IMPACT TEST CHARACTERIZATION OF CARBON-CARBON COMPOSITES FOR THE THERMOELECTRIC SPACE POWER SYSTEM

Glenn R. Romanoski and Hui Pih
Oak Ridge National Laboratory
P.O. Box 2008, Oak Ridge, TN 37830-6088 USA

ABSTRACT

Thirty-eight unique carbon-carbon composite materials of cylindrical architecture were fabricated by commercial vendors for evaluation as alternative impact shell materials for the modular heat source of the thermoelectric space power system. Characterization of these materials included gas gun impact tests where cylindrical specimens containing a mass simulant were fired at 55 m/s to impact a target instrumented to measure force. The force versus time output was analyzed to determine: peak force, acceleration, velocity, and displacement. All impact tests exhibited an equivalence between preimpact momentum and measured impulse. In addition, energy was conserved based on a comparison of preimpact kinetic energy and measured work. Impact test results showed that the currently specified material provided impact energy absorption comparable to the best alternatives considered to date.

INTRODUCTION

The Department of Energy provides radioisotope thermoelectric generators to the National Aeronautics and Space Administration for powering deep space missions to the outer planets. These generators convert the decay heat from encapsulated radioisotope fuel into usable electricity to power a host of scientific instruments. The heat source shown in Fig. 1 is modular in design. Each module consists of a carbon-carbon composite aeroshell and two carbon-carbon composite impact shells that encapsulate four iridium-alloy-clad fuel pellets. This assembly provides thermal isolation and impact protection.

The ability of the modules to withstand impact without significant fuel clad damage was demonstrated in a series of tests [1] which simulated reentry of the general purpose heat source modules into earth atmosphere and impact at terminal velocity (55 m/s). Impact tests were conducted on single assemblies using a gas gun to accelerate modules into a hardened steel target. The impact orientation was either face-on or side-on with the longitudinal axis of the impact shell parallel to the impact target in all cases. Postimpact analysis showed that impact shells typically fractured parallel to their longitudinal axis at four locations where fiber bundles intersected at 45° to the circumferential direction. The fuel pellet and cladding deformed during impact. Although the current configuration and material has proven to be adequate, increased margins of impact performance are of interest. A program is underway to develop and...
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
characterize alternative carbon-carbon composite materials for the impact shell having greater circumferential strength and higher energy absorption.

EXPERIMENTAL PROCEDURE

Materials

The aeroshell and impact shell are currently machined from a block of Textron 3D Fineweave™ [2] carbon-carbon composite (FWPF). This material is a high density, orthogonal weave composite. Specification of a new material was guided by the early experience with the spherical impact shell of the multihundred watt, radioisotope thermoelectric generator [3] where energy absorbed during deceleration of the fuel assembly was shown to be a function of the bulk density, bulk modulus, available crush volume and crush strength. An intermediate density around 400 kg/m$^3$ above the preform density gave the greatest impact protection. Thirty-eight materials with fiber volume content ranging from 33% to 60% and densities ranging from 750 kg/m$^3$ to 1880 kg/m$^3$ were fabricated by commercial vendors. These materials shown in Table 1 included: eight different braided architectures each densified to four levels, one fine-weave cylindrical architecture densified to four levels and one coarse-weave cylindrical architecture densified to two levels. All composites were fabricated using polyacrylnitrile fibers and pitch or resin matrix precursor. The objective in fabricating alternative materials was to make a crushable structure which would be compacted during impact. The impact shell would then protect the fuel pellet by extending the time and distance over which it came to rest, thus reducing deceleration loads. The currently specified FWPF material was also evaluated to serve as a comparative baseline.
Impact Test

The simple and economic impact test shown in Fig. 2 was developed to evaluate candidate materials. Impact tests were performed at room temperature using a low pressure gas gun. Single specimens of candidate material containing one copper mass simulant were fired against a hardened steel anvil at 55 m/s. The ability of candidate materials to protect the mass simulant should be an indication of their ability to protect the radioisotope fuel. Each composite material was machined to the nominal impact shell configuration, but only half the standard length and had no closures. A reflective foil was adhered to one end of each specimen to allow for optical measurement of velocity using proximity sensors. The mass simulants were machined from oxygen-free electrical copper to have a geometry identical to the external geometry of the iridium alloy clad. The average mass of the copper simulants was 0.178 kg. This value compares to 0.216 kg for the iridium-alloy-clad fuel pellets.
The impact transducer was an aluminum cylinder strain gaged to provide a calibrated measure of force versus time during impact of the carbon-carbon composite specimen and mass simulant with the hardened steel anvil. Four orthogonally positioned strain gages, two transverse and two longitudinal, were wired into a full Wheatstone bridge so that the output of the bridge was about 2.6 times that of a single longitudinal gage. A signal conditioning amplifier with 125 kHz frequency response completed this force measuring system. The transducer was calibrated quasistatically in a mechanical test machine from 0 to 222.4 kN and showed an error of less than 1%. The analog force signal was filtered using an active lowpass filter set at 6 kHz to remove the reflected wave signal from the load cell output. The filtered signal was then digitized at a rate of 10^6 samples per second using a high-speed input board. The data acquisition system is built around a 486-50 MHz personal computer using LabVIEW software [4].

![Figure 2. Illustration of the impact test.](image)

**RESULTS AND DISCUSSION**

A Qualitative Assessment

The following general observations can be made concerning the post-test condition of the carbon-carbon composite impact specimens and mass simulants. The impact surface of the composite specimens disintegrated into small fragments leaving highly compressed graphitic debris adhered to the impact surface of the copper mass simulants. The multilayer braided architecture materials exhibited delamination in the balance of the specimen. The FWPF material also disintegrated at the impact surface leaving three segments resulting from failure of the 45° weak planes. The impact left a deformation flat on the mass simulants indicating that they had not come to rest after full compaction of the 4-mm thick specimen wall. It would be impossible to make a numerical ranking of the impact protection provided by these 38 unique materials based on visual observations alone.
A Quantitative Assessment

The force versus time pulse contains the information needed to fully characterize the impact. Force versus time can be converted to acceleration versus time by using Newton's second law.

\[
a(t) = \frac{F(t)}{m}
\]  \hspace{1cm} (1)

where \( t \) is the time, \( a \) the acceleration, \( F \) the force, and \( m \) the total mass of the decelerating specimen and mass simulant. This acceleration versus time relationship can be converted to a velocity versus time relationship using the equation

\[
v_t = v_o - \int_o^t a \, d\tau = v_o - \int_o^t \frac{F}{m} \, d\tau
\]  \hspace{1cm} (2)

where \( v_t \) is the velocity at elapsed time \( t \) and \( v_o \) the initial velocity, i.e., just before impact when \( t = 0 \). Similarly, the velocity versus time relationship can be used to determine the deformation versus time relationship by using the expression

\[
X_t = \int_o^t v_o \, d\tau = \int_o^t v_o \, d\tau - \int_o^t \int_o^t a \, d\tau \, d\tau
\]  \hspace{1cm} (3)

where \( X_t \) is the displacement at elapsed time \( t \), i.e., deformation of the impact shell assembly. Knowing the force versus time relationship and the deformation versus time relationship, the energy absorbed can be calculated from the expression

\[
U = \int_o^X F \, dX
\]  \hspace{1cm} (4)

where \( U \) is the energy absorbed for a specific amount of deformation, and \( X \) the deformation. At the end of the impact, at which time the velocity has become zero, the calculated absorbed energy should be approximately equal to the kinetic energy of the pre-impact assembly less the work associated with irreversible processes such as deformation and fracture. Consider Eq. (2) for the case when the impact event is completed, the impact assembly has come to rest, i.e., \( v_t = 0 \) then

\[
v_o \, m = \int_o^t F \, d\tau
\]  \hspace{1cm} (5)

where \( v_o \, m \) is the momentum just before impact and the integral of the force versus time curve up to the peak force is the impulse required to arrest the specimen and mass simulant. In this case, momentum is conserved during impact.

The primary data from the impact was a measure of actual velocity just before impact and the force versus time pulse from the impact transducer, i.e., the reaction force of the anvil acting on the impact specimen and mass simulant as they came to rest. Consider, for example, the impact test of braided architecture FMI 4-4 having a density of 1370 kg/m³ and a highly circumferential fiber lay-up. The mass of the impact specimen and copper mass simulant were, 0.0251 kg and 0.1781 kg, respectively. A total mass of 0.2032 kg was used as the impact mass. Measured pre-impact velocity was 55.6 m/s. The force versus time curve of Fig. 3 shows the peak force was 103 kN and the impact duration approximately 150 \( \mu \)s. The impact event was considered to be complete, i.e., the specimen and mass simulant had come
to rest \( (v = 0) \), near the peak force where the impact transducer was at full compression. The decay side of the force versus time curve represents elastic decompression of the impact transducer with, perhaps, some continued residence of the specimen and mass simulant as they rebounded. According to Eq. (5), the integral of the force versus time curve up to the maximum force, the impulse, should be equivalent to the momentum \( (m \cdot v = 11.30 \text{ kg} \cdot \text{m/s}) \). This analysis was automatically made by the data acquisition program. They are in fact precisely equivalent if the upper limit of integration is taken to be approximately 7 \( \mu \text{s} \) beyond the actual peak. This was the point at which the impact transducer began to decompress. Thus, momentum was conserved in every impact test.

The velocity versus time curve for impact test FMI 4-4 is shown in Fig. 3. Impact began at \( \tau = 70 \mu \text{s} \) where the velocity began to decrease and was complete at \( \tau = 220 \mu \text{s} \) where the velocity equals zero. This curve was generated by integrating the acceleration versus time curve according to Eq. (2) and is representative of all tests.

The displacement versus time curve for impact test FMI 4-4 is also given in Fig. 3. This curve was generated by integrating the velocity versus time curve according to Eq. 3. The displacement experienced by the impact mass from the beginning to the end of impact, i.e., from \( \tau = 70 \mu \text{s} \) to \( \tau = 220 \mu \text{s} \), was 5 mm. This value is consistent with the physical evidence. Full compression of the 4-mm thick impact specimen wall plus a 1-mm deep indentation on the mass simulant accounts for a total displacement of 5 mm for the specimen's nominal center of gravity. This displacement versus time curve is representative of all tests.

Figure 3. Impact test results for braided architecture specimen FMI 4-4
The force versus displacement curve for impact test FMI 4-4 was achieved parametrically from the force versus time curve and the displacement versus time curve of Fig. 3. The integral of the force versus displacement curve up to maximum displacement according to Eq. (4) is equivalent to the work done by decelerating the impact specimen and mass simulant. The work measured in test FMI 4-4 was 305 N·m. This value compares to a total kinetic energy of \((0.2032 \text{ kg})(55.6 \text{ m/s})^2 = 314 \text{ N·m}\). Hence, energy was nearly conserved during impact. This force versus displacement behavior and energy work balance is representative of all tests.

It was generally anticipated that the material which could provide the greatest impact protection would decelerate the mass simulant more slowly and thus have a lower peak force. The data suggests a relationship between density and impact protection. Peak impact force is plotted versus density in Fig. 4. The general trend was for peak impact force to decrease almost linearly with density until about 1400 kg/m³ where a plateau around 100 kN was reached. Peak impact force was less strongly dependent on circumferential strength. Even H-451 graphite containing no carbon fibers and having a circumferential strength of only 15 MPa provides a comparatively good level of impact protection. The reason for the 100 kN plateau observed in Fig. 4, rather than a continuous decrease with respect to increasing density is presently unresolved. Since all mass simulants were at least somewhat flattened, the peak force was likely associated with the force required for plastic flow of the copper simulant. The peak force was greater for the least protective materials because the mass simulant had greater residual velocity after full compaction of the 4-mm thick specimen wall. Hence, the magnitude of the peak force is a quantitative indication of impact protection.

The results to date suggest that a 4-mm thick impact shell wall fabricated from any given carbon-carbon composite may be incapable of decelerating a clad without some deformation. This is not a reasonable conclusion if one considers that the deceleration of the impact shell and its contents is further aided by crushing of the FWPF aeroshell wall along an internal area.
of contact with the outside surface of the impact shell. The aeroshell has a 5-mm minimum thickness at this location. A more realistic impact test for impact shell candidates would include the impact protection provided by the aeroshell. Additional tests were performed wherein the impact anvil was covered with a 5-mm thick coupon of FWPF to simulate the protection of the aeroshell. Five impact tests were conducted in this manner using four of the thirty-eight new impact shell materials and one test of FWPF impact shell material. These results are also shown in Fig. 4. The additional protection of the FWPF coupon resulted in a significant reduction in the peak impact force. For these five impact experiments, the copper mass simulants showed absolutely no deformation. This is not, however, an indication that deformation of the iridium-clad fuel would not have occurred. Additional tests will be performed using nickel-clad hafnia mass simulants which should provide greater mechanical similitude with the fuel pellets.

CONCLUSIONS

The impact test method presented here has proven successful in defining the ability of alternative materials to protect a mass simulant at 55 m/s. Impact protection was strongly dependent on density with higher density carbon-carbon composites providing the greatest impact protection. The currently specified material provided impact energy absorption comparable to the best alternatives considered to date. A modified impact test configuration which better simulates the intervening aeroshell may provide a better comparison of material energy absorption.

ACKNOWLEDGEMENTS

This work was sponsored by the Department of Energy Office of Space and Defense Power Systems, Radioisotope Power Systems Division. Credit is due Mr. Charles Whoosley, National Instruments for contributing significantly to data acquisition software development.

REFERENCES

2. Textron Specialty Materials, 2 Industrial Avenue, Lowell, MA 01851
4. National Instruments, 6504 Bridge Point Parkway, Austin, TX 78730-5039

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.