CHARACTERIZATION OF THERMOPHYSICAL PROPERTIES OF LAYERED PERFORATED ALUMINUM AND ARAMID CLOTH

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ABSTRACT

Sandia National Laboratories has developed and tested a package design for air transport of plutonium that can survive a "worst-case" aircraft crash. This design utilizes layered perforated aluminum metal and aramid cloth for the primary structural and thermal protection of the contents during a hypothetical aircraft accident. The thermophysical properties of these materials were characterized in order to have a better understanding of the thermal behavior of perforated aluminum combined with KEVLAR® when used as an overpack for a transportation container in both the normal and accident conditions of transport. Samples of perforated aluminum with different percent of crush were prepared and their thermal conductivity (k) at different temperatures, both perpendicular to the plane as well as parallel to the plane, were measured. The specific heat (C_p) of the samples was also measured. The results obtained show the relationship between the thermal conductivity and the percent of crush. Equations of the effective thermal conductivity as a function of percent crush were developed for both the in-plane and through-plane directions. Plots of density and thermal conductivity as a function of percent crush are presented in this paper.

INTRODUCTION

The United States Department of Energy (U.S. DOE) has a continuing need to develop and evaluate state-of-the-art packagings for transport of hazardous and radioactive materials. This has resulted in a Sandia National Laboratories (SNL) program to develop and evaluate new concepts for nuclear transportation packages. Since U.S. requirements governing plutonium air transport are currently the most stringent of all hazardous material regulations, one emphasis has been on the development of air transport packagings for plutonium. SNL has previously developed and tested a package design for air transport of plutonium that can survive a "worst-case" aircraft crash using technology developed at SNL for DOE (US Patent 5,337,917) [1]. This work has been performed for the Japan Nuclear Cycle Development Institute (JNC) using the technology developed by SNL for the U.S. DOE. The aforementioned design [2] utilizes layered perforated aluminum metal and aramid cloth for the primary structural and thermal protection of the contents during a hypothetical aircraft accident.

In general, thermophysical properties of a material are reported by the manufacturer only at room temperature and/or the normal state of the material. These limited data pose a problem when trying to predict the behavior of the material when it is exposed to higher temperatures and becomes even more complicated if the material is deformed or crushed. This is the case that the Transportation Risk and Packaging Department of Sandia National Laboratories has found when trying to

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KEVLAR® is a DuPont registered trademark.

understand the behavior of perforated aluminum when used as an overpack for a transportation container and the container is subjected to a series of regulatory tests. In trying to address this problem, several samples of perforated aluminum with different percent of crush were prepared and sent to the Thermophysical Properties Research Laboratory (TPRL), in West Lafayette, Indiana, to measure their conductivity (k) and specific heat (C_p) at different temperatures. Since KEVLAR® is another material that is part of the overpack design, a sample of it was also prepared and sent to TPRL. The objective of these measurements was to collect previously unknown data in order to build better computer models to predict the performance of the package being analyzed.

TEST SAMPLES

The transportation container under study is built by winding a long sheet of perforated aluminum. These materials will have an anisotropic thermal behavior. For this reason, the thermophysical properties were measured in the through-plane and in-plane directions. Half-inch thick disks (1-7/8-inch in diameter) were assembled from layers of material that were cut from a 0.0315-inch thick aluminum sheet (Aluminum 3003-H14) that had open holes 0.115-inch in diameter, staggered 0.117-inch apart. Samples of different crush levels were provided to TPRL in order to understand the thermal performance of the layered material at different crush percentages.

The aluminum samples were identified as IP-%crush, for the in-plane measurements, TP-% crush for the through-plane measurements. The KEVLAR® cloth was only measured in the through-plane direction since it will have a more isotropic behavior.

MEASURING METHODS AND THEIR UNCERTAINTIES

The Three-Point Technique

A method known as the three-point technique was used to determine the through-plane thermal diffusivity (α) of the samples. In this method, one face of a two-layer specimen is subjected to a known uniform heat flux and the temperature response at the front face, back face, and in between the two layers is recorded. A 600-Watt quartz-iodide tungsten element bulb mounted within an aluminum parabolic reflector is the controllable heat flux source. Temperature history data from the front and rear face of the sample are used as boundary conditions for the calculation of the temperature response between the two layers of known thickness. Diffusivity values are determined using the temperature response data, specimen dimensions and the method of parameter estimation [3]. In addition to accounting for interior temperature measurements and allowing front face temperatures to be a function of time, the parameter estimation technique also allows sequential calculation of the sensitivity of the experiment. Sensitivity analysis produces criteria for best locations of interior thermocouples and sampling times that produce theoretical optimum estimates of the diffusivity. Once α, C_p, and density (ρ) are known, the thermal conductivity of the studied material can be determined with the following formula: $k = \alpha * \rho * C_p$. The experimental error of this method was estimated to be about ±4%.

The Heated Probe Method

The heated probe method, which may be considered as a variant of the line source method, was used for the in-plane thermal conductivity measurements. In this method the line source and temperature sensor are combined in one small diameter probe. This probe is inserted into the sample and the heater turned on for a pre-selected time interval. During this time interval, the rate of heating of the probe is measured. This heating rate quickly becomes semi-logarithmic and from this semi-logarithmic rate, the thermal conductivity of the sample is calculated. The experimental uncertainty of this method was estimated to be about ±7% for the samples IP-0 and IP-20. For higher crush percent samples (IP-35 and IP-50) the experimental uncertainty is estimated to be about ±12% due to the fact that these samples had relatively high thermal conductivities for the method used. This method is traceable to ASTM Standard D5334-92.

The Differential Scanning Calorimeter

Specific heat is measured using a standard Perkin-Elmer Model DSC-2 differential scanning calorimeter with sapphire as the reference material. The standard and sample were subjected to the same heat flux as a blank and the differential powers required to heat the sample and standard at the same rate were determined using a digital data acquisition system. From the masses of the sapphire standard and sample, the differential power, and the known specific heat of sapphire, the specific heat of the sample is computed. The experimental error of this method was estimated to be about ±3%. All measured quantities are directly traceable to NIST standards.

RESULTS AND DISCUSSION

Perforated Aluminum

The average measured specific heat of perforated aluminum was very close to the specific heat of solid aluminum at room temperature, but slightly higher, maybe because of the oil content of the samples. The handbook value of specific heat for aluminum 3003 alloy at room temperature is 893 J/kg-K.[4] The specific heat at room temperature of a nearly clean material was 904.5 J/kg-K and for a more oily material was 909.0 J/kg-K. The later is the most likely to be used for the construction of the overpack/impact limiter because it comes in a roll, and this facilitates the manufacturing process. The oil is added to the aluminum sheets to facilitate the hole punching process to make the perforations. In addition, it is considerably cheaper to buy the material with the oil on it (no special cleaning process is needed) and the thermophysical properties are very similar. The average measured values at different temperatures are presented in Table 1 and a curve fit of the data is shown in Figure 1.

Table 1. Average specific heat of perforated 3003 aluminum.

Temperature (°C)	Specific Heat (J/kg-K)
23	907
50	921
100	945
200	979
300	1012
400	1049
500	1103

The measured values of the thermal conductivity, k, in the through-plane direction are presented in Table 2. Since relatively large differences were seen in the thermal conductivity values between the 40% and 50% crush, some refinement of crush percent was done in order to have a better description of the behavior of the material in that region. The average of the thermal conductivity over the temperature range was then calculated and used to create a plot of the thermal conductivity as a function of percent crush. Table 3 has the nominal and actual percent of crush and the corresponding density and thermal conductivity. The difference of the nominal and actual percent crush is due to some elastic resilience (hysteresis) of the samples after they were crushed. The data in Table 3 is plotted in Figures 2 and 3.

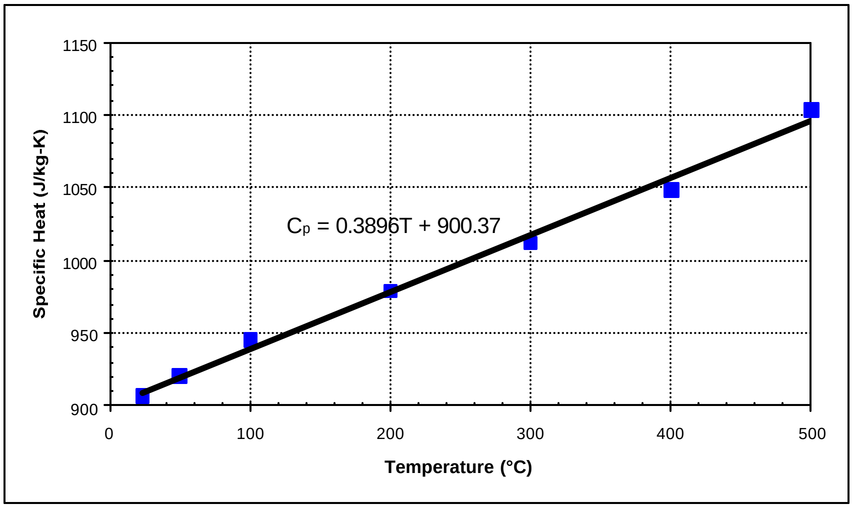

Figure 1. Specific heat of perforated 3003 aluminum as a function of temperature.

Table 2. Through-plane thermal conductivity of perforated aluminum.

Temperature (°C)	Thermal Conductivity (W/m-K)										
	TP 0	TP 20	TP 35	TP 35N	TP 40	TP 42.5	TP 45	TP 45N	TP 47N	TP 48.5N	TP 50
23	0.7	2.5	3.6	5.5	8.2	5.9	15.9	13.4	18.0	22.2	17.9
50	0.8	2.7	3.9	5.6	8.2	6.0	16.0	13.4	17.9	22.3	18.0
100	1.0	2.9	4.2	5.7	8.0	6.2	16.3	13.4	17.7	22.6	18.0
200	1.1	3.1	4.4	5.8	7.6	6.5	16.4	12.3	18.0	23.1	18.4
300	1.2	3.3	4.5	6.0	7.8	6.7	15.9	11.9	17.8	23.0	18.1
400	1.2	3.6	4.7	6.1	7.8	6.7	15.3	11.9	17.2	23.0	17.3
500	1.2	3.6	4.7	6.0	8.3	6.8	15.7	11.6	17.0	22.0	17.0
Avg.	1.0	3.1	4.3	5.8	8.0	6.4	15.9	12.6	17.7	22.6	17.8

Table 3. Density and average through-plane thermal conductivity

Nominal %Crush	Actual %Crush	Density (kg/m^3)	Average k (W/m-K)
0	0.0	1217	1.03
20	18.4	1517	3.09
35	33.7	1786	4.28
35 N	36.2	1939	5.81
40	39.3	2116	7.98
42.5	42.5	2048	6.40
45	43.7	2203	15.95
45 N	46.8	2240	12.56
47 N	45.1	2335	17.69
48.5 N	48.8	2390	22.59
50	48.6	2211	17.81

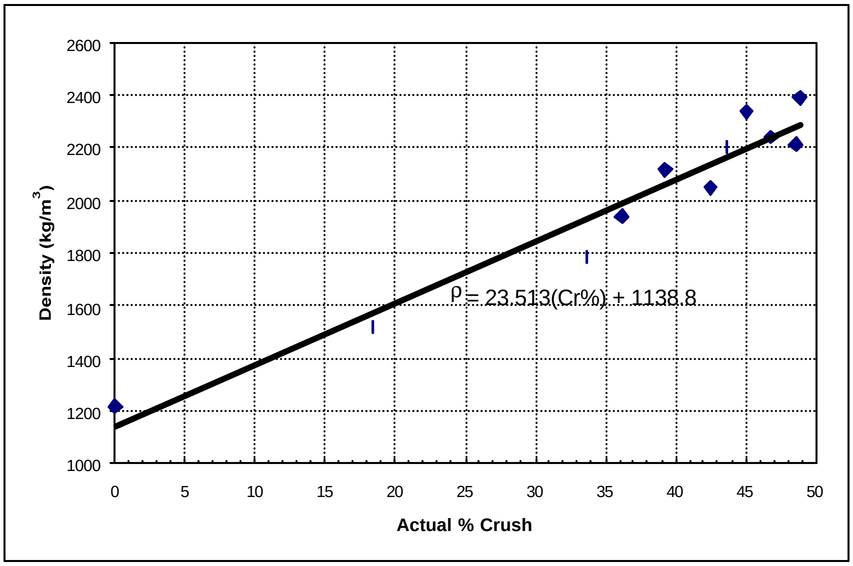

Figure 2. Density-% crush relationship.

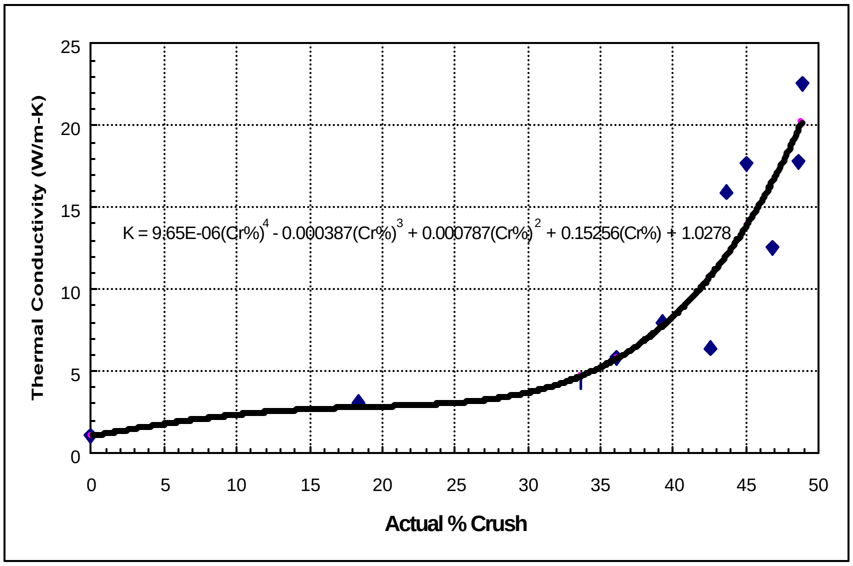

Figure 3. Through-plane thermal conductivity as a function of % crush.

The in-plane thermal conductivity values are presented in Table 4. The average thermal conductivity values are given in Table 5. These data were plotted against the actual percent crush in Figure 4.

Table 4. In-plane thermal conductivity of perforated 3003 aluminum.

Temperature (°C)	Thermal Conductivity (W/m-K)								
	IP 0	IP 20	IP 35	IP 35N	IP 42.5	IP 45N	IP 47N	IP 48.5N	IP 50
23	2.9	6.3	12.6	14.9	16.1	19.8	21.3	24.7	22.3
100	3.1	7.4	13.7	16.1	17.0	20.4	22.2	25.2	23.1
200	3.3	8.3	14.7	16.7	17.6	20.8	22.8	25.6	23.5
300	3.4	8.6	15.0	16.9	17.8	20.9	22.9	25.7	23.8
400	3.5	8.9	15.4	16.7	17.5	20.5	22.6	25.4	23.6
500	3.6	9.0	15.5	16.6	17.2	20.2	22.0	24.7	23.2
Avg.	3.3	8.1	14.5	16.3	17.2	20.4	22.3	25.2	23.3

Table 5. In-plane thermal conductivity of perforated 3003 aluminum.

Actual %Crush	Average k (W/m-K)
0.0	3.3
18.4	8.1
33.7	14.5
36.2	16.3
42.5	17.2
46.8	20.4
45.1	22.3
48.8	25.2
48.6	23.3

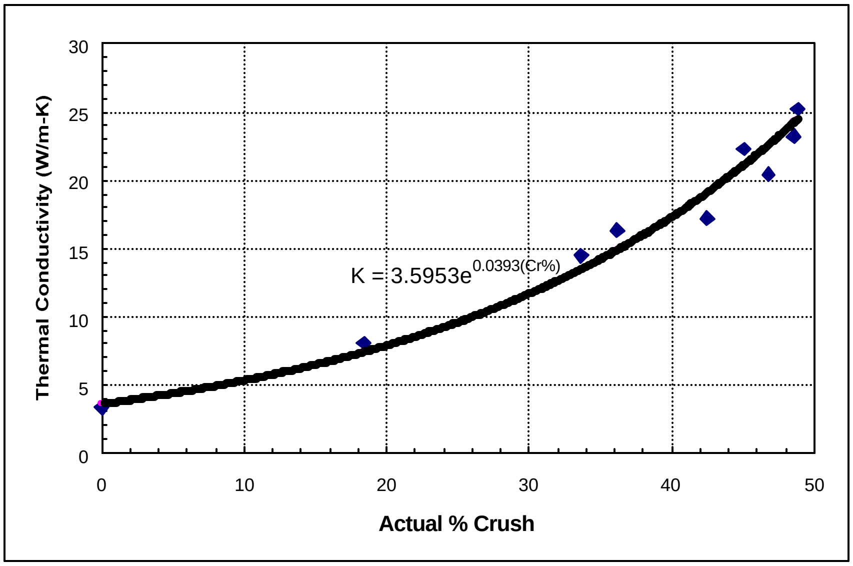

Figure 4. In-plane thermal conductivity of perforated 3003 aluminum as a function of % crush.

KEVLAR® Properties

Aramid cloth (KEVLAR® 29 cloth, fabric style 710) is another material that is part of the overpack design. Therefore, the same thermophysical properties were measured but only in the through-plane direction since it is understood that this material is more isotropic. The experimental values of ρ, C_p, and k for the through-plane measurements on KEVLAR® 29 are presented in Table 6. Results presented in this table show that the recommended values (average values) for the thermal modeling of KEVLAR® 29 cloth, fabric style 710 are a density of 795 kg/m^3, an effective thermal conductivity of 0.0808 W/m-K, and the specific heat as a function of temperature as it is shown in Figure 5. A plot of the thermal conductivity as a function of temperature is shown in Figure 6.

Table 6. Thermophysical Properties of KEVLAR®

Temperature °C	Density (kg/m^3)	Specific Heat (J/kg-K)	Thermal Conductivity (W/m-K)
23	794.90553	1135	0.0812
100	-	1355	0.0819
200	-	1596	0.0787
300	-	1849	0.0808
350	-	1975	0.0816

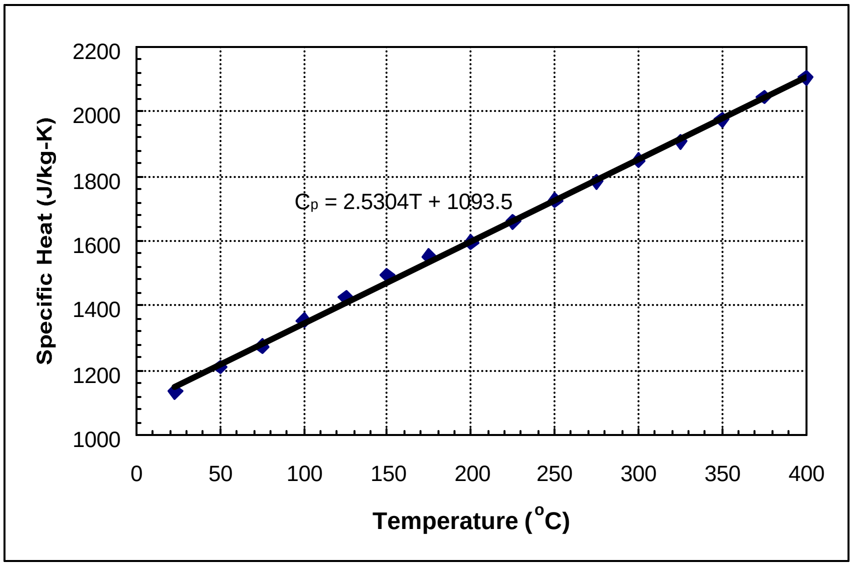

Figure 5. Specific heat of KEVLAR® 29 cloth, fabric style 710 (extra experimental data is shown).

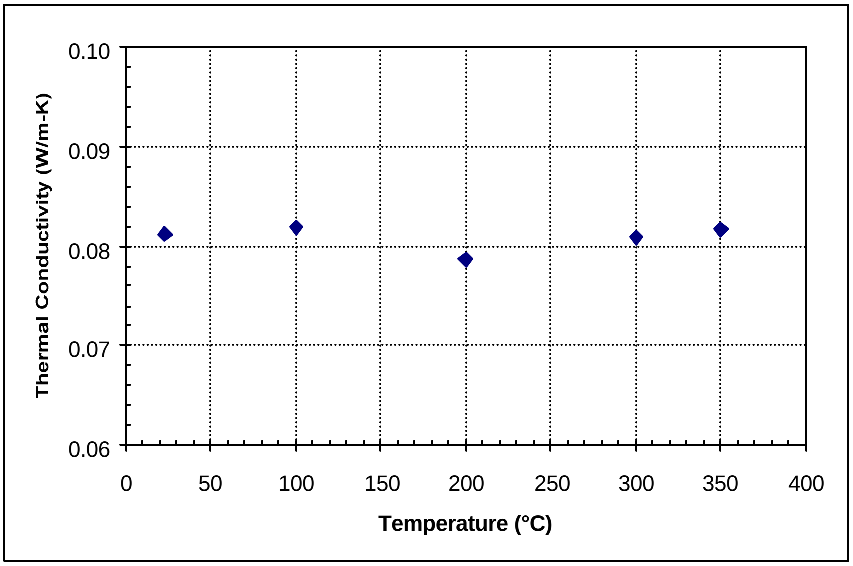

Figure 6. Measured thermal conductivity of KEVLAR® 29 cloth fabric style 710.

Note that the thermal conductivity of KEVLAR® was relatively constant over the possible temperature range for testing. It had an average thermal conductivity of 0.0808 W/m-K. KEVLAR®, started to deteriorate (carbonize) at about 400°C. Therefore the temperature range reported was from room temperature to 350°C.

SUMMARY

The data presented in this paper enable computer modelers to construct more accurate thermal models of overpacks and/or impact limiters that make use of the perforated metal/aramid cloth impact protecting technology. The next step is to create a finite element model of a package constructed using these materials and compare the predictions with experimental data in order to validate the results presented in this report.

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