if full power were being removed through the insulation. The outputs of one of the thermocouples on the heater surface and one thermocouple on the screen inner surface were recorded continuously from the time the power was increased to the meltdown level. A complete set of temperature readings were made after the temperature of the heater surface had leveled off. It was planned to continue the test until the temperatures at the outer screen surface reached equilibrium, but the test was prematurely terminated because the heater rod overheated locally and burned out at a point under the fibrous insulation at the top end. Sufficient information was gathered from the test, however, to determine the surface emissivity of the screen specimen.

Method of Calculation

The apparent thermal conductivity of the insulation specimen was calculated from the experimental data by the following equation for heat conduction through a hollow cylinder:⁸

$$q' = \frac{2\pi k (T_i - T_o)}{\ln (D_o/D_i)}$$

Solving the above equation for k yields,

$$k = \frac{q' \ln (D_o/D_i)}{2\pi (T_i - T_o)}$$

where

k = thermal conductivity, Btu/hr-ft-°F

D_i = ID of insulation

D_o = OD of insulation

q' = heat input, Btu/hr-ft

T_i = temperature at inner surface of insulation

T_o = temperature at outer surface of insulation

The heat input, q' , was taken as equal to the electrical power input divided by the heated length of the cartridge heater. The screen temperatures T_i and T_o were the average of the temperatures measured 180 deg apart at the central axial position.

The emissivity of the surface of the insulation specimen was calculated from the relationship for radiation heat transfer between parallel surfaces with different areas:⁹

$$q_r = \frac{\sigma A_R (T_R^4 - T_S^4)}{\frac{1}{E_R} + \left(\frac{1}{E_S} - 1 \right) \frac{A_R}{A_S}}$$

Solving for E_S gives

$$E_S = \frac{1}{1 + \left[\frac{\sigma A_R (T_R^4 - T_S^4)}{q_r} - \frac{1}{E_R} \right] \frac{A_S}{A_R}}$$

where

A_R = surface area per foot of heater rod, ft²

A_S = surface area per foot of screen, ft²

σ = Stefan-Boltzmann constant, 0.1713×10^{-8} Btu/hr-ft²-°R⁴

T_R = heater surface temperature, °R

T_S = screen surface temperature, °R

q_r = radiation heat transfer rate, Btu/hr-ft

E_R = emissivity of heater surface

E_S = emissivity of screen surface

The radiation heat transfer rate, q_r , was calculated from the difference between the total heat input and the heat transferred by conduction:

$$q_r = q_T - q_C$$

The heat transferred by conduction through the gas gap between the heater rod and the screen was calculated from the equation used above for the screen,

$$q_C = \frac{2\pi k (T_R - T_S)}{\ln (D_S/D_R)}$$

where

k = air thermal conductivity, Btu/hr-ft-°F

D_R = diameter of heater rod, in.

D_S = inside diameter of screen, in.

T_R = heater surface temperature, °F

T_S = screen surface temperature, °F

The Grashof number was evaluated to determine if the effective air thermal conductivity between the heater and the screen would be enhanced above the static value by natural convection, and the Grashof number was found to be low enough that the static thermal conductivity applies in the equation above. In order to calculate the screen emissivity for the meltdown test, it was necessary to assume that the screen surface temperature was the melting point of the aluminum because the inner screen surface thermocouples were no longer in contact with the screen.

The emissivity of the heater surface was calculated from temperature measurements taken with the heater rod open to the atmosphere so that it lost its heat by natural convection and radiation to the surroundings which were at room temperature. A value of 0.732 was calculated for the emissivity at a heater surface of 1030°F, and this value was used to calculate all the screen emissivity data.

Results and Discussion

Thermal conductivity values calculated from the data taken in the preliminary test are shown in Fig. 3 as a function of the mean temperature of the insulation at the central axial position. The thermal conductivity is much higher than had been predicted from the French data. The value at a mean temperature of 400°F was found to be 0.07 Btu/hr-ft-°F as compared to

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Fig. 3. Apparent thermal conductivity vs. mean temperature of aluminum screen insulation at atmospheric pressure.

the predicted value of 0.042. The higher results are attributed to natural convection within the screen matrix. The insulation temperatures and thermal conductivity values are tabulated in Appendix A.

The surface emissivity of the screen is shown as a function of the screen inner surface temperature in Fig. 4. The emissivity increases with temperature up to the melting of the aluminum and then there appears to be an abrupt decrease when melting occurs. The emissivity at the melting point, 0.3, is high enough, however, to prevent the radioisotope fuel can temperature from exceeding 2000°F if there should be a loss of normal cooling of the heat block.

The effects of melting the screen are shown in Figs. 5, 6, and 7. Although some oxidation of the screen occurred, relatively large globules of aluminum were formed, thus indicating that the oxide layer on the surface of the aluminum wire did not interfere seriously with the screen melting out.

Since it was felt that it would be desirable to operate the organic system with a pressure of 0.1 psia in the containment vessel to minimize in-leakage to the condenser, it was decided to perform further testing on the aluminum screen insulation to determine its thermal conductivity at reduced pressures down to 0.1 psia.

Small-Scale Tests in Vacuum Tank

Apparatus

Three aluminum insulation specimens were tested in a series of tests performed in a 6-in. diameter vacuum tank: a 1-in. thick specimen of clad aluminum alloy 5056 screen, a 2-in. thick specimen of alloy 1100 screen, and a 2-in. thick specimen of alloy 1100 screen interspersed with aluminum alloy 5052 foil.

The first specimen was fabricated of alloy 5056 wire screen of the same geometry as used in the preliminary test. The screen was rolled with an ID of 1.5 in., an OD of 3.5 in., and a length of 48 in.

The thermoelectric power conversion system requires the operating temperature of the heat block-shield to be about 1100°F at the outer surface, thus making it necessary to select an aluminum alloy with a melting point

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Fig. 4. Screen surface emissivity vs. temperature of aluminum screen insulation at atmospheric pressure.

PHOTO 78036

Fig. 5. Aluminum screen insulation test assembly after meltdown test with heater partially withdrawn.

PHOTO 78034

Fig. 6. Closeup view of the debris from meltdown test of aluminum screen insulation with heater partially withdrawn.

Fig. 7. Closeup view of total debris from meltdown test of aluminum screen insulation.

somewhat above 1100°F for the insulation material for the thermoelectric system. Since the 5056 alloy material did not meet this requirement, another material, alloy 1100, was chosen for evaluation as a possible fusible insulation for both the thermoelectric and organic systems. It has a melting range of 1190-1215°F and a chemical composition as shown in Table 2.⁶ The screen is woven of 0.011 in. diameter wire on a mesh of 16 x 16 wires per inch in a width of 48 in. The complete specifications for the screen are given in Appendix B.

Table 2. Composition of Aluminum Alloy 1100

Material	Percent
Silicon plus iron (max)	1.0
Copper (max)	0.20
Manganese (max)	0.05
Zinc (max)	0.10
Other elements	
Each	0.05
Total	0.15
Aluminum (min)	99.00

The second insulation specimen was rolled with an ID of 1.62 in., an OD of 5.62 in., and a length of 48 in. It was wound on an inner cylinder made of stainless steel screen with a wire diameter of 0.032 in. on a mesh of 4 x 4 wires per inch and an ID of 1.5 in. The stainless steel screen simulated the inner liner of the full scale system. It was painted with PT404A ceramic silicone paint to give it a high emissivity and to protect it from possible attack by the aluminum at high temperature. A photograph of the assembled test specimen is shown in Fig. 8.

A third insulation specimen designed for improved performance was fabricated from alloy 1100 screen with aluminum foil interspersed at every eighth layer of screen. The foil was 0.002 in. thick and composed of aluminum alloy 5052. The chemical composition of this alloy is given in Table 3. Alloy 5052 has a melting point of about 1125°F. This lower

PHOTO 78812

Fig. 8. Aluminum screen insulation test specimen assembly.

melting point was selected so that the foil would reach its melting point while some of the screen layers ahead of it were still intact between the foil and the heat block. It was hoped that in this manner the screens would increase the effective emissivity of the foil surface and thus lead to lower block temperatures during the meltdown. The foil had an H 19 temper so that it would remain smooth during fabrication and minimize the amount of surface contact as a consequence of imbedding of the screen wire. The test specimen was rolled with an ID of 1.5 in., an OD of 5.62 in., and a length of 48 in. The stainless steel liner screen was omitted from this specimen to compare the meltdown results.

Table 3. Composition of Aluminum Alloy 5052

Material	Percent
Silicon plus iron (max)	0.45
Copper (max)	0.10
Manganese (max)	0.10
Magnesium	2.2-2.8
Chromium	0.15-0.35
Zinc (max)	0.10
Other elements	
Each	0.05
Total	0.15
Aluminum	Remainder

The heater for the tests was an electric cartridge heater with an 0.75 in. OD Inconel sheath with a 48 in. heated length. It had a power rating of 5 kW at 230 V. The heater sheath was painted with PT-404A paint to give the surface an emissivity of about 0.89. A new heater was used for each of the meltdown tests. The heater was centered inside the test specimen with webbed stainless steel spacers at the ends.

The vacuum tank was fabricated of stainless steel pipe with an ID of 6.357 in. and an overall length of 57 in. It was flanged at both ends with removable flat heads for assembly and access purposes. A cooling water

coil of copper tubing was silver soldered to the outside of the tank over most of its length to provide cooling at the heat removal surface. A photograph of the vacuum tank and overall test assembly is shown in Fig. 9.

Thermocouples were located at 12, 24, and 36 in. along the heated length of the heater 180 deg apart and also at the inner and outer surfaces of the insulation matrix at the same levels and angular positions. Additional thermocouples were located internally in the combined foil-screen insulation specimen. Chromel-alumel thermocouples clad in 0.040 in. OD stainless steel sheath were used.

The same electrical power supply, voltage and current meters, and temperature indicator were used for these tests as were used in the atmospheric test.

The vacuum system consists of a mechanical vacuum pump connected to the tank with a 3/4 in. copper line. An isolation valve and vent valve are connected in the vacuum line. A 3/8 in. connection on the vacuum tank was used to bring out a 3/8 in. pressure-measuring line containing an isolation valve. The pressure was measured with a Bourdon vacuum gage or a McLeod gage with a range of 1 to 5000 μ m Hg.

The nitrogen used as a cover gas in some of the tests was supplied from a high-pressure gas bottle through two regulators in series with pressure gages at the outlet of each regulator.

The cooling water was supplied to the copper coil on the outside of the tank from the cold process water line. A vent valve was located at the outlet of the coil to remove air from the line, and a bypass line and block valves were provided to drain the coil.

Procedure

The thermal conductivity tests on the first two specimens were run in air at pressures from 0.012 mm Hg abs up to atmospheric pressure. The screen inner surface temperatures ranged from 500 to 1050°F. The third specimen was tested over the same range of temperature and pressure, but with nitrogen as the ambient gas in the vacuum tank.

The thermal conductivity tests were performed using similar procedures for each of the test specimens. The pressure for a particular series of tests was set in the tank using the vacuum pump and throttling valve. The

Fig. 9. Small-scale insulation test facility.

power was held constant until the system came to thermal equilibrium. The time required to reach steady state was usually about 5 to 7 hr, so that only one set of data could be taken each day. The power was then increased and the procedure was repeated at each temperature level.

Meltdown tests were run on the second and third test specimens, but not on the first, because alloy 5056 was felt to have too low a melting point for the thermoelectric system. The meltdown test for each of the last two specimens was run at the end of its thermal conductivity tests. The ambient gas was air for specimen No. 2 and nitrogen for No. 3. In each test, the pressure was set at 0.1 psia and the screen temperature was brought to steady state at about 1050°F. The power input was then increased to give the heat flux that would exist on the full-scale heat block insulation with full power being removed through the insulation. Temperatures at three elevations on the heater rod surface were recorded until no further increase was noted. These temperatures were recorded for about 30 hr on the meltdown test of specimen No. 3.

Method of Calculation

The thermal conductivity and surface emissivity were calculated for these tests in the same manner as for the atmospheric test.

Results and Discussion

The results of the thermal conductivity tests on the 1-in. thick alloy 5056 specimen at five pressure levels is shown as a function of the mean insulation temperature in Fig. 10. The results indicate that natural thermal convection contributes to the effective screen thermal conductivity at pressures above about 1 psia, and at lower pressures the screen thermal conductivity falls off because of the effect of the increased molecular mean free path on the thermal conductivity of the air.

All of the results give higher values of thermal conductivity than those predicted from theoretical considerations. It was at first thought that these differences were caused by an increased emissivity of the wire surface brought about when an aluminum pigmented paint, which had been applied to the screen during manufacturing, boiled off in testing and left a dark deposit on the wire. Later tests indicated, however, that the thermal

Fig. 10. Thermal conductivity vs. mean insulation temperature at reduced pressures of aluminum screen insulation.

conductivity is not affected by the emissivity of the wire, but rather is controlled by the geometry and void volume fraction of the screen matrix.

Values for the thermal conductivity at four pressure levels are plotted in Fig. 11 for the 2-in. thick alloy 1100 test specimen. The results at the three lower pressures are the same as for the 1-in. thick alloy 5056 specimen. It was thus concluded that the heat transferred by radiation is not controlled by the surface emissivity of the wire, but by the geometry and void fraction of the insulation matrix. The data at atmospheric pressure is somewhat higher than that for the 1-in. thick specimen, indicating that the effect of natural convection was greater in the 2-in. thick specimen.

The meltdown test on the 2-in. thick alloy 1100 specimen yielded a heater surface maximum temperature of about 1600°F at the central axial position about 3 hr after the beginning of the test and then decreased slowly. Examination of the partially melted screen after the test indicated that there was sufficient oxidation of the aluminum so that during the meltdown a rather large quantity of oxide whiskers were formed. These whiskers were held in place by the 1/4-in. mesh stainless steel screen on which the aluminum screen was rolled. As the melting continued, it appears that the molten aluminum that flowed from the central region of the screen carried the oxide debris to the bottom where it was trapped by the stainless steel screen, thus forming an insulating layer. These results indicated that a larger mesh stainless steel screen should be used, and that an inert gas should be used instead of air in order to minimize the thickness of the aluminum oxide layer on the screen.

Inasmuch as the thermal conductivity was higher than expected, it was decided to attempt to improve the performance by placing a number of solid sheets of aluminum foil spaced several layers of screen apart in the insulation. It was hoped that this would reduce the thermal conductivity by lowering the radiant heat transmission through the insulation.

Results of the thermal conductivity tests on the foil-screen insulation specimen run in nitrogen at four pressure levels are shown in Fig. 12. The performance is considerably improved over that of the insulation composed of screen alone. The proposed operating conditions for the insulation in the thermoelectric system are a mean temperature of about 600°F and a pressure of 1 psia. The measured thermal conductivity at these conditions is about

Fig. 11. Thermal conductivity vs. mean temperature of alloy 1100 aluminum screen insulation.

Fig. 12. Thermal conductivity vs. mean temperature of combined aluminum foil-screen insulation in nitrogen.

0.077 Btu/hr-ft-°F. This should give heat losses that will be low enough to be acceptable. The thermal conductivity values at 0.012 mm Hg are quite low and indicate that the layers of aluminum foil are effective in reducing the heat transfer by radiation.

The meltdown test was run in nitrogen at 0.1 psia. Temperatures at three elevations on the heater rod surface were recorded for about 30 hr after the test was begun. A plot of these temperatures is shown in Fig. 13 for the first 18 hr. There was essentially no change in the temperatures for the remainder of the time. The top thermocouple reached a peak temperature of about 1525°F in a few minutes, dropped sharply, oscillated once, and then leveled off at about 1450°F. The central thermocouple reached a peak temperature of about 1445°F and leveled off at 1360°F.

The emissivity of the melting screen was calculated for two values of the heater temperature and an assumed screen temperature of 1200°F. The resulting values for the emissivity were 0.26 based on the peak heater temperature of 1525°F and 0.477 based on the heater average temperature of 1456°F. This range of values of emissivity would yield fuel cladding temperatures of 1900-2000°F in the isotope heat block-shield unit in the event all of the cooling from the power conversion system were lost.

The insulation specimen was removed from the vacuum tank for examination after the test was completed. The condition of the insulation after the test is shown in Fig. 14. About one-half of the thickness of the insulation had melted over most of the length. The next layer of aluminum foil had melted with three layers of screen ahead of it still intact, indicating that the lower melting point of the foil was allowing it to melt ahead of some of the screen layers. Areas were found where the foil had partially melted and had rolled up in patches with pieces of one or two layers of screen ahead of it torn and carried along with it. A black deposit was found on the inner portion of the screen and foil layers at the top end of the specimen, and it is believed that this stemmed from a residue from a petroleum wax left on the screen from the drawing and weaving process.

The performance of the combined foil-screen insulation both as a thermal fuse and insulation indicated that it will be satisfactory in the radioisotope system. Further testing was then planned for larger specimens in the 1/4-scale insulation test system.

Fig. 13. Heater rod temperatures vs. time in the course of the meltdown of the combined aluminum foil-screen insulation operated in nitrogen at 0.1 psia.

Fig. 14. Foil-screen insulation specimen after meltdown test in nitrogen.

One-Quarter Scale Thermal Insulation TestsApparatus

The insulation test specimens for the 1/4-scale tests were fabricated from aluminum alloy 1100 wire and alloy 5052 foil. A foil was placed at every eighth layer of screen wire. A cylinder rolled from a sheet of expanded metal stainless steel mesh was placed at the inner and outer surfaces of the insulation matrix to serve as a support for the insulation assembly. The expanded metal had a thickness of 0.045 in. and had an open mesh with 75% open area. Four staples made of 0.035 in. diameter stainless steel wire were installed radially in the assembly 90 deg apart at the ends to prevent any loosening or slippage between the screen layers. The test specimen assembly had an ID of 10.81 in. and an OD of 17.25 in. Photographs of the test specimen are shown in Figs. 15 and 16.

Three 1/4-scale test specimens were fabricated. They were all made using the same design, but there was some variation stemming from small changes in the fabrication procedures. The assembly for the first test was rolled more loosely and had a packed density about 20% less than the one with foil tested in the 6-in. diam tank. The specimen was deliberately rolled loosely to determine if the heat transfer by conduction from one layer of wire to the next could be reduced by decreasing the contact pressure. The second specimen was rolled more tightly to give a higher packed density. The tighter packing was characterized by a radial thickness of 5/32 in. for every 8 layers of wire screen, while the looser packing gave a radial thickness of 3/16 in. for 8 layers. The third specimen was rolled with the 5/32 in. thickness for 8 layers, but the outside sheet of expanded metal was inadvertently pulled down more tightly than before resulting in wrinkling of the screen at one point and an even tighter packing of the screen assembly.

Before fabrication the aluminum foil and screen was cleaned in a bath of ethyl alcohol with ultrasonic vibrators agitating the alcohol for a period of 30 min. Examination with a microscope showed that the drawing wax on the screen was removed by this cleaning process. The oil film on the aluminum foil was removed, but traces of stain were left on the foil where a solid residue from the oil remained after the alcohol evaporated.

PHOTO 79328

Fig. 15. Foil-screen insulation test specimen for 1/4-scale test.

PHOTO 79325

Fig. 16. End view of 1/4-scale insulation test specimen.

A 1/4-scale model of the radioisotope heat block was used in this series of insulation tests. The primary purpose of using a model of the heat block was to provide a surface for the heat source that would have similar geometric characteristics for radiation heat transfer for the melt-down tests, and thus yield block surface temperatures that would closely approximate those that would occur on the full-scale heat block. The 1/4-scale heat block was made of low-carbon steel and had an OD of 8 in. and a length of 59 in. There were 24 fins 1/4 in. x 1 in. high x 50 in. long welded to the outer perimeter of the heat block. The block had a 4.5 in. diameter central hole over its entire length into which a bundle of electric cartridge heaters were placed. The block was supported by a carbon steel angle frame from the bottom head of the vacuum tank. A photograph of the assembled heat block is shown in Fig. 17.

Four electric cartridge heaters each with a power rating of 5 kW at 230 V were used as the heat source for the heat block. The heaters were clad with a 3/4 in. OD Inconel sheath with a 48 in. heated length. The four heaters were supported by stainless steel spacers held together by a 1/2 in. diameter central tie rod. A cross-section drawing of the 1/4-scale test assembly is shown in Fig. 18.

The vacuum tank for the 1/4-scale tests was fabricated of carbon steel pipe with an ID of 17.376 in. and an overall length of 80 in. The top head was made of 3/4 in. thick plate and was welded in place. The bottom head was flanged and bolted to the tank so that it could be removed. Evacuation and pressure gage connections were located in the top head. Thermocouple and electrical penetrations were located in the bottom head. A 3/4 in. copper coil on a 1.5 in. pitch was silver soldered to the outside of the tank for cooling water. A 3/8 in. copper coil was soldered to the outside of the bottom head. The vessel and both heads were nickel-plated to prevent rusting. Kaowool ceramic blanket insulation was installed at the upper and lower ends of the tank to reduce heat losses from the ends. The tank was installed on a frame that could be rotated 90 deg so that it could be tested with the heat block in either a vertical or a horizontal position. A photograph of the vacuum tank is shown in Fig. 19.

The electric power supply to the heaters consisted of two variable transformers each of which had a range of output voltage of 0 to 270 V and

PHOTO 79327

Fig. 17. Heat block for 1/4-scale insulation test.

PHOTO 79435

Fig. 19. Vacuum tank for 1/4-scale insulation test.

a maximum power rating of 7.5 kva. Two cartridge heaters were connected in parallel to each of the variable transformers. The voltage across the heaters was measured with voltmeters that had full-scale ranges of 30, 75, 150, and 300 V. The current was measured with an ammeter with full-scale ranges of 3, 7.5, and 20 A.

Thermocouples were located at the base and tip of two fins on the heat block 180 deg apart at 12, 24, and 36 in. along the heated length. Thermocouples were installed at the same axial and angular positions just beneath the inner and outer layers of aluminum screen on the test specimen, and at 0.5 and 1.5 in. from the inner surface at the 24 in. axial position. The location of the thermocouples is shown in Fig. 18. The thermocouple readings were made with the precision temperature indicator used in the earlier tests. Multi-point strip chart recorders were also used to record the temperatures continuously during the tests.

The moisture content of the gas inside the tank was measured with a Consolidated moisture monitor. It was calibrated to indicate the moisture level for a pressure of 10 psig in the tank and a gas-flow of 20 cm³/min. The full-scale range varied from 10 ppm to 10,000 ppm by volume. Gas samples were taken in evacuated glass bulbs and run on a mass spectrograph analyzer to determine the oxygen content of the gas inside the tank.

A mechanical vacuum pump was used to evacuate the system through a 1 5/8 in. copper line. A 3/4 in. isolation valve and a 3/8 in. vent valve were located in the vacuum line. The pressure was measured with a McLeod gage or a Bourdon vacuum gage through a 3/8 in. connection in the top head.

Nitrogen and argon were used as inert cover gases for the tests. Two bottles of the gas being used were connected to a common gas header. The gas was then supplied through two pressure regulators in series through a 3/8 in. copper line to a connection at the lower end of the vacuum tank.

The vacuum tank was cooled with cold process water supplied to the copper coils. Rotameters were used in the supply lines to each of the two coils so that the proper flow rates were maintained. A vent valve was located at the outlet of the tank wall coil to remove air from the line.

Procedure

Three series of tests were performed in the 1/4-scale insulation test rig. The first series was carried out with nitrogen as the cover gas and with the heat block in the vertical position. The next series was also carried out with the heat block vertical, but with argon as the cover gas. The last series was carried out with the heat block in the horizontal position using an argon atmosphere. Upon completion of a series of tests, a new test specimen and new thermocouples were installed in the system before the next series were run.

Prior to the first test series, the heat block was heated in air for two days up to 750°F to oxidize the surface in order to increase its emissivity. After the heat block was cooled down, the aluminum insulation specimen and vacuum tank were put in place for the nitrogen tests. The system was leak-tested with an internal pressure of 10 psig nitrogen in the course of which leaks at thermocouple connectors were found and eliminated. To remove oxygen and moisture as thoroughly as possible, the tank was then evacuated three more times and refilled with fresh nitrogen between evacuations. Thermal conductivity tests were then run at 0.1, 1, and 15.4 psia. The screen inner surface temperature was varied from 500 to 1050°F at each pressure level. The pressure was set in the tank using the vacuum pump and the throttling valve. The power was then set for an inner screen temperature of about 500°F and held constant until the system came to thermal equilibrium. The time required to reach steady state was about 100 hr. The data were then recorded, and the power was increased to the value for the next temperature level. The procedure was repeated for each pressure.

The meltdown test for the first specimen was run at 0.1 psia. The screen temperature was set at about 1050°F at the beginning of the test. The power was increased in steps so that the block surface temperature increased at about 60°F per hr, which is the calculated rate of increase of the full-scale heat block for a sudden loss-of-cooling. When the power input was equivalent to the full power heat flux, it was then held constant. Temperatures at three axial positions on the heat block were recorded continuously during the test. It was planned to hold the power at this level for at least 24 hr, but the test was prematurely terminated at 9.92 hr by

a short between the leads of one of the heaters resulting in the burnout of the leads and a short to the heater sheath. It appeared that the block temperatures were near the maximum values when this occurred. The vacuum tank was opened after cooling down, the insulation material was removed and the block was cleaned up. New heater rods, thermocouples, and a new test specimen were then installed for the next series.

The results of the first 1/4-scale meltdown test led to the decision to try argon as the cover gas. Since argon has a lower thermal conductivity than nitrogen, it was felt the system could be operated at atmospheric pressure and still have the same heat loss. This would prevent the possibility of air inleakage, which may have occurred in the nitrogen vacuum tests. All of the tests in argon were run at about 15.4 psia.

Argon with a purity of 99.998% and an oxygen content of less than 0.0001% by volume was used to fill the tank. The tank was evacuated and refilled with argon three times. The power was turned on and the heat block was heated to a temperature of about 180°F and held there for 24 hr with the vacuum pump purging the tank. The tank was refilled with argon and a gas sample was taken for analysis. The block was heated to 200°F for periods of 48 and 96 hr with samples taken following each period. The tank was then evacuated and refilled five times. This was followed with a continuous purge of argon with the tank at 7 psig discharging to the atmosphere for a period of 24 hr. Another gas sample was taken and analyzed and found to contain 0.0003% oxygen. This was considered to be satisfactory. The moisture monitor was connected to the system with the tank at 10 psig at room temperature. At a flow rate of 20 cm³/min, the moisture content was found to be 15 ppm by volume.

Thermal conductivity tests were made with the block again in the vertical position for inner screen temperatures of 500 to 1050°F. The data were taken at each temperature level about 100 hr after the power was set for that phase of the test. The power was then increased and the procedure repeated.

The meltdown test with the block in the vertical position in argon was also run at 15.4 psia. The same procedure as that used in the test in nitrogen was followed. Block temperatures were recorded for a period of 23 hr and no heater failures occurred.

The insulation debris was removed from the tank and the block was cleaned up. The heat block was sand-blasted and coated with PT-404A silicone ceramic paint to provide protection from the molten aluminum in the horizontal meltdown test. The cartridge heaters were reused, but new thermocouples and a new test specimen were installed.

The heat block was heated to about 200°F and the tank was evacuated for 26 hr. The system was then purged for 32 hr with argon with a pressure of 6 psig in the tank. The moisture content was measured at this point and was found to be 23 ppm with the block at 200°F. A gas sample was taken for analysis and the oxygen content was found to be less than 0.0001%.

Thermal conductivity tests were run at inner screen temperatures of 800 and 1050°F at an argon pressure of 15.4 psia with the heat block in the horizontal position.

The meltdown test was run with the block in the horizontal position following the same procedure as before. The test was terminated after 19 hr by a heater failure which shorted out one entire circuit of two heaters so that the load could not be shifted from the failed heater to the other in its circuit. The block temperatures had reached a maximum value before the failure and were decreasing at the end of the test.

The test specimen was removed from the tank for examination after the system was allowed to cool down.

Method of Calculation

The thermal conductivity was calculated using the same equation as that used for the atmospheric data:

$$k = \frac{q' \ln (D_o/D_i)}{2\pi (T_i - T_o)}$$

The heat input, q' , was assumed to be equal to the electrical power input divided by the heated length of the cartridge heater minus the heat conducted toward the end of the heat block. The thermal conductivity was based on the average of the screen temperatures measured at the central axial position. The correction for heat conduction along the block was

based on the difference between the block temperature at the central axial position and the block temperature at the lower, or the 12 in. position.

The heat input q' , is given by

$$q' = \frac{q_e}{L} - k_s \frac{A_B}{x} (T_c - T_L)$$

where

q_e = electrical heat input

L = heated length

k_s = thermal conductivity of steel

A_B = transverse area of heat block

x = distance between thermocouples (12 in.)

T_c = heat block temperature at center

T_L = heat block temperature at lower end

The thermal conductivity of 1023 low-carbon steel as a function of temperature is given in Fig. 20; this curve was used for the calculations.

Results and Discussion

Thermal conductivity data for the first 1/4-scale insulation specimen are shown in Fig. 21. These tests were for the heat block in the vertical position with nitrogen as the ambient gas at three pressure levels. Higher values were found in these tests and the thermal conductivity has a steeper slope with temperature than was found in the previous tests on the smaller specimen of foil-screen insulation. The probable explanation for this is that the 1/4-scale specimen was rolled more loosely and had a packed density about 20% less than before. This specimen was packed more loosely intentionally to determine if the heat transferred by conduction could be reduced. Instead, it appears that the thermal conductivity was increased by increasing the radiation heat transfer. The original density appears to be more nearly the optimum value.

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Fig. 20. Thermal conductivity of 0.23 percent carbon steel.

Fig. 21. Thermal conductivity vs. mean temperature of 1/4-scale specimen of aluminum foil-screen insulation in nitrogen.

The meltdown test was run on the first 1/4-scale specimen with the heat block vertical in nitrogen at 0.1 psia. Temperatures at three elevations on the heat block surface were recorded continuously during the test. A plot of these temperatures is shown in Fig. 22. The highest temperature occurred at the central axial position for about 8.5 hr, whereupon the bottom temperature rose more rapidly and crossed above the top and center temperatures and reached a value of 1514°F at 9.92 hr. The average of the heat block temperatures was 1492°F at this time. The test was prematurely terminated at this point because of a short between the leads of one of the heaters resulting in the burnout of the leads and a short to the heater sheath. The heat block temperatures appeared to be leveling off, so that the temperatures at the end of the test are probably near the maximum values that would have occurred. A further indication of this is that the heater rod surface temperatures had been constant for several minutes before the heater failed. The average temperature, 1492°F, is higher than the desired maximum temperature on the full-scale heat block, and would result in a fuel cladding temperature of about 2062°F, 62°F higher than the original objective.

The melted material from the thermal insulation specimen was removed from the vacuum tank for examination after the test was completed. A large quantity of molten aluminum had run from the screen and solidified in the region below the screen. See Fig. 23. The outer portion of the screen was intact with a final thickness of about 3/4 in. at the center and 1 in. at the top. The lower portion of the screen up to about 10 in. above the bottom was packed with a mixture of metal globules and debris that had not melted. This is seen in a photograph of the bottom end of the insulation specimen after meltdown in Fig. 24. This debris consisted of a very thin transparent film from the foil and a dark gray, fragile hollow shell of the screen. The packing of this unmelted debris probably accounts for the temperature at the bottom exceeding that at the center.

A photograph showing the top end of the insulation specimen following the meltdown test is seen in Fig. 25. It may be observed here that the inner portion of the insulation matrix has completely melted or fallen away in the upper section of the test specimen.

Fig. 22. Block surface temperature vs. time for vertical meltdown test on 1/4-scale insulation test rig.

PHOTO 79439

Fig. 23. Aluminum that flowed from the screen during the first 1/4-scale meltdown test and solidified at the lower end of the heat block.

Fig. 24. Lower end of insulation specimen after meltdown test.

Fig. 25. Top end of insulation specimen after meltdown test.

Seven samples of the unmelted debris from the 1/4-scale insulation meltdown specimen were analyzed spectrographically to determine the relative quantities of a number of the metallic elements and three of the light elements: carbon, oxygen, and nitrogen. One sample was analyzed for sulfur and two of them for hydrogen. The weight percent of each element as found by the analysis is given in Table 4. Sample No. 1 consisted of a thin, translucent gray, fragile film which was left behind from the surface of the foil. Samples No. 2, 3, and 4 were the hollow shell of the screen left where the metal had melted and run out. Sample No. 5 was dark gray, powdery screen material that had settled in the bottom of the insulation specimen. Sample No. 6 was a mixture of debris from the screen and the foil. Sample No. 7 was a piece of unmelted foil with a dark purple and gray film coating taken from the top part of the insulation specimen.

The metallic elements were found to be present in about the expected quantities for the aluminum alloys used for the screen and foil. The fact that the Fe, Ni, and Cr contents were normal seemed to indicate that no mass transfer had occurred from the stainless steel expanded metal liner. The principal light element found to be present was oxygen. Sample No. 1 had about 3% carbon and 0.05% nitrogen. Only a minor amount of carbon or nitrogen was found in the other samples.

It was concluded that the debris left after melting the screen and foil is composed mainly of aluminum oxide. The nitrogen used to fill and blanket the vacuum tank generally contained only about 5 ppm of oxygen. The greater source of oxygen was probably from air inleakage to the blanket gas and then into the vacuum tank. There was a thin aluminum oxide film present, of course, on the aluminum when it was installed.

It was decided at this point to perform the next tests at 15.4 psia to prevent air inleakage that might cause accelerated oxidation of the aluminum while it was operating at elevated temperatures. The thermal conductivity of the insulation in nitrogen at 15.4 was higher than desired, so argon was chosen as the alternate cover gas since it appeared that the lower thermal conductivity of the argon gas would result in an overall thermal conductivity of the insulation at 15.4 psia of about the same value as found with nitrogen at 1 psia.

Table 4. Report of Spectrographic Analysis on Samples of Unmelted
Material from Aluminum Insulation Meltdown Test

Element	Weight Percent						
	Sample No.						
	1	2	3	4	5	6	7
Al	Majority	Majority	Majority	Majority	Majority	Majority	Majority
B	.02						
Ca					.05		
Cr	.05	.04	.05	.03	.03	.02	.3
Cu	0.2	0.3	0.2	0.2	0.2	0.3	0.1
Fe	0.2	0.2	0.2	0.2	0.2	0.2	0.2
K	0.1				.03		
Mg	>5	1	1	0.8	0.8	~5	~5
Mn	.04	.05	.05	.03	.04	.02	.06
Na	.05						
Ni	Not detected	Not detected	Not detected	Not detected	Not detected	Not detected	Not detected
Si	.02	0.2	0.2	0.2	0.2	0.2	0.2
Sn	.02					.02	
Ti	.03	.02	.03	.02	.07	.02	.04
Zn	0.2						
C	3.06	0.77	0.33	0.57	0.61	0.26	.061
S	Not analyzed	< .01	Not analyzed	Not analyzed	Not analyzed	Not analyzed	Not analyzed
O	Not analyzed	3.36	2.20	1.92	2.36	2.22	1.26
N	.0544	.0032	.0031	.0086	.0084	.0115	.0057
H					.012	.0019	

The second 1/4-scale test specimen was then run in the vertical position with argon as the cover gas at a pressure of about 15.4 psia. The thermal conductivity data are shown in Fig. 26 as a function of the mean insulation temperature. This test specimen run in argon yielded a thermal conductivity of about 0.077 Btu/hr-ft-°F at a mean temperature of 600°F as compared with a value of about 0.085 for the previous specimen run in nitrogen at 1 psia, and about 0.092 for nitrogen at 15.4 psia. The reduction in thermal conductivity found with argon was largely owing to the lower thermal conductivity of the gas, but it was due in part to the higher packing density of the insulation specimen used in the argon test. The use of argon as the cover gas at about 15.4 psia with the foil-screen insulation would appear to give an acceptable heat loss for the thermoelectric system.

A plot of the block surface temperatures recorded during the meltdown test is shown in Fig. 27. The maximum temperatures occurred at about 10 hr after the test was begun. The maximum temperature found was 1564°F at the central axial location. The average block temperature at that time was 1520°F, which would yield a fuel cladding temperature of about 2090°F in the full-scale heat block.

The insulation specimen was removed for examination after the meltdown test. The results were similar to those for the meltdown test in nitrogen except that the degree of oxidation of the screen was much less and a considerably smaller quantity of unmelted material from the screen was present. A thin transparent film from the foil was again found to have remained unmelted.

Apparently the initial oxide film present on the screen and foil at the time of fabrication is of sufficient thickness to prevent complete melting, thus resulting in block temperatures higher than would be the case if the material all melted at about 1200°F. It appears unlikely that a block surface temperature lower than about 1500°F can be achieved for the loss-of-cooling accident case.

Spectrographic analyses were performed on the samples of the debris from the 1/4-scale meltdown test in argon. The results are shown in Table 5. Sample No. 1 was composed of a thin, fragile transparent film left behind from the aluminum foil when it melted. Sample No. 2 consisted of

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Fig. 26. Thermal conductivity vs. mean temperature of 1/4-scale specimen of aluminum foil-screen insulation in argon at 15.4 psia with the heat block vertical.

Fig. 27. Block surface temperature as a function of time for the vertical meltdown with argon at 15.4 psia in the 1/4-scale insulation test rig.

screen material having a dark color and coated with a film of yellow powder. Sample No. 3 was composed of screen material dark in color. Sample No. 4 was composed of screen material with a white coating. The most significant finding is the high oxygen content reported for Sample No. 1. Apparently the aluminum foil surface has a relatively heavy oxide film resulting from fabrication or storage. This was present when the insulation was installed. This oxide film evidently inhibits the melting of the aluminum foil and may largely account for the high temperatures found in the meltdown test.

Table 5. Report of Spectrographic Analysis of Aluminum Insulation Meltdown Samples from Argon Test

Sample No.	Weight Percent			
	1	2	3	4
Element				
C	2.82	3.50	0.22	0.89
N	.075	.023	.003	.025
O	7.06	2.31	0.19	0.72
S	.022	.20	.002	.002
Al	56.2	84	>90	>90
Cr	.08	.05	.07	.2
Cu	.08	.1	.1	.2
Fe	.1	.1	.1	.5
Mg	6.4	.63	.14	.41
Mn	.05	.04	.02	.1
Ni	<.02	<.02	.01	.3
Si	.1	.1	.1	.2
Ti	.02	.01	.01	.02

Tests of the third 1/4-scale aluminum insulation specimen with the heat block in the horizontal position were then conducted. Thermal conductivity measurements were taken at two temperature levels in argon at 15.4 psia. The results of the tests are shown in Fig. 28. The data for the horizontal test is about 25% higher than for the vertical test. This is thought to be largely owing to a difference in the assembly of the test specimen. The

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Fig. 28. Thermal conductivity vs. mean temperature of 1/4-scale specimen of aluminum foil-screen insulation in argon at 15.4 psia with the heat block horizontal.

expanded stainless steel sheet on the outside of the horizontal test specimen was pulled down tighter on the aluminum screen than before, causing wrinkling of the screen material and compaction of the insulation matrix.

Block surface temperatures taken during the meltdown test are shown in Fig. 29. The upper side of the block reached a maximum temperature of 1640°F and the lower side reached 1517°F. The central fuel element in the full-scale heat block would probably be affected by an average of these temperatures, or about 1580°F. This should yield a surface temperature of about 2150°F on the central fuel element for the loss-of-cooling accident in the horizontal position.

The meltdown test was terminated after 19 hr by a heater failure which shorted out one entire circuit of two heaters so that the load could not be shifted from the failed heater to the other in its circuit. The block temperatures had reached a maximum value before the failure, however, so that only slightly lower temperatures would have occurred at longer times.

The test specimen was removed from the vacuum tank for examination. The most interesting result was that none of the molten aluminum from the upper half of the insulation had run down on the heat block. Instead, it ran around the inner circumference of the remaining insulation material and accumulated in the lower half of the specimen. The molten aluminum formed a puddle that was slightly above the inner liner of expanded stainless steel on the lower side. Some of the liquid ran out of the hotter end of the insulation and solidified after the system cooled down. The higher temperatures measured on the upper side of the heat block probably resulted from the unmelted debris of aluminum oxide that was left behind on the expanded stainless steel liner after the molten aluminum ran around the screen to the lower side. The lower side of the heat block apparently ran cooler in part because the molten aluminum provided a path for heat removal with a higher thermal conductivity than that of the unmelted debris left behind on the upper side. A photograph of the insulation specimen following the meltdown test is shown in Fig. 30.

Fig. 29. Block surface temperature vs. time for horizontal meltdown test.

Fig. 30. Insulation Specimen after horizontal meltdown test in argon.

CONCLUSIONS

The following conclusions were reached from the results of the tests on aluminum insulation:

1. Combined aluminum foil-screen insulation should yield heat losses of about 10% for normal operation of the thermoelectric radioisotope power system for a heat block surface temperature of 1100°F with either argon at 15.4 psia or nitrogen at 1 psia as the cover gas.
2. The insulation yields the lowest value of thermal conductivity when the screen is rolled with an average spacing of the layers of 0.0195 in.
3. For the hypothetical accident conditions of complete loss-of-cooling of the heat block by the working fluid in the power conversion system and with a low carbon steel heat block, the aluminum insulation will melt and limit the maximum fuel element cladding temperature to about 2090°F with the heat block vertical or about 2150°F with the heat block turned horizontal with argon or nitrogen as the cover gas. With a nickel heat block these temperatures would be about 200°F lower.
4. A considerable amount of unmelted debris of aluminum oxide from the screen and foil is left behind when the aluminum melts and runs out. This results from the oxide layer that is formed on the aluminum at room temperature before it is placed in an inert atmosphere.

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APPENDIX A

Experimental Data and Results

Table A-1. Thermal Conductivity Data

Test Specimen and Conditions	Pressure	Thermal Conductivity Btu/hr-ft-°F	Mean Temperature of Insulation Specimen °F
Alloy 5056 screen 3.5 in. OD x 32 in. long in air	Atmospheric	0.0729	431
		0.0897	551
		0.1023	660
		0.1085	702
		0.1247	788
Alloy 5056 screen 3.5 in. OD x 48 in. long in air	0.02 mm Hg abs	0.0322	373
		0.0413	454
		0.0507	545
		0.078	664
	0.2 mm Hg abs	0.0455	381
		0.0548	472
		0.0641	555
		0.0787	639
	0.1 psia	0.0558	381
		0.0781	547
		0.0907	611
		0.1015	660
	1.25 psia	0.0585	350
		0.0786	504
		0.0907	584
		0.1153	645
	Atmospheric	0.0766	304
		0.0879	406
		0.0952	473
		0.1036	532
Alloy 1100 screen 5.62 in. OD x 48 in. long in air	0.02 mm Hg abs	0.0292	334
		0.0352	383
		0.0449	490
		0.057	585
	0.1 psia	0.0478	322
		0.0593	424
		0.0738	512

Table A-1 (continued)

Test Specimen and Conditions	Pressure	Thermal Conductivity Btu/hr-ft-°F	Mean Temperature of Insulation Specimen °F
Screen-Foil- 5.62 in. OD x 48 in. long in nitrogen	1.25 psia	0.0522	298
		0.0631	388
		0.076	493
		0.097	614
	Atmospheric	0.0887	280
		0.092	336
		0.0966	389
		0.1068	507
	0.012 mm Hg abs	0.0108	407
		0.01285	508
		0.01424	561
		0.01563	592
	0.1 psia	0.04075	370
		0.04766	510
		0.05915	595
	1 psia	0.04692	341
		0.05435	458
		0.0676	561
		0.078	602
		0.0807	619
Screen-Foil- 17.25 in. OD x 48 in. long in nitrogen	15.4 psia	0.0667	324
		0.0710	452
		0.0778	584
		0.0802	616
	0.1 psia	0.0384	248
		0.0482	365
		0.0618	497
		0.0721	596
	1 psia	0.0456	234
		0.0549	344
		0.0686	460
		0.086	607
	15.4 psia	0.0629	256
		0.0727	360
		0.0822	471
		0.0945	618

Table A-1 (continued)

Test Specimen and Conditions	Pressure	Thermal Conductivity Btu/hr-ft-°F	Mean Temperature of Insulation Specimen °F
Screen-Foil- 17.25 in. OD x 48 in. long in argon-vertical	15.4 psia	0.0344 0.0469 0.0601 0.0829	283 389 514 621
Screen-Foil- 17.25 in. OD x 48 in. long in argon-horizontal	15.4 psia	0.0647 0.0996	436 592

APPENDIX B

Specification

Wire Fabric for Thermal Insulation

Scope

This specification covers wire mesh fabric for use as thermal insulation in a special application.

Requirements

Material. The wire fabric shall be of aluminum alloy wire having a minimum tensile strength of 18,000 psi and a chemical composition within the following limits:

Material	Percent
Silicon + iron	1.0
Copper	0.20
Manganese	0.05
Zinc	0.10
Other elements	
Each	0.05
Total	0.15
Aluminum (minimum)	99.00

Dimensions. The width of the wire fabric shall be 48 in. with a permissible tolerance of plus or minus 1/8 in. from outside wire to outside wire. The wire fabric shall be provided in rolls of 200 linear feet plus 2 or minus 0 linear feet.

Continuity. Each roll shall be of one continuous length.

Splices. Splices not more than 1 in. in length, showing no tails, shall be permissible at any point of any individual wire provided that the

number of such splices shall not exceed 30 per 100 linear feet nor more than 2 in any single square foot of finished wire fabric.

Selvage. The wire fabric shall be selvaged by one or more wires in each edge.

Mesh Size. The mesh size (count) shall be 16 x 16 wires per inch. Permissible tolerances in the mesh size shall be plus or minus 1/4 mesh per linear inch and plus or minus 1/2 mesh per linear in. in the filling.

Wire Size. The wire shall have a diameter of 0.011 in. plus or minus 0.0005 in.

Finish. The wire fabric shall be of bare aluminum alloy wire without any coating.

Certification. The wire fabric shall be certified by the contractor to have successfully completed tests for chemical analysis within the limits of chemical composition as specified above.

Workmanship. The wire fabric shall have no defects which adversely affect its serviceability or appearance.

Quality Assurance Provisions

Responsibility for Inspection

The supplier is responsible for the performance of all inspection requirements as specified herein. The supplier may utilize his own facilities or any commercial laboratory acceptable to the buyer. The buyer reserves the right to perform any of the inspections set forth in the specification where such inspections are deemed necessary to assure that supplies and services conform to prescribed requirements.

Inspection

Unit of Product. For purpose of inspection, the unit of product shall be the first 2-ft segment for the entire width of each roll in the sample.

Sampling. Sampling for examination and tests shall be in accordance with MLL-STD-105, inspection level I.

Examination. The wire fabric samples shall be examined for the following defects. Acceptable quality level shall be 2.5 percent defective.

1. Dimensions not as specified.

2. Mesh count not as specified.
3. Continuity not as specified.
4. Splices not as specified.
5. Selvage not as specified.
6. Workmanship not as specified.

Tests. The following tests shall be performed on each sample. Acceptable quality level shall be 2.5 percent defective.

1. Tensile Strength - A specimen shall be taken of the wire fabric and shall consist of undistorted wires from two cut edges at right angles to each other so as to include an equal number of warp and filler wires. The wires shall be tested in accordance with method 211.1 in Fed. Test Method Std. No. 151, except that, at the option of the inspector, the specimen may be loaded by dead weight. Failure of the wire at a tensile strength of 18,000 psi or less shall constitute failure of this test.
2. Chemical Analysis - Each sample shall be analyzed by the wet method or spectrographic methods according to method 111 or 112, respectively, of Fed. Test Method Std. No. 151. In case of dispute, chemical analysis by wet chemical methods shall be the basis of acceptance. Certification that the wire conforms to chemical composition requirements may be supplied in lieu of chemical analysis.

Packaging

Each roll of wire fabric shall be packaged in a close-fitting commercial fiberboard container having all joints and seams sealed with reinforced glass tape.

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