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REPORT

on

GOALS OF RTG IMPACT MEMBER RESEARCH

by

W. H. Duckworth

May, 1978

Prepared for Advanced Systems and Materials Production
Division, U. S. Department of Energy
Under Contract No. W-7405-eng-92 Task 94

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GOALS OF RTG IMPACT MEMBER RESEARCH

by

W. H. Duckworth

INTRODUCTION

During recent years, Battelle has been engaged in research on impact members of radioisotope thermal generators (RTGs) for space use.⁽¹⁾ Emphasis in the research to date has been on developing a materials technology. This effort has now reached a stage where consideration can be given to engineering measures for assessing and upgrading the performance of impact members in RTGs of current interest, including particularly General Electric Company's Multi-Hundred Watt (MHW) RTG and the General Purpose Heat Source (GPHS) being developed by Los Alamos Scientific Laboratory. New research goals have been set accordingly. The purpose here is to present these goals, give the rationale for them, and indicate the research approaches for meeting them.

STATEMENT OF PROBLEM

In RTGs for use in space, the PuO_2 fuel is contained in a ductile refractory metal cladding. Surrounding the metal-clad fuel is a shell of carbon-base material whose function is to prevent rupture of the cladding in the event of impact with a rigid target. Since the cladding can stretch appreciably without rupturing, it is not intended that the impact shell dissipate all of the available energy. The fuel can deform and consume energy to the extent that it does not experience a surface strain sufficient to rupture the cladding.

The effectiveness of an impact member depends on the energy it dissipates on a weight or thickness basis in the most severe impact anticipated for the fuel assembly. Impact materials, therefore, can be rated according to their energy-absorption capacity under appropriate loading

conditions, but with an important stipulation - the impact material must have properties that cause it to absorb energy in preference to the PuO_2 fuel during deceleration of the impacting mass. Any energy absorbed by the impact member subsequent to rupture of the metal cladding or after the fuel's energy-absorption capacity is exhausted is, of course, worthless. In nonprecise terminology, this means that the impact material must be "softer" than the fuel, as will be explained.

Initially, the impact loading will generate rapidly increasing stresses in both the impact member and the fuel; i.e., kinetic energy is converted to stored strain energy in both components. Following this, the strain limit of either the impact material or PuO_2 will be reached, causing it to yield by either fracturing or plastic flow*. The basic nature of the process changes at this point to one in which energy is consumed, and if the impact member is the component which suffers damage, it has started to perform its function. Ideally this will be the case, but whether it will obtain depends on the rates of stress build-up, on stress distributions, and on the stress levels at which yielding occurs in both the impact member and the fuel. These factors are difficult to assess. Even more difficult to assess is the effect of progressive damage on stresses experienced by each component, and this effect will largely determine whether the ideal result is obtained - that of impact member continuing to consume energy in preference to the fuel after sustaining initial damage.

RESEARCH GOALS

The initial thrust of future research on the problem would be directed to the key question of how much energy the impact member of the MHW on GPHS consumes prior to extensive fuel damage, and then to improving the member's performance by appropriate material adjustments. In case the impact member consumes energy in preference to the fuel, as desired, the adjustments to be made would be aimed at increasing the material's energy absorption capacity, and in case the fuel consumes energy first a "softer" impact material would be sought.

*Investigation revealed that there is little prospect of developing an impact member that would not undergo damage; i.e., dissipation of the impact energy through elastic recoil is not a promising approach. (2)

REVIEW OF PAST RESEARCH

In the Battelle research to date, emphasis has been on developing knowledge of the properties and behavior of carbon-based materials needed to permit sound engineering practices in selecting, testing, developing, and optimizing them for impact-member use.

Carbon-base materials do not exhibit plastic flow at impact-member temperatures, limiting the practical mechanisms for energy dissipation to that consumed in the formation of new surface by fracturing; i.e., by work of fracture. In fracturing, a carbon-base impact member might either shatter or crush, and the member's performance depends on which of these two fracture behaviors obtains. Much higher energy-absorption capacities are associated with crushing than with shattering.

Studies of various types of carbon-base materials indicate that rather simple fracture-mechanics tests in which a single crack is propagated in the specimen can reveal the tendency of a material to crush.⁽³⁾ High ratios of the total energy consumed in breaking a standardized specimen, U_f , to that required for crack initiation, U_i , are indicative of a strong crushing tendency. Bulk graphite were found to exhibit very small U_f/U_i ratios while 2-D carbon-carbon composites with fibers aligned normal to the propagating fracture crack had large ratios. Among the carbon-base materials investigated the 2-D golf-ball wound composite used in the MHW RTG exhibited by far the highest ratio.

The 2-D carbon-carbon composites also were found superior on a thickness basis to other types of carbon-base materials with respect to energy-absorption capacity. In tests using a loading configuration that approximated impact-member service, capacities of 3-D composites varied widely, with the best equivalent to the worst 2-D composite. Carborundum Company's "Carbitex 700", a 2-D cloth lay-up composite, exhibited the greatest energy-absorption capacity. As an indication of "hardness", the maximum load sustained by specimens in this test ranged among the 2-D composites from 3350 to 9500 lb, with the MHW golf-ball wound composite being softest.

Considering all three essential qualities - crushing tendency, energy-absorption capacity, and "hardness", the golf-ball wound composite was judged the best carbon-base material for impact-member service. Detailed studies therefore were made to characterize and understand its performance as an impact member.⁽⁴⁾ A first question was whether it could consume a significant portion of the impact energy in the most severe impact anticipated for the MHW. This energy is about 15,000 in.-lb (1-pound fuel assembly impacting at 285 ft/sec). Tests of actual MHW impact shells indicated that they had the capacity to absorb ~ 7500 in.-lb of energy, or about half that required to completely decelerate an MHW fuel assembly at the maximum expected impact velocity. This potential for energy dissipation is considered significant if it is realized. However, as discussed above, whether it is realized or not depends on whether the PuO_2 fuel is "hard" or "soft" relative to the impact-member material. The importance of this factor was clearly shown in tests of MHW impact shells with soft (plastic) fuel simulants in which the shell dissipated only a few hundred in.-lb of energy, and failed from hoop tension due to lateral fuel expansion rather than from crushing as in the case of a hard fuel simulant (steel).

Studies of the load-deformation behavior of golf-ball wound shells during crushing and of debris from crushed shells have provided important insight on the mechanism of energy consumption and of factors controlling hardness. The standard shell made from Thornel 50 graphite yarn yields under about 30,000 lb load after it has compressed to about half its original thickness. The load drops gradually with continued thinning until a hole is opened at the crushed site. With complete crushing (when the energy-absorption capacity is exhausted), the crushed debris contained fibers broken into very short lengths, -- of the order of the fiber diameter. Prior to this, the debris featured longer lengths of broken fiber, suggesting that energy consumption is associated with breaking of fiber into progressively shorter lengths.

The onset of yielding apparently occurs when fibers begin breaking, and subsequent yielding behavior appears to be controlled by progressive fiber breakage. Tensile stresses to cause fiber breakage and the consumption

of energy through the formation of new surfaces could be developed during the compressive loading from bending of one fiber over another, or they could be the result of Hertzian contact stresses in the fiber surfaces. In either case, the load required to initiate yielding would depend significantly on the tensile strength of the fiber used in the composite. This dependency was confirmed in tests of special shells made with various graphite fibers. Yielding tended to occur at higher loads with stronger fibers. Thus, the hardness of an impact shell can be adjusted by changing to a stronger or weaker fiber as needed. Although it is a predominant factor, fiber strength alone however does not control shell hardness, no doubt because the level of tensile stress in an individual fiber subjected to given load depends on its cross section and on details of the fiber array in the composite.

By changing the fiber from which impact shells were made, the load at which yielding occurred was varied by more than a factor of two. As might be expected, energy absorption capacity generally increased with the yield load, and observed capacities varied by about a factor of two depending on the fiber used to make the shell.

Yielding load as well as energy-absorption capacity was found to increase with shell thickness. Temperatures to 2500 F had little effect on energy absorption or hardness of the impact shells, making room-temperature data applicable in interpreting performance at service temperatures.

Study of the effects of loading rate is incomplete. Initial results indicate that the hardness of an impact shell increases with loading rate as expected, but there appeared to be no basic difference in performance attributable to loading rate. With respect to hardness, the yielding load of an MHW shell increased from the static value of 30,000 lb to 38,000 lb when loaded at 150 ft/sec.

Interestingly, the shell in the high-loading rate tests caused complete deceleration from 150 ft/sec without exhausting its energy-absorption capacity and there was no apparent damage of the hard fuel simulant (steel) or the target. The energy absorbed in crushing the shell was practically

equivalent to the available kinetic energy. In contrast, tests under the same conditions of an ATJ bulk graphite shell resulted in damage to both the steel fuel simulant and target. This dramatic difference in results with the two fuel simulants demonstrates the importance of using an impact material that is crushable; i.e., has sufficient lateral tensile strength to retain the material between fuel and target so that it may be crushed. The carbon-carbon shell performance in the test demonstrates that fuel deformation can be completely prevented with a soft impact member when the impact energy is within the energy-absorption capacity of the member.

RECOMMENDED FUTURE WORK

Two general approaches are recommended for answering the key question of how much energy the impact member dissipates prior to extensive fuel damage. In one approach, impact tests of actual MHW or GPHS fuel assemblies would be made at velocities near those to provide kinetic energies equivalent to the energy-absorption capacity of the impact shell. If little or no damage is experienced by the fuel, it would indicate that the shell material is performing effectively. On the other hand, if damage to the fuel is extensive, it would indicate that the shell is too hard.

In the other approach, debris from impact shells of actual fuel assemblies after tests at maximum anticipated impact velocities would be examined to determine the extent and nature of fiber breakage and, from this, an estimate of the energy absorbed by the shell would be obtained. This approach requires a special study of debris from shells damaged in controlled laboratory tests in which known amounts of energy have been consumed by the shell in producing the damage.

Work on these approaches can proceed now with standard MHW shells, but in the case of GPHS fuel assemblies the work must await fabrication of special 2-D carbon-carbon composite shells and characterization of their energy-absorption capacities for different impact orientations.

Once it is determined whether or not significant energy consumption by the impact shell precedes extensive damage of the fuel, work would

concentrate on improving the impact material. If it is found that the impact material is too hard, approaches discussed earlier can be used to soften it. On the other hand, if it is found that energy consumption by the impact material precedes that by the fuel, effort would be directed to increasing the material's energy-absorption capacity, again following approaches discussed previously.

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