# HIGH TEMPERATURE TESTING OF STRUCTURALLY DAMAGED IMPACT AND PUNCTURE PACKAGE PROTECTION SYSTEMS*

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## Abstract

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Heat transfer through materials which change phase or combust is a complex process. It is important to understand the heat transfer in such materials in order to analyse and predict the survivability of a nuclear material transportation package in a hypothetical thermal accident. Therefore, several high temperature tests were conducted to study the behaviour of some common materials used in such nuclear material transportation packages.

## INTRODUCTION

Materials which change phase or combust are very difficult to numerically analyze. Kevlar, honeycomb, and rigid polyurethane foam are commonly used to protect packages from the regulatory [1] hypothetical impact, puncture and thermal accident conditions. The sequential nature of the regulatory tests dictates thermal testing of structurally damaged systems. Several test series were conducted to assess the behavior of Kevlar, honeycomb, and polyurethane foam when exposed to high temperature environments typical of JP-4 fueled open-pool fires [2]. The tests were configured to represent components found in the TRansUranic PACkage Transporter Model-I (TRUPACT-I [3]) and the Beneficial Uses Shipping System (BUSS, [4]) cask, as shown in Figs 1 and 2, respectively. Some of the component tests are summarized in the following sections with more detailed information presented in [5].

## TRUPACT-I COMPONENT TEST 1 (CT-1): NEW VERSUS OLD KEVLAR

The Kevlar's primary function in TRUPACT-I is puncture resistance. CT-1 was designed to evaluate the relative behavior

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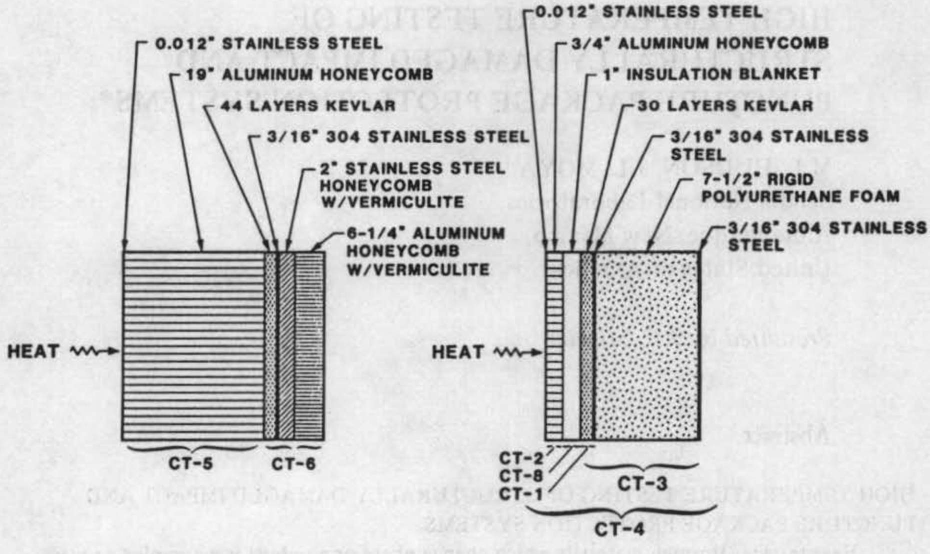


*FIG. 1. TRUPACT-I component test materials. (Note: 1 in = 25.4 mm)*

of 30 layers of laminated Kevlar with different binder materials when directly exposed to a high temperature environment. The tested binder materials include those on the old and new TRUPACT-I design.

Seven 0.305 m x 0.305 m (12 in x 12 in) test pieces were fabricated with different types of Kevlar. The Kevlar samples were laminated with a plastic, silicone, or a manufacturer's proprietary material. Each test piece included 30 layers of laminate Kevlar bonded to a 0.00476 m (3/16 in) thick 304 stainless steel plate. Each test piece was exposed to a 1093°C (2000°F), high emissivity radiant heat source for 30 minutes at the Radiant Heat Facility. Infrared quartz halogen lamps radiate to a stainless steel plate (shroud) coated with high emissivity paint ($\epsilon \approx 0.95$) which then reradiates to the front surface of the test item. Power to the lamps is computer controlled to obtain the desired shroud temperature. The test facility is located in an outdoor three-sided enclosure to allow viewing and natural venting of gases.

For each test material, flames and black smoke were observed continuously during the 30 minute exposure. The temperature response of the Kevlar with plastic binder was similar to the Kevlar with silicone binder. The organic proprietary binder material caused approximately all of the Kevlar to burn, whereas the Kevlar with the other binders only burned 45% by weight. The plastic and silicone laminates charred and delaminated approximately 10 layers with layers 11 through 17 increasing in strength. The remaining 13 layers were undamaged. Thus, the high temperature performance of a laminated Kevlar is governed by the combustibility of the binder material.

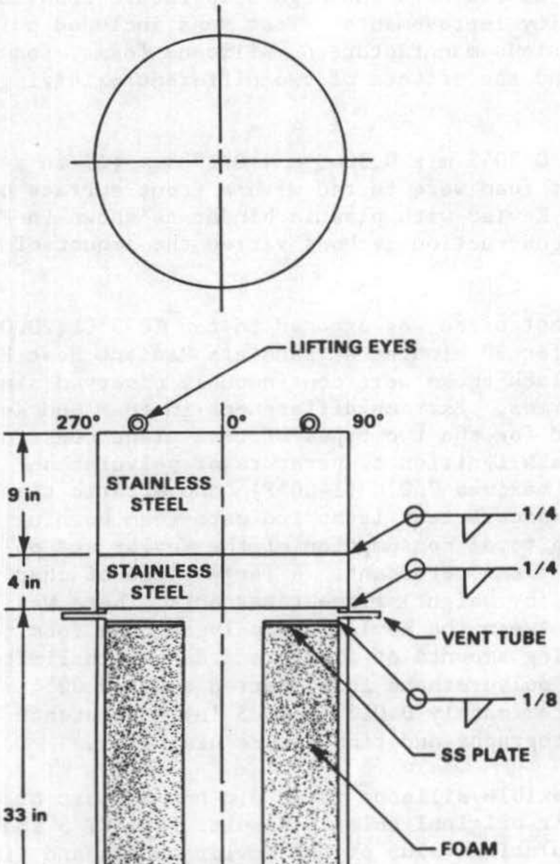


*FIG. 2. BUSS cask one-dimensional impact limiter model.*

## TRUPACT-I COMPONENT TEST 3 (CT-3): ALTERNATE FOAMS

The purpose of the rigid polyurethane foam ($\rho$ = 96 kg/sq m or 6 lb/sq ft) in the TRUPACT-I is to insulate the containment during the regulatory hypothetical thermal accident and to provide structural support between the inner and outer structure. The foam is an excellent insulator if it does not burn. Based on extensive burned and charred foam in TRUPACT-I, Unit 0 [6,7], CT-3 was designed to evaluate the high-temperature behavior of the foam and to identify improvements. Test runs included polyurethane foam from various manufacturers, silicone foams, foams with flame retardant and the effects of two different oxidizing environments.

Eleven 0.3048 m x 0.3048 m x 0.1905 m (12 in x 12 in x 7.5 in) pieces of foam were tested with a front surface of 30 layers of laminated Kevlar with plastic binder as shown in Fig. 1. Two test piece construction methods varied the amount of air access to the foam.

Each test piece was exposed to the 1093°C (2000°F) radiant heat source for 30 minutes at Sandia's Radiant Heat Facility. Flames and black smoke were continuously observed similar to the CT-1 test series. Extreme differences in foam and Kevlar behavior were observed for the two types of test piece constructions. Since the flash ignition temperature of polyurethane foam is 454°C (850°F), the maximum 760°C (1400°F) and erratic temperatures in the high air access test items indicate foam burning. Disassembly confirmed the total consumption of the Kevlar and polyurethane foam with no flame retardant. A large piece of char remained for foam with 8% (by weight) flame retardant. There was little difference between the Kevlar and polyurethane foam performance with increasing amounts of flame retardant with limited air access. The polyurethane foam charred about 0.0254 m (1 in) and expanded approximately 0.0127 m (0.5 in). Reference [5] gives detailed photographs and temperature histories.

The flexible silicone foams did not combust or char and retained their original color. Results from CT-3 indicate that with the insulating value of the Kevlar panels and limited air access, the polyurethane foam in TRUPACT-I should adequately protect the containment liner. The silicone foam can be used in areas of potentially high structural damage to prevent polyurethane foam combustion.

## TRUPACT-I COMPONENT TEST 4 (CT-4): WALL SYSTEM VERIFICATION

A 1.22 m x 2.44 m (4 ft x 8 ft) section of the TRUPACT-I body was tested in a fire environment. This test of a full-length damaged main body assembly provided further information and verification before performing a final regulatory test of the package.

The 1.22 m x 2.44 m (4 ft x 8 ft) panel included an aluminum honeycomb exterior skin assembly, a 0.0254 m (1 in) thick insulation blanket, 30 layers of Kevlar laminated with plastic binder (as tested in CT-1) and poured-in-place polyurethane foam with 8% flame retardant (as tested in CT-3). For conservatism, a simulated puncture per TRUPACT-I 1/4-scale model test was included to provide a direct heat and air path to the foam. The sides and back of the test item were insulated with board and blanket insulation.

The CT-4 test panel was engulfed in flames at Sandia's wind-shielded fire test facility for 30 minutes . The 3.05 m (10 ft) diameter pool was filled with 757 liters (200 gallons) of JP-4 aviation fuel floating atop 0.417m (16.5 in) of water. An electronic controller regulated the air flow via louvers to maintain the flame temperature at 1010°C (1850°F) at the bottom of the test piece. The test panel was suspended 0.91m (3 ft) above the initial fuel level from an insulated, water-cooled beam.

The test panel was completely disassembled post-test. As expected, the aluminum honeycomb skin melted with a portion left at the top of the test piece. The front polyurethane foam surface appeared virgin, but was charred from the back plate towards the front plate through about half of its 0.19m (7.5in) thickness due to the heat input from the back insulation. The exposed foam at the puncture hole charred through the entire thickness, but the charring did not propagate up the panel. CT-4 results support the adequacy of the TRUPACT-I body thermal design.

TRUPACT-I COMPONENT TEST 5 (CT-5): CRUSHED VERSUS UNCRUSHED ALUMINUM HONEYCOMB

In anticipation of structural damage, the thermal behavior of crushed and uncrushed aluminum honeycomb was compared. Four runs were conducted to assess the extent of aluminum melting and the thermal protection afforded by each. One 0.46 m (18 in) cubic test piece was constructed from bonded, straight cell aluminum honeycomb and one from triaxial cell. Similarly, two test pieces were constructed from crushed honeycomb.

Each test piece was exposed to the radiant heat source of 1093°C (2000°F) for 30 minutes at the Radiant Heat Facility. No significant thermal difference was found between the straight cell and triaxial cell aluminum honeycomb. The uncrushed honeycomb pieces flamed 17 minutes during the test with no significant aluminum dripping. Both crushed samples flamed for 37 minutes with extensive aluminum melt. Flaming was due to burning of the stainless steel skin adhesive and possibly the honeycomb bonding material. Approximately 0.102 m (4 in) of the uncrushed honeycomb melted. Although the remaining 0.36 m (14 in) of honeycomb appeared intact, the bond strength had significantly decreased such that it totally delaminated when an axial compressive load was applied post-test. A solid honeycomb residue remained from the crushed samples. The 0.46 m (18 in) thick uncrushed honeycomb provides better thermal protection than the 0.051 m (2 in) thick crushed aluminum honeycomb.

## TRUPACT-I COMPONENT TEST 6 (CT-6): OUTER DOOR REDESIGNS FOR THE 0.21 METER (8.25 INCH) SPACE

CT-6 was designed to evaluate the insulating value of various honeycombs filled with vermiculite. Six test pieces were constructed using vermiculite-filled, bonded aluminum and stainless steel honeycomb with various side and back surface materials (Fig. 1). Each test piece was exposed to the 1093°C (2000°F) radiant heat source for 30 minutes at the Radiant Heat Facility. In all tests, the Kevlar with plastic binder responded as in CT-1, charring and delaminating approximately 17 layers. The honeycomb samples were all intact upon disassembly with no apparent signs of thermal decomposition. The back plate temperature of 177°C (351°F) with vermiculite-filled aluminum honeycomb indicates adequate thermal protection of the TRUPACT-I inner door and seal region.

## BUSS COMPONENT TEST 1 (BCT-1): FOAM PERFORMANCE

The air ingress to typical foamed impact limiters, such as on the Beneficial Uses Shipping System (BUSS) cask [4], cannot be predicted in the hypothetical thermal accident. The foam could provide an extended heat source next to the seals if it continues to burn. The behavior of the foam in a damaged impact limiter must be understood to predict the cask seal survivability. Thus, a one-dimensional mock-up of an impact limiter with puncture damage was tested in an enclosed JP-4 fueled fire. The fire test was designed to quantify the extent of burning and to assess the resulting temperatures at the seal/lid interface.

The test piece was fabricated from a steel pipe filled with 168 kg/cu m (10.5 lb/cu ft) rigid polyurethane foam (Fig. 2). The 2.54 cm (1.0 in) air gap between the inner surface of the impact limiter and the BUSS cask lid was simulated and air access was provided using four 0.635 cm (0.25 in) diameter vent tubes. Thus, a complete air circulation path was established in the test unit to enhance burning if such phenomena were to occur. The 33.0 cm (13 in) thick stainless steel plate welded to the back end of the pipe simulated the mass of the cask lid. A 0.030 cm (0.012 in) stainless steel sheet was welded to the front end of the pipe with a 15.2 cm (6.0 in) diameter hole bored through the entire length of the foam to simulate puncture damage. To record temperatures through the foam and at the simulated lid, twenty-five thermocouples were installed. To ensure one-dimensional modeling (minimizing the heat input in the radial direction and to the back side) the test piece was insulated with five layers of 2.54 cm (1.0 in) thick fibrous blanket insulation with a nominal density of 128 kg/cu m (8 lb/cu ft).

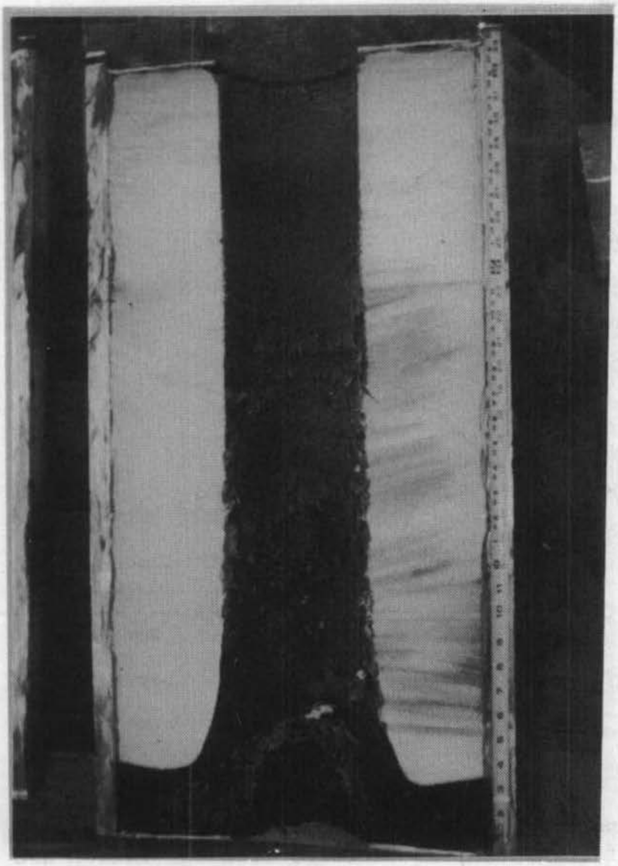

*FIG. 3. Post-test cross-section of BUSS one-dimensional impact limiter model.*

Sandia's one-tenth scale wind-shielded fire facility consists of an enclosed 1.82 m (6 ft) diameter fuel pool. Air for combustion is introduced by natural draft through four air ports symmetrically located around the perimeter of the base. The test piece was suspended 1.0 m (39.4 in) above the fuel surface from a water-cooled beam. Due to the difference in density between the fuel and water, 10.16 cm (4.0 in) of jet aviation fuel (JP-4) floated on top of 40.64 cm (16 in) of water.

The test piece was engulfed for 27 minutes with fire temperatures in excess of 980°C (1800°F). Post-test inspection of the sectioned test piece showed that fire had progressed all the way to the back of the test piece (Fig. 3). However, sometime during the test, the hole in the foam was sealed off by the extrusion of the porous char. The char separated from the virgin

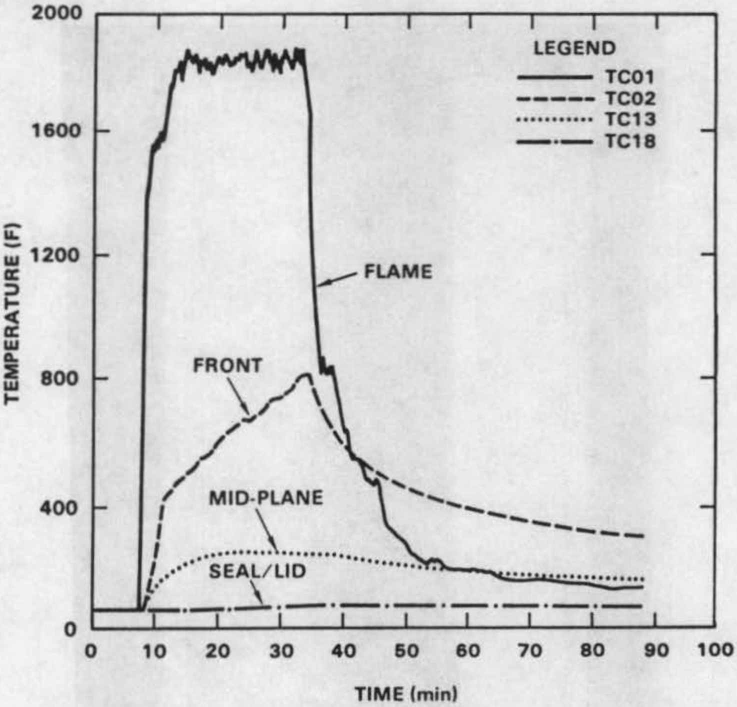


*FIG. 4. BUSS foam temperature history.*

foam and expanded inwards toward the center of the hole until the remainder of the foam was isolated from the flames and oxygen. Thus, the foam behind the char line exhibited no damage, discoloration or other degradation. Figure 4 illustrates the excellent temperature insulating properties exhibited by the foam during the fire test. No enhancement of thermal heat input to the seal area is expected as a result of the polyurethane foam present in the impact limiters.

The polyurethane foam acts as a structural member in TRUPACT-I, as well as an energy absorber and thermal insulator in the BUSS cask impact limiter and in TRUPACT-I. In both applications, the polyurethane foam chars and expands with limited amounts of air ingress. More extensive structural damage to the foam, resulting in sufficient oxygen access and heat exposure, could lead to extensive foam combustion. The foam behavior is very environment and configuration-dependent and may require more representative testing depending on the application.

## CONCLUSIONS

This extensive series of component tests provided information on the high-temperature behavior of unique materials which was not previously available or reliably attainable by numerical analysis. These tests were a timely and cost effective means of providing an indication of the thermal design validity of a structurally damaged component in a nuclear material transportation package. The material behavior presented are intended to guide the thermal designer in materials selection and analysis.

## REFERENCES

[1] Code of Federal Regulations, Title 10, Part 71 (10CFR71), "Packaging and Transport of Radioactive Materials," USGPO, Washington, DC, August 24, 1984.

[2] MATA, R., GREGORY, J. J., MOYA, J. L., A Facility for Large Item Fire Testing, SAND84-1721 (TTC-503), Sandia National Laboratories, Albuquerque, New Mexico, to be published.

[3] Transuranic Package Transporter, TRUPACT-I, Safety Analysis Report for Packaging (SARP), SAND83-7077 (TTC-0338), Sandia National Laboratories, Albuquerque, New Mexico, to be published.

[4] Beneficial Uses Shipping System Cask, BUSS, Safety Analysis Report for Packaging (SARP), SAND83-0698 (TTC-0430), Sandia National Laboratories, Albuquerque, New Mexico, December 1985.

[5] HUDSON, M. L., High Temperature Testing of TRUPACT-I Materials: Kevlar, Honeycomb, Rigid Polyurethane Foam, SAND85-1299 (TTC-0638), Sandia National Laboratories, Albuquerque, New Mexico, Fall 1986.

[6] MIHALOVICH, G. S., HUDSON, M., JOSEPH, B. J., ROMESBERG, L. E., Data Report TRUPACT-I, Unit 0, SAND85-1695 (TTC-0553), Sandia National Laboratories, Albuquerque, New Mexico, September 1985.

[7] ROMESBERG, L. E., HUDSON, M. L., OSBORNE, D. M., TRUPACT-I, Unit 0 Test Data Analysis, SAND85-0943 (TTC-0555), Sandia National Laboratories, Albuquerque, New Mexico, September 1985.