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MASTER

SIZE EFFECT ON THE IRRADIATION PERFORMANCE OF COATED FUEL PARTICLES

by
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SEPTEMBER 1980

GENERAL ATOMIC COMPANY

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SIZE EFFECT ON THE IRRADIATION PERFORMANCE OF COATED FUEL PARTICLES

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ABSTRACT

Outer coatings that were as near alike as possible were applied to two different sizes of inert TRISO particles that were larger than those commonly used to fuel HTGR reactors, and these particles were then irradiated in a test reactor to observe the influence of particle size on outer coating failures that resulted from irradiation-induced shrinkage of coatings onto the more stable SiC substrates over which they were applied. Outer coatings of plain pyrocarbon and of Si-alloyed pyrocarbon were used to make up two test pairs of particles with diameters of about 1050 μm and 1300 μm . For a fast-neutron fluence of $5.5 \times 10^{25} \text{ n/m}^2$ ($E > 29\text{fJ}$) at an irradiation temperature of 1125 K, failure was about twice as high in the larger 1300 μm particle of each test pair as in the smaller 1050 μm particle (16% versus 8%), with each of the coating types having roughly the same behavior. This observed size effect is somewhat greater than predicted by volume-dependent Weibull theory, which estimates failure of the larger size particles at 13% when the smaller size particles fail at a rate of 8%. However, experimental uncertainties are sufficient to account for the difference between observed size effects and those predicted by Weibull theory. The conclusion that the irradiation performance of coated particles is size dependent is reinforced by the fact that failure for regular 850 μm fueled particles in the same irradiation test was essentially zero.

1. Introduction

Nuclear fuel particles of the type used in high-temperature gas-cooled reactors (HTGRs) consist of a spherical fuel-containing substrate that is surrounded by a gas-tight structural coating for holding fission products within the particle. The particle substrate itself consists of a spherical kernel of nuclear fuel that is over-coated with spongy pyrocarbon to form the so-called buffer layer, which serves to: isolate the structural coating from mechanical interactions caused by the kernel swelling accompanying fission product accumulation, stop energetic recoil atoms ejected from the kernel by nuclear reactions, and provide void volume for accommodating gaseous fission products. The structural coating surrounding this substrate can be a discretely layered composite material, such as silicon carbide (SiC) sandwiched between dense pyrocarbon (PyC) layers as in TRISO fissile particles, or it can be a single composition, such as the dense pyrocarbon used in BISO fertile particles. In addition, any of the individual structural layers above can consist of a dispersed composite, such as PyC and SiC simultaneously deposited to form a so-called Si/PyC alloy.

The structural coatings on fuel particles are brittle materials that can withstand extremely high temperatures, but as such they should also be expected to show the same type of strength dependence on size that has been observed for other brittle materials [1]. Thus, as the particle substrate size increases, more irradiation-induced coating

failure should begin to occur for the same level of coating stress near the design limit of a fuel particle. However, this size effect is often obscured in irradiation testing of actual fuel particles within the rather narrow size range used because of complications that arise as a result of the several competing failure mechanisms that operate in fueled particles, with these mechanisms being sensitive in various degrees to neutron fluence, irradiation temperature, temperature gradient, fuel burnup, and fission-product concentration [2]. Many of these complications can be eliminated through the use of special diagnostic particles in which the nuclear fuel in TRISO-coated particles is replaced by an inert carbon kernel, leaving only the restrained-shrinkage mode of failure operative in which the outermost layer of the composite structural coating fractures because of the stress buildup caused by irradiation-induced shrinkage of the outer coating layer onto the more dimensionally stable underlying SiC layer. In the irradiation experiment to be reported on herein, the size effect on the strength of the outermost coating layer in inert TRISO particles was evaluated by testing particles of different sizes that had both PyC and alloyed Si/PyC coatings.

2. Coating Failure Theory

To better understand the simplifications resulting from the use of inert TRISO particles in studying the size dependence on coating failure, a brief sketch will be given of the often dominant pressure-vessel mode of failure in fueled particles and of the sole failure mode of restrained shrinkage in inert TRISO particles, which also operates in fueled TRISO particles.

2.1 Pressure-Vessel Theory

The tangential tensile stress within the structural coating of a loose fuel particle resulting from the exertion of a uniform fission-gas pressure P against the inner surface of the spherical coating shell is given as a function of the radial distance r from the center of the fuel kernel by [3]

$$\sigma_t(r) = \frac{P}{2} \left[\frac{r_i^3 (r_o^3 + 2r^3)}{r^3 (r_o^3 - r_i^3)} \right], \quad (1)$$

where r_i and r_o are radial distances from the center of the spherical fuel particle to the inner and outer surfaces of the structural coating, respectively. Therefore, the stress will have a maximum value at the inner surface of the coating of

$$\sigma_t(\max) = \sigma_t(r_i) = \frac{P}{2} \left[\frac{3r_i^3}{r_o^3 - r_i^3} + 1 \right] \quad (2)$$

and will fall off steadily with depth into the coating to reach a value at the outer surface of

$$\sigma_t(r_o) = \frac{P}{2} \left[\frac{3r_i^3}{r_o^3 - r_i^3} \right] = \sigma_t(\max) - \frac{P}{2}. \quad (3)$$

Equation (2) can be rewritten as

$$\sigma_t(\max) = \frac{P}{2} \frac{r_i}{r_o - r_i} \left[1 + \frac{(1 + r_o/r_i)(r_o - r_i)^2}{r_o^2 + r_o r_i + r_i^2} \right], \quad (4)$$

and when the coating thickness $t = r_o - r_i$ is thin in relation to the

substrate radius r_i , this can be approximated by

$$\sigma_t(\max) \approx Pr_i/2t. \quad (5)$$

Thus, in the thin-shell approximation, the maximum stress in a coating caused by a given internal gas pressure alone is directly proportional to the substrate radius and is inversely proportional to the coating thickness. However, other mechanical stresses in the coatings are caused by their irradiation-induced shrinkages [4], and at the same time these stresses are being partially relieved during high-temperature irradiation by creep. Thus, mechanical stresses in the coatings are sufficiently complicated to require complex computer programs for their computation [5]. Nevertheless, in principle, one could design fuel particles of different sizes and test the influence of this on mechanical strengths of coatings stressed to the same level through combined effects of pressure buildup, coating shrinkage, and coating creep. However, even this is further complicated in fueled particles by degradation of coating strength caused by fission-product attack and by kernel migration into coatings [2]. It is very difficult, therefore, to isolate size effects in actual fuel particles, particularly since these effects have generally been relatively small for the range of particle sizes previously tested. This is why the elimination of all failure mechanisms other than restrained shrinkage through the use of inert TRISO particles is of great advantage in such a study.

2.2 Restrained-Shrinkage Theory

The stress state caused by the restrained irradiation-induced

shrinkage of the outermost layer in the triplex structural coating of a TRISO particle, in which the outer coating of inner radius r_j would undergo a radial shrinkage strain of $\Delta r_j/r_j$ if unhindered by the substrate sphere bounded by the dimensionally stable SiC layer, is conceptionally equivalent to that arising from forcing a separate substrate sphere into the smaller spherical cavity within a coating shell despite a mismatch in the radius of Δr_j . One can imagine accomplishing this by applying the same uniform interfacial pressure P_i inside the coating shell and on the surface of the substrate sphere and then adjusting the pressure so that the misfit Δr_j in the radius disappears, which will occur when the sum of the absolute values of the resulting radial expansion of the outer shell and of the radial compression of the substrate sphere is equal to the shrinkage misfit.

Considering the coating shell first, which has a modulus of elasticity E_c and a Poisson's ratio ν_c , the expansion there will be given by [6]

$$\Delta r_c = \frac{r_j P_i}{2E_c} \left[\frac{2r_j^3(1-2\nu_c) + r_o^3(1+\nu_c)}{r_o^3 - r_j^3} \right], \quad (6)$$

and the tangential tensile stress that results in the coating will again be described by Eq.(1), where the inner radius r_j of the outermost coating layer is now substituted for the inner radius r_i of the entire structural coating composite and the interfacial pressure P_i caused by restrained shrinkage is substituted for the fission-gas pressure P . Likewise, the

decrease in radius of the substrate sphere will be given by [6].

$$\Delta r_s = r_j P_i (1 - 2\nu_s) / E_s. \quad (7)$$

Therefore, the total shrinkage misfit Δr_j will be given by the sum of Eqs. (6) and (7), and this result can be solved to find the unknown interfacial pressure needed to make the radial misfit Δr_j disappear. This pressure P_i , in turn, can be substituted into Eq.(1), where $r_i = r_j$ and $P = P_i$, to obtain the restrained-shrinkage tensile stress in the tangential direction as a function of the radius r into the outermost coating layer as

$$\sigma_t(r) = \frac{\Delta r_j / r_j}{2K} \left[\frac{r_j^3 (r_o^3 + 2r^3)}{r^3 (r_o^3 - r_j^3)} \right], \quad (8)$$

where

$$K \equiv \frac{2r_j^3 (1 - 2\nu_c) + r_o^3 (1 + \nu_c)}{2E_c (r_o^3 - r_j^3)} + \frac{1 - 2\nu_s}{E_s}. \quad (9)$$

Therefore, the maximum tensile stress will occur at the inner surface of the outer coating layer, and since the second term in Eq.(9) is negligible in comparison to the first term for $r_j \gg (r_o - r_j)$, this maximum stress will have a value of

$$\sigma_t(\max) \approx \frac{E_c (\Delta r_j / r_j) (r_o^3 + 2r_j^3)}{r_o^3 (1 + \nu_c) + 2r_j^3 (1 - 2\nu_c)}. \quad (10)$$

Moreover, for the extremely thin coatings considered in this study, the error in maximum stress will not be greater than 5% if one sets $r_j = r_o$ in Eq.(10) to obtain

$$\sigma_t(\max) \approx E_c (\Delta r_j / r_j) / (1 - \nu_c). \quad (11)$$

Thus, within the approximations made, the maximum restrained-shrinkage stress in a coating is independent of the size of the substrate sphere on which the coating is applied and of the thickness of the coating. Also, the stress is essentially constant throughout the coating thickness, having the value given by Eq.(11). Theory also predicts that stresses will be independent of particle size for well-separated spherical inclusions cast within a continuous matrix that shrinks down onto the particles during cool-down following high-temperature fabrication [7]; this is mathematically equivalent to the shrinkage problem considered here, except that the outer radius of matrix in the composite is large in relation to the particle radius (which is the opposite extreme to the thin-shell approximation holding for a fuel particle) and Eqs. (8) and (9) then reduce to give a maximum matrix tensile stress at the particle interface of [7]

$$\sigma_t(\max) = \frac{(\Delta r_j / r_j)}{2} \left/ \left[\frac{1+\nu_c}{2E_c} + \frac{1-2\nu_s}{E_s} \right] \right. \quad (12)$$

2.3 Weibull Size Effect

Now, according to Eq.(11), shrinkage stresses will be the same in outer coatings of the same type no matter what the size of the SiC-coated substrate particle to which they are applied. However, according to Weibull theory [8], not only the stress but also the size of a brittle material is important in determining its failure probability, with more failure occurring at the same stress as the size increases. The basic idea here is that the worst flaw present in a uniformly stressed brittle material will govern its strength and that the severity of the

flaw will increase as the sample size increases, thereby lowering the strength. The Weibull probability of survival for a brittle specimen having flaws distributed throughout its volume is given for a multiaxial stress state in which all stresses are tensile in nature by [9]

$$S = \exp \left\{ - \int \left[\frac{2m+1}{2\pi} \int_0^{\pi/2} \int_0^{2\pi} \left(\frac{\sigma_n}{\sigma_0} \right)^m \cos \phi d\psi d\phi \right] dV \right\}, \quad (13)$$

where m is the Weibull shape parameter or modulus and σ_0 is the scale parameter.

The quantity inside the brackets in Eq. (13) is general for any application and represents integration of the normal tensile stress σ_n over one half the surface of a unit sphere centered at the coordinate origin for the actual specimen geometry, over which the indicated volume integration is taken. For a triaxial stress state, the normal stress at each point on the unit sphere is given in terms of the principal stresses involved by [9]

$$\sigma_n = \cos^2 \phi (\sigma_x \cos^2 \psi + \sigma_y \sin^2 \psi) + \sigma_z \sin^2 \phi,$$

with ϕ and ψ being the usual angles of latitude and longitude in the spherical coordinate system (Fig. 2 of Ref. 9). When the specimen in question is a spherical coated particle, one can set $\sigma_x = \sigma_y =$ tangential stress σ_t and $\sigma_z =$ radial stress σ_r , so that in general

$$\sigma_n = \sigma_t \cos^2 \phi + \sigma_r \sin^2 \phi.$$

However, the radial stress from restrained shrinkage is small in thin coating shells, being proportional to $r_0^3 - r^3$ instead of $r_0^3 + 2r^3$ as for tangential stresses [3], and to a good approximation $\sigma_r \approx \sigma_t \cos^2 \phi$.

Moreover, σ_t for restrained shrinkage is essentially constant in a thin coating, having the value given by Eq.(11) throughout the coating. Therefore, rewriting Eq. (13) in the form $S = \exp (-B)$, one has for this case

$$\begin{aligned} B &= \int_V \left[2m+1 \left(\frac{\sigma_t}{\sigma_0} \right)^m \int_0^{\pi/2} \cos^{2m+1} \phi d\phi \right] dV \\ &= m \pi^{1/2} \left(\frac{\sigma_t}{\sigma_0} \right)^m \frac{\Gamma(m)}{\Gamma(m+1/2)} \int_{r_j}^{r_0} 4\pi r^2 dr \\ &= \frac{4\pi}{3} (r_0^3 - r_j^3) \left(\frac{\sigma_t}{\sigma_0} \right)^m \frac{m\pi^{1/2} \Gamma(m)}{\Gamma(m+1/2)}, \end{aligned}$$

where $\Gamma(x)$ is the Gamma function of argument x , so that

$$S = \exp \left[- V_{\text{shell}} \left(\frac{\sigma_t}{\sigma_0} \right)^m \chi f(m) \right]. \quad (14)$$

Hence, if outer coatings of near constant thickness and structure are applied to inert substrate spheres of two different sizes to give outer coating volume of V_1 and V_2 , then irradiation survival probabilities for the two sizes of particles under the same stress state should from Eq. (14) satisfy the relationship

$$\frac{\ln S_1}{\ln S_2} = \frac{V_1}{V_2}, \quad (15)$$

with ratios of mean coating strengths for the two sizes of particles following the usual uniaxial-tensile formulation of

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{V_2}{V_1} \right)^{1/m} \quad (16)$$

Equation (15) will be used to compare measured and calculated values of $\ln S_1 / \ln S_2$ to see how well Weibull size predictions agree with the observed irradiation survivability of inert TRISO particles.

3. Experimental Details

Two sizes of inert TRISO particles having similar outer coatings consisting of both plain pyrocarbon (particles A and D) and of a Si/PyC alloy (particles B and E) were irradiated in the High-Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) during capsule test HRB-15B[10], which began in July of 1978 and terminated in January of 1979. These particles were exposed to fast-neutron fluences that ranged from about 3.4 to $6.5 \times 10^{25} \text{ n/m}^2$ ($E > 29 \text{ fJ}$), and the nominal irradiation temperature for all particles was about 1125 K . A description of these two pairs of test particles in terms of their components is given in Table 1, along with deposition conditions for their outer coatings that were being tested. Particle sizes were controlled by varying the thickness of the inner pyrocarbon layer, with this layer being roughly twice as thick for the larger $1300\mu\text{m}$ particle of both test pairs as for the smaller $1050\mu\text{m}$ particle. Other coating thicknesses were roughly comparable for all particles. Relative sizes of the two particle pairs are illustrated in Figures 1 and 2, which show typical intact particles following irradiation.

The deposition rate of Table 1 strongly influences the structure and related irradiation behavior of particle coatings. To isolate the influence of particle size on the irradiation performance of coated particles, it is necessary that the orientations of crystallites within outer coatings on the different size particles be similar enough to produce comparable dimensional strains [4]. Otherwise, the $\Delta r_j/r_j$ term of Eq. (11) will be different for the two sizes of test particles at a common fluence, and consequently the requirement that size effects be evaluated by comparing failure fractions of the different particles at a common stress will not be satisfied. For a given deposition temperature, the coating rate seems to be the most important variable with regard to lattice orientation and the related dimensional changes of coatings under irradiation [11]. In particular, irradiation-induced dimensional strains for coatings deposited at about the same temperature have near-constant minimum values for coatings deposited at rates greater than 42 m/Gs (2.5 $\mu\text{m}/\text{min}$), but strains increase sharply if the coating rate falls much below this value [11]. The coating rates for both pairs of test particles were greater than this critical value (Table 1), so that dimensional strains at a common fluence for each particle in a test pair should be approximately the same.

Within the HRB-15B irradiation capsule, inert particles of each of the types described in Table 1 were stacked on one another in single columns to fill holes of 44 mm depth that were drilled into either end of the graphite spines of four 106 mm long spool-like assemblies over which annular graphite

trays containing fueled particles were placed. These drilled holes were considerably larger than the diameter of the particle that they contained, but they were much smaller than two times the particle diameter. Thus, there was no possibility of particle settling during irradiation, which could cause spine-particle interaction stresses during thermal cycling. Particle locations within these spines and fast-neutron fluences at those locations are given in Table 2.

4. Irradiation Results

Failure statistics for outer coatings on the different inert particles are also given in Table 2. These data for the two different sizes of particles having similar coatings of plain pyrocarbon (A and D) and of Si-alloyed pyrocarbon (B and E) are plotted as a function of fluence in Figure 3, and the wide range of fluence involved is observed to have a significant effect on coating failure. Failure fractions of the larger size particles for each of the coating types (D and E) were considerably higher than for the smaller particles of the test pairs (A and B), with factors of difference ranging from about two to four over the fluence range. Thus, there does appear to be a very definite size effect present in the irradiation performance of the coated particles, with failure rates running at least twice as high for 45 μm outer coatings of either type on 1300 μm particles as on 1050 μm particles. Typical shrinkage-type failures of outer coatings are shown in Figure 4.

The fact that there was any failure at all in the inert particles is in itself a strong argument in favor of a size effect, because coating failure was essentially zero for pyrocarbon and for Si-alloyed pyrocarbon coatings over the full-fluence range investigated for nominal 850 μm fueled TRISO particles with several different kernel types that were irradiated along with the two larger sizes of inert particles in capsule HRB-15B[12]. Making use of this additional data on fueled particles, a plot of coating failure as a function of particle size is shown in Figure 5 for a common fluence of $5.5 \times 10^{25} \text{ n/m}^2$, where values for all four inert test particles are well defined in Figure 3. The strong increase of failure with particle size above a diameter of 850 μm is readily apparent for both coating types. There is very little difference between the failure rates of pyrocarbon and of Si-alloyed pyrocarbon coatings at a fluence of $5.5 \times 10^{25} \text{ n/m}^2$ (Fig. 5), although the alloyed coating seems to offer some advantage at lower fluence (Fig. 3). Flat strips of the stronger alloyed material are known to be more stable than pyrocarbon dimensionally when irradiated unrestrained [13]. However, when restrained on a coated particle, the alloyed coatings are apparently not able to relieve stresses through irradiation-induced creep as readily as plain pyrocarbon coatings. Consequently, failure rates were not too much different for the two types of coatings under the irradiation conditions in question.

From Eq. (15) and the outer coating volumes listed in Table 1, the failure fraction F_2 for the large particle in each of the inert test

pairs can for any given fluence be calculated from Weibull theory [8] knowing the measured failure fraction F_1 for each of the small particles. These theoretical predictions of failures for the larger particles in each test pair are compared in Table 3 to the measured results from Figure 5 for a fluence of $5.5 \times 10^{25} \text{ n/m}^2$, and the measured size effect on failure exceeds Weibull predictions by about 30%. Thus, while theory suggests that failure for the 1300 μm particle of each type should be about 1.5 times as great as that for the 1050 μm particle, measurements show failures that are about twice as great. These comparisons are not in bad agreement considering the uncertainties involved in fluence, temperature, and coating structures themselves. Therefore, Weibull theory is not inconsistent with the observed size differences on inert particle failures.

The irradiation-induced shrinkage of particle components found inside the stable SiC layer of inert TRISO particles had a different character for the two different sizes of particles tested (Figs. 1 and 2), but this apparently had no significant influence on the shrinkage-type failure of the outer coating layer that occurred for both sizes of particles (Fig. 4). In the smaller particle, the inner pyrocarbon layer remained tightly bonded to the SiC layer in most cases, and a 60 to 120 μm annular gap opened up as a result of relative shrinkage between the kernel and the separated buffer layer that remained attached to the inner pyrocarbon coating (Figs. 1-A and 2-A). In the larger particle, on the other hand, the inner pyrocarbon layer separated cleanly from the SiC coating in most cases, and the inner pyrocarbon and buffer layers

then shrank down as a single unit onto the carbon kernel (Figs. 1-B and 2-B), leaving a 15 to 35 μm gap inside the SiC layer. Nevertheless, the largely unsupported SiC layer in the larger particles was still sufficiently strong and rigid enough in compression to cause tensile failures in the more rapidly shrinking outer coatings (Fig. 4-B), which was similar to that found in the better supported smaller particles (Fig. 4-A). Such shrinkage failures can also be the dominant mode of failure in fueled TRISO particles under certain irradiation conditions [14].

5. Conclusions

The failure rate of outer coatings on TRISO particles, caused by irradiation-induced shrinkage of these coatings onto the more stable SiC substrates within the particles, increases for a given neutron fluence and irradiation temperature as the particle size increases. For a fluence of $5.5 \times 10^{25} \text{ n/m}^2$ ($E > 29\text{fJ}$) at a temperature of 1125 K, the failure rate for either a plain pyrocarbon or a Si-alloyed pyrocarbon coating of the types tested in irradiation capsule HRB-15B increased from zero at a particle size of 850 μm , to about 8% at 1050 μm , and to about 16% at 1300 μm . These increases in outer coating failure with particle size are somewhat larger than would be predicted from Weibull theory for the weakest-link failure of a brittle material, but experimental uncertainties are probably sufficient to account for this discrepancy.

As the fueled TRISO particle size increases and the outer coating thickness is increased proportionately to control pressure-vessel failure, the limiting failure mode is likely to be restrained-shrinkage failure of the type studied here for larger sizes of inert TRISO particles. Therefore, without altered coating designs to allow for more compliance between the outer coating layer and the unyielding SiC substrate, it may not be practical to increase the TRISO particle diameter much beyond 850 μm .

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Table 1. Description of Inert TRISO Particles in Irradiation Capsule HRB-158

Particle Components, their Properties, and Deposition Conditions	Particle Description - Designation			
	Small PyC- A	Large PyC- D	Small Si/PyC- B	Large Si/PyC- E
Batch Number	6351-05-010	6351-05-040	6351-05-020	6351-05-050
<u>Kernel</u>				
Composition	C	C	C	C
Diameter (μm)	450	450	450	450
<u>Buffer PyC</u>				
Thickness (μm)	97	97	97	97
<u>Inner PyC</u>				
Thickness (μm)	131	240	123	226
<u>SiC</u>				
Thickness (μm)	34	48	34	47
Density (Mg/m^3)	3.17	3.21	ND	3.22
<u>Outer Coating</u>				
Composition				
Wt % C	100	100	77	76
Wt % Si	0	0	23	24
Thickness (μm)	44	46	40	43
Volume (mm^3)	0.143	0.232	0.125	0.206
Density (Mg/m^3)	1.90	1.83	2.12	2.08
Coating Conditions				
Temperature (K)	1558	1573	1648	1648
Time (s)	660	696	900	750
Rate (m/Gs)	66.7	66.1	44.4	57.3
Gas Flows (m^3/Hs)				
Coating Gases				
C_3H_8	17.5	12.2	6.5	6.5
C_2H_2	8.7	6.1	3.3	3.3
He/Silane	0	0	25.7	26.7
He Diluent	99.0	150.0	47.0	156.0
Total Flow	125.2	168.3	83.5	192.5
Charge Wt (g)				
In	52.75	48.00	54.36	50.00
Out	67.15	57.80	68.09	61.40
<u>Total Particle</u>				
Diameter (μm)	1061	1312	1037	1276
Density (Mg/m^3)	1.95	1.97	1.97	2.00
Composition				
Wt % C	80.6	79.9	77.9	75.8
Wt % Si	19.7	22.7	24.1	23.2

Table 2. Failure Fractions for Inert Particles in Capsule HRB-15B

Particle Designation And Type	Particle Location and Fast Fluence (10^{25} n/m ² with E > 29 fJ)							
	Spine 1		Spine 2		Spine 3		Spine 4	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
	3.9	5.4	6.0	6.5	6.4	5.7	4.9	3.4
A (Small PyC)	3/106 = 2.8%	-	-	-	10/80 = 12.5%	-	-	-
D (Large PyC)	-	-	-	13/62 = 21.0%	-	-	-	7/63 = 11.1%
B (Small Si/PyC)	-	5/101 = 5.0%	-	-	-	7/64 = 10.9%	-	-
E (Large Si/PyC)	-	-	13/62 = 21.0%	-	-	-	7/61 = 11.5%	-

Table 3. Comparison of Measured Size Effects on Coating Failure with Weibull Predictions.

Coating Type	Volume (mm ³)		Survivability		$\ln S_2 / \ln S_1$		Failure Fractions		
	V ₁	V ₂	S ₁	S ₂	Measured	Theory ^a	F ₁ Measured	F ₂ Measured	Theory ^a
PyC	0.143	0.232	0.91	0.82	2.10	1.62	0.09	0.18	0.14
Si/PyC	0.125	0.206	0.93	0.85	2.24	1.65	0.07	0.15	0.11

^a $\ln S_2 / \ln S_1 = V_2 / V_1$ and $F_2 = 1 - (1 - F_1)^{V_2 / V_1}$

Figure 1. Two sizes of irradiated particles with outer pyrocarbon coatings. Particle A on the left and D on the right have nominal diameters of 1060 and 1310 μm , respectively.

Figure 2. Two sizes of irradiated particles with outer Si-alloyed pyrocarbon coatings. Particle B on the left and E on the right have nominal diameters of 1040 and 1280 μm , respectively.

Figure 3. Outer coating failure as a function of neutron fluence for two sizes of particles with two different types of coatings.

Figure 4. Typical shrinkage-type failures of outer coatings on the two different sizes of irradiated TRISO particles.

Figure 5. Outer coating failure as a function of particle size for two types of coatings having common irradiation exposures.