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FABRICATION AND IRRADIATION TESTING OF SOL-GEL FUELS
AT OAK RIDGE NATIONAL LABORATORY

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A. R. Olsen, J. D. Sease, R. B. Fitts, and A. L. Lotts

For presentation at the CNEN symposium on "Sol-Gel Processes for
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ABSTRACT

Alternate procedures under development at ORNL for fabricating oxide fuels from Sol-Gel process products are reviewed. Procedures include (1) Vi-Pac, the high-energy vibratory compaction of angular particles; (2) Sphere-Pac, the low-energy vibratory compaction of microspheres; (3) powder preparation and pelletizing; (4) extrusion of concentrated sols or "clays"; and (5) pyrolytic carbon coating of microspheres. Also reported are compressive creep behavior of ThO₂ pellets, thermal conductivity of thorium and thorium-uranium pellets and Sphere-Pac thorium beds, and irradiation performance of the various fuel forms.

INTRODUCTION

The principal objective of the Oak Ridge National Laboratory program on sol-gel-derived fuels is to establish an economically optimized fuel cycle technology for a variety of fuels and reactors. To attain this objective it is necessary to do development in a number of different areas and to maintain a continuous economic assessment of the various stages of development. Other papers at this symposium¹⁻³ describe the development of the sol-gel processes and discuss the economic evaluation of the various processes. This paper will briefly survey only those portions of the overall program that are aimed at the development of fabrication techniques, the characterization of the fuel, and the irradiation performance evaluations.

FABRICATION DEVELOPMENT

The versatile sol-gel process is applicable to a wide variety of fissile and fertile fuels, both as pure materials or as mixtures. The sols may be blended to form intimate mixtures of any composition. The

final steps of the processing can be adjusted to yield an oxide product in different forms. Figure 1 shows schematically the alternate routes for producing four separate products - microspheres, shards, concentrated sol (clay), and sinterable powder - each suitable for a different fabrication scheme required for a specific reactor fuel element design. The microspheres of controlled size can be used for (1) low-energy vibratory compaction (Sphere-Pac) for metal-clad bulk oxide fuels, (2) as the oxide phase in dispersion fuels, or (3) coated with pyrolytic carbon and incorporated into graphite-matrix elements. The dense angular particles, called shards, are suitable for high-energy vibratory compaction (Vi-Pac) for metal-clad bulk oxide fuels. Concentrated sols and sinterable powders can be further processed by extrusion and pelletizing, respectively, to produce dense sintered bodies for incorporation in metal cladding. Water- or organic-cooled thermal converter reactors can use the metal-clad bulk oxides of thoria, $(\text{Th,U})\text{O}_2$, and $(\text{Th,Pu})\text{O}_2$, while fast breeder reactors would use metal-clad bulk oxides of UO_2 or $(\text{U,Pu})\text{O}_2$. Pyrolytic-carbon-coated microspheres of ThO_2 , UO_2 , and $(\text{Th,U})\text{O}_2$ are intended for advanced high-temperature gas-cooled reactors. It is well to note here that all of the fabrication schemes being considered are designed for adaptation to either semiremote or totally remote operation. This additional requirement is imposed by the buildup of activity in recycled fuels, which would severely hamper contact fabrication.

Vi-Pac

Since the original sol-gel process was developed for ThO_2 and $(\text{Th,U})\text{O}_2$ angular particles, our initial fabrication development involved the evolution of the Vi-Pac fabrication techniques and the establishment of the irradiation characteristics of these sol-gel-derived fuels. This work has been reported rather extensively in the literature.⁴⁻⁸ Consequently, we will only summarize here the current status. The Vi-Pac development culminated in the fabrication of 1100 Zircaloy-2-clad rods containing $(\text{Th}-3\% \text{ }^{233}\text{U})\text{O}_2$ fuel packed to 90% of theoretical density in the semiremote "Kilorod" facility. In addition, a remote system was designed for Vi-Pac fabrication of metal-clad fuel rods in the Thorium-Uranium Recycle Facility (TURF)⁹ recently constructed at ORNL.

Fig. 1. Alternate Sol-Gel Processes and Products.

The sol-gel product used for Vi-Pac fabrication consists of theoretically dense angular particles, roughly $1.2 \times 1.2 \times 0.6$ cm. The shards for Vi-Pac fabrication are prepared by crushing, grinding, and classifying this product into a suitable size distribution. Blended composites of the proper size distribution are then fed into a metal tube while vibratory energy is applied. After loading, a weight is applied to the top of the fuel column and the vibration is continued for a specified length of time. This rod is allowed to vibrate freely to add additional inertia to the fuel column and permit the compaction of the upper one-third of the fuel. The weight used in the Kilorod was 1 kg.

The energy source used in the Kilorod facility and designed into the TURF equipment line is a pneumatic vibrator or, more aptly, an air hammer. A wide range of energy outputs can be obtained by varying the air chamber pressure. We use a frequency of approximately 300 cps. The energy is transmitted to the fuel rod through a chucking anvil arrangement similar to that shown in Fig. 2. The chuck must grasp the rod tightly; any detectable looseness can reduce the final compaction density from 5 to 7%. The anvil must be completely free to reciprocate within its restricted travel of 1.6 mm. This arrangement results in a sharp upward acceleration and a rapid deceleration; the deceleration is quite important as it is during this phase that powder redistribution occurs.

The particle size distribution required for Vi-Pac compaction is a function of the diameter, wall thickness, and length of the fuel tube. In our Kilorod experience, in which we loaded tubes 1.27 cm OD $\times$ 1.09 cm ID $\times$ 117 cm long, we used two size fractions: 55 wt % of a -6 +16 mesh fraction and 45% of a process-controlled fine fraction. The coarse fraction was obtained by jaw crushing the as-received sol-gel product. The fine fraction was obtained by ball-milling -6 mesh material for a specified period of time. The fine-fraction particle size distribution obtained in ball-milling is shown in Table 1. During vibratory compaction considerable degradation of the charged powder was observed. A vibratory feeder was used to load the fuel tube. To prevent segregation of the blend, the hopper of the feeder must be isolated from the vibrating feeding trough. Interruption in the loading

Fig. 2. Chuck-Anvil Arrangement in Vibratory Compactor.

Table 1. Particle Size Distribution for Fine Fraction Obtained from Ball-Milling -6 Mesh Material

Mesh Size ^a	Particle Size (μ)	Amount (wt %)
-6 + 10	3327 to 1981	20
-10 + 16	1981 to 1168	13
-16 + 50	1168 to 295	9
-50 + 140	295 to 105	9
-140 + 200	105 to 73	6
-200 + 270	73 to 53	5
-270	< 53	38

^aU.S. standard sieve numbers.

operation must not occur, as it will cause the development of a low-density region in the finished rod. The rate of loading is not critical; the Kilorod feed rate was approximately 500 g/min. The complete design of a vibratory compaction unit for installation in the TURF has been reported elsewhere.¹⁰

Pelletizing

Concurrently with the development of the Vi-Pac process on the sol-gel thorium- UO_2 fuels we were developing a pelletizing procedure.¹¹ The sol-gel materials are desirable for pelletizing because they can be sintered at relatively low temperatures and can contain very homogeneous mixtures of fissile and fertile material. Our immediate interest in sol-gel pellets was to provide material for characterization and to compare their irradiation performance with that of conventionally prepared pellets and other fabrication forms. Initially, we dried the sol to a gel at a temperature of approximately 100°C to produce shards of $(\text{Th}-3 \text{ to } 8\% \text{ U})\text{O}_2$, which contained about 2.3% nitrate and 3% water. This material was then pulverized to pass a 200-mesh sieve. The resulting powders were calcined to remove some of the volatiles, then formed into pellets in a steel die, and finally isostatically pressed. Isostatic pressing of the $\text{ThO}_2\text{-UO}_2$ material prepared in this manner was necessary to give high

densities ($\geq 95\%$ of theoretical) after sintering. The pellets were sintered using a very slow heating rate at 1450°C . So far our work has concentrated on establishing optimum conditions for calcining and the investigation of the effects of sintering atmospheres on density. The highest pellet densities were obtained with powders calcined at low temperatures, as shown in Fig. 3. Uncalcined material often cracked during the sintering process, probably due to the release of volatiles. As calcining temperatures were increased above 400°C the fabrication became more difficult because the pellets tended to lose strength in the green state. Sintering in air produced higher densities than sintering in hydrogen; helium was equivalent to hydrogen. We suspect that this effect is due to maintaining a high oxygen-to-uranium ratio during the air sintering. Although we know this is true in sintering of conventional UO_2 powders, the influence of the small quantities of uranium in the thorium-uranium mixtures is subject to some doubt. One disadvantage of air firing is that the resulting pellet has an oxygen-to-uranium ratio of about 2.67 (U_3O_8), which is reduced by a subsequent hydrogen treatment to 2.005. Sintering has been accomplished at temperatures ranging from 1200 to 1650°C . The sintered density increased only 2 to 3% in going from 1200 to 1425°C , and there was essentially no increase above this temperature. We have achieved densities up to 96% of theoretical with $(\text{Th},\text{U})\text{O}_2$ specimens but only 90% for pure ThO_2 . Pellets produced in this study have been used in the investigation of thermal conductivity and mechanical properties.

More recently we started the development of pelletizing processes using sol-gel-derived UO_2 powders. This is aimed at the eventual production of pellets from mixed $(\text{U},\text{Pu})\text{O}_2$ powders. The powders have been obtained from both nitrate and chloride sols by vacuum drying and grinding and from nitrate sols by freeze drying. Powders, both uncalcined and calcined at 400°C , have been cold pressed and sintered under a variety of conditions. Although this development is in the early stages, we have derived the following tentative conclusions.

1. Powders from more highly concentrated sols yield pellets of higher green densities.

Fig. 3. Effect of Green Density and Calcining Conditions on the Sintering Characteristics of ThO_2 -8 wt % UO_2 Powder Derived From the ORNL Sol-Gel Process. Sintering temperature, 1450°C.

2. The addition of steam to an Ar-4% H₂ atmosphere during heating appears to increase the density of sol-gel UO₂ pellets sintered at 1000°C but has no appreciable effect on the density of pellets sintered at 1600°C.

Extrusion

The sol-gel extrusion fabrication procedure is a combination of the standard extrusion procedure, which is a high-production-rate fabrication technique, and the sol-gel process, which yields a homogeneous clay-like material that will sinter at low temperatures. The sol-gel clay is formed by concentration of the sol of the desired oxide material. This sol-gel clay at 10 to 12 M concentration may be extruded with standard ceramic extrusion equipment and sintered to form very high density bodies (approximately 99% of theoretical density). Alternately, the sol-gel clay may be mixed before extrusion with a sol-gel-derived powder to produce bodies with controlled densities in the range from 75 to 98% of theoretical. These two processes are shown schematically in Fig. 4. This process has been demonstrated on a laboratory scale, producing both solid and cored thoria extrusions in diameters up to 1/2 in. and lengths up to 3 in. The effects of different calcining conditions for the sol-gel powders and of various drying techniques for the extrusions on density, microstructure, and dimensional tolerance have been defined. Although this work has been reported in detail elsewhere,^{12,13} some of the specific effects are included here. For example, the sol-gel powder additions to the mixed extrusions were all in the -325 mesh (< 44 μ) size range. We used four different types of powders - (1) dried at 100°C, (2) calcined at 900°C, or sintered at 1150°C either (3) as-crushed or (4) after ball-milling. The extruded green bodies were air dried either in a tray or placed on rollers to straighten them while drying. Although each of the powders has a specific influence on the extrusion technique, in most practical applications the use of a fully sintered powder is likely. With such a powder the effects of the amount of powder added, the molarity of the clay, and the drying technique on density are shown in Fig. 5. It is interesting to note that in this process no plasticizer or binder is used,

Fig. 4. Extrusion of Sol-Gel Derived Ceramic Fuel Compacts.

Fig. 5. Effect of Powder Added, Moisture, and Drying Technique on Green and Sintered Density.

and only the sol-gel-derived materials are included. The resulting ceramic bodies have a uniformly distributed porosity that is all surface connected at all densities. Another unique characteristic of these extrusions is their remarkable mechanical strength even at the very low densities. We have used this process to fabricate a variety of miscellaneous thorium bodies, as shown in Fig. 6.

We have extended this work using the same techniques to a study of the extrusion of sol-gel-derived uranium. We intend to apply the technology developed in these studies to the extrusion of $\text{UO}_2\text{-PuO}_2$ sol-derived materials. Unlike the thorium sols, nitrate-prepared uranium sols of low molarity could not be concentrated by evaporation of the liquid to the required molarity without gelling. They could be concentrated, however, by a freeze-dry technique. The fine sol-gel powders that we add to the clays for property adjustment can be prepared, without grinding, by freeze-drying the sols to complete dryness. We have also prepared clays from chloride sols, which do not tend to gel during concentration as readily as nitrate sols. However, extrusions made with these materials retained 130 ppm Cl during the standard sintering treatment, heating in an Ar-4% H_2 atmosphere for 1 hr at 1600°C. Presintering the chloride sols in a steam-Ar-4% H_2 atmosphere at 1000°C for 1 hr reduced the final chlorine content to less than 1 ppm. Adding 30% of powder calcined at 400°C, we obtained bulk densities of 68 and 72% of theoretical on extrusions from the nitrate-prepared and the chloride-prepared clays, respectively. Since this work is in the early stages of development, the effect of various process parameter modifications on the resulting extrusions has not yet been fully defined. This work is continuing.

Sphere-Pac

We are currently concentrating on two fabrication techniques that use the sol-gel microspheres. One of these is the Sphere-Pac technique for fabricating metal-clad bulk oxide fuels while the other involves the pyrolytic carbon coating of the microspheres for high-temperature gas-cooled reactors. These will be discussed separately.

Fig. 6. Typical Sol-Gel Thoria Extrusion Products Used in Our Programs.

Sphere-Pac fabrication is the sequential loading of two or more sizes of microspheres into a tube with low-energy 60-cps vibration. By increasing the number of size fractions used, packing densities from 85 to about 92% of theoretical can be attained.¹⁴ However, in our work we have concentrated on the use of two size fractions, a large size fraction of approximately 400 μ produced by the sol-gel column-forming technique and a fine fraction of less than 44 μ produced by the sol-gel stirred-pot forming technique. All attempts at mechanical blending or simultaneous separate feeding resulted in gross segregation with low packing densities. Consequently, following the work of Ayer,¹⁵ we have been using the sequential loading technique. The coarse fraction is first loaded into the tube, and the fine fraction is then infiltrated from the top to produce a relatively high density and very uniform packing. The coarse particle bed must be restrained during infiltration to prevent segregation. A light follower rod on top of the fine particle bed will prevent the expansion of the coarse particle bed and will increase the packing density. However, for fabrication where reduced contamination of the upper part of the tube is desirable, we have used a funnel with a screen in the bottom as suggested by Ayer to hold the coarse bed during infiltration.

We tested a variety of vibrational frequencies and modes of energy input. Frequency had little effect on density, but a frequency of 60 cps provided the best loading rate. Vibration that included a lateral component provided more rapid and denser packing than did pure axial vibration. We have obtained 84%-dense packing in 9 min using a 0.58-cm-ID tube with a column height of 30 cm.

The use of the Sphere-Pac technique appears to offer some advantages over the Vi-Pac technique in that one avoids the need for complicated remote equipment for crushing, grinding, and sizing. There is a considerably lower vibrational energy input. The disadvantages that may accrue from the use of this process are the need for a two-step loading procedure and the practical limit on densities. In addition, the performance characteristics of such a packed bed under irradiation have not been firmly established. We have fabricated a variety of irradiation test capsules of both $\text{ThO}_2\text{-PuO}_2$, $\text{UO}_2\text{-PuO}_2$, and UO_2 fuels by the Sphere-Pac

technique. The irradiation performance of these tests will be discussed later in this paper.

Sol-Gel Coated-Particle Fuels

We are currently working on the design and development of the remote fabrication line to be installed in the TURF to fabricate high-temperature gas-cooled-reactor fuel elements containing pyrolytic-carbon-coated sol-gel (Th, ^{233}U)O₂ microspheres.

For the design of the fabrication line, the reference fuel element is based on the proposed design of the Public Service of Colorado Company Fort St. Vrain Reactor (PSC) fuel element modified to fit the existing Peach Bottom Reactor core. A segment of the reference fuel element, showing the pertinent design features, is shown in Fig. 7. The fuel holes are filled with pyrolytic-carbon-coated microspheres in a carbonaceous matrix.

The equipment for this plant will be a scaled-down version of a production facility to provide both technological and economic information. The process equipment will be such that only minimum retooling will be required to make the larger elements for PSC (14.5-in.-diam hexagonal block in 30-in.-long segments containing 210 fuel holes). The design production rate for the fabrication line has been established at 10 kg/day of fissile material plus 10 kg/day of fertile material. The equipment will handle and fabricate any combination of $^{235}\text{UO}_2$, $^{233}\text{UO}_2$, and ThO₂ that may be selected for the fuel cycle. Production capacity in the 24-hr day with a 70% plant factor is approximately 30 Peach Bottom segments or two PSC elements.

The process flow diagram that has been developed for the TURF fueled-graphite refabrication line is shown in Fig. 8. A critical path schedule has been developed and is being used in the execution of the project. A general division of the process line in the hot cells based on contamination levels is represented by the shading around segments of the flow-sheet. The operations that involve potential contamination or direct contact with fuel particles will be carried on in Cell D. Particles in coating operations will be transferred by a pneumatic system.

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Fig. 7. Modified PSC Element for the Peach Bottom Reactor.

Fig. 8. Process Flow Diagram for Recycle HTGR Fuel in TURF.

The development work in support of the TURF fueled-graphite line includes particle grading and handling, coating microspheres with duplex pyrolytic carbon coatings, inspection of bare and coated particles, blending, forming bonded fuel bodies, loading, and inspection of completed fuel elements. Details of the equipment development and status are reported elsewhere.^{16,17} Although not specifically a part of the sol-gel process, the establishment of coating parameters and coating processes is a requirement in establishing the utilization of sol-gel-derived microspheres in high-temperature gas-cooled reactors. Recent coating development has been reported elsewhere.^{18,19}

CHARACTERIZATION OF SOL-GEL FUELS

In evaluating the potential of any fuel process and fabrication technique it is essential to establish some of the characteristics of the particular material. This information is also invaluable in the evaluation of the results of irradiation test performance.

Thermal Conductivity Studies

We have measured the thermal conductivity of sol-gel-derived fuels on two types of specimens. In one study,²⁰ sintered pellets of sol-gel ThO₂ were used to determine the effect of porosity, UO₂ content, and sintering conditions on the thermal conductivity (k) between 30 and 120°C. A second study involved Sphere-Pac beds of sol-gel thorium to determine the effects of temperature, gas, and gas pressure on thermal conductivity between 50 and 1000°C.

Sintered Specimens

A longitudinal heat flow technique was used to measure thermal conductivity on the nine specimens described in Table 2. The two sol-gel ThO₂ samples had equivalent densities and showed little effect of sintering conditions on k. The three oxalate ThO₂ specimens show a 30% higher k than sol-gel thorium for equivalent densities at 75°C. The data predict a thermal conductivity of 0.122 w cm⁻¹ °C⁻¹ for

Table 2. Specimen Description and Thermal Conductivity
Data for Thoria and Thoria-Urania

Specimen Description	Density (g/cm ³)	Sintering Conditions	Thermal Conductivity ^a (w cm ⁻¹ °C ⁻¹)		
			30 °C	75 °C	120 °C
Sol-gel thoria	9.046	In hydrogen at 1750 °C	0.0828	0.0702	0.0596
Sol-gel thoria	9.046	In air at 1650 °C	0.0817	0.0692	0.0509
Oxalate thoria	9.525	In air at 1650 °C	0.1260	0.1100	0.0958
Oxalate thoria	8.582	In air at 1650 °C	0.0934	0.0800	0.0683
Oxalate thoria	8.116	In air at 1650 °C	0.0593	0.0523	0.0480
Th _{0.953} U _{0.047} O _{2.026} ^b	9.067	In air at 1650 °C	0.0351	0.0347	0.0340
Th _{0.939} U _{0.061} O _{2.026} ^b	9.043	In air at 1650 °C	0.0245	0.0244	0.0243
Th _{0.937} U _{0.063} O _{2.000}	8.796	c	0.0972	0.0832	0.0708
Th _{0.953} U _{0.047} O _{2.000}	8.733	In hydrogen at 1750 °C	0.0852	0.0769	0.0683

^aSmoothed values are tabulated here. Measured values were precise to within $\pm 1/4\%$ and have a probably accuracy of $\pm 1\ 3/4\%$. Some of these specimens were ground flat in a solution of ethylene glycol and water. The solution had a noticeable effect on the specimen conductivity when the measurements were made shortly after grinding. It was necessary, therefore, to thoroughly dry the samples by heating to 400 or 500 °C in air prior to making measurements.

^bTwo samples of each material were measured, with similar samples agreeing to within $1/2\%$.

^cSintered in air at 1650 °C followed by sintering in hydrogen at 1750 °C.

theoretically dense ThO_2 at 75°C . The results are calculated with the following formula for porosity correction:

$$k = k_{\text{TD}} \left(\frac{1 - P}{1 + \beta P} \right)$$

where P is the pore volume fraction and β is an empirical parameter describing the effect of porosity. Oxalate ThO_2 has a β of 1.2 at 75°C , whereas a β of 6.5 is required for sol-gel ThO_2 , indicating a large porosity effect.

The thermal conductivity results on sol-gel $\text{Th}_x\text{U}_{1-x}\text{O}_{2+y}$ for various uranium percentages are plotted in Fig. 9. The oxygen-to-metal ratio was maintained at essentially 2.000 when specimens were sintered in hydrogen or when they were sintered in air and reduced in hydrogen; that is, the y value was less than 0.001. However, for air-sintered materials the oxygen-to-metal ratio was significantly higher, and the y values ranged from 0.028 to 0.026. The significant effect of this change in oxygen-to-metal ratio is clearly seen in the figure, where the air-sintered materials have half the thermal conductivity. With the pure thorium there is essentially no difference between the values for air- and hydrogen-sintered material. Therefore the vast difference in the mixed oxide specimens must be attributed to the effect of the change in oxygen-to-metal ratio for the uranium atoms. If the excess oxygen atoms in the air-sintered materials exist as interstitials in the lattice, the thermal conductivity would be reduced by the increase in the number of phonon scatterers. This effect has been shown by Godfrey *et al.*²¹ to be large in hyperstoichiometric UO_2 .

Sphere-Pac Bed Microspheres

A radial heat flow apparatus similar to one described by Flynn²² was used to measure the thermal conductivity of two vibratorily compacted beds of thorium microspheres in helium and argon up to 1000°C . The gas pressure ranged from 0.3 to 2 atm abs. One bed consisted of thorium microspheres less than $44\ \mu$ in diameter packed into the measurement chamber to a powder density of about 64% of the theoretical density

Fig. 9. Thermal Conductivity of $(\text{Th}_x\text{U}_{1-x})\text{O}_{2+y}$ Samples Versus Temperature. Results obtained on sol-gel thoria specimens are included for comparison.

of thoria. The second bed consisted of a typical duplex-particle Sphere-Pac loading with 420- μ and less-than-44- μ microspheres loaded to give a bed density of about 84% of theoretical.

The thermal conductivity as a function of temperature at 1 atm of gas pressure is shown in Fig. 10. The results are accurate to better than $\pm 3\%$. In addition to the packed-bed conductivity we have included a curve for theoretically dense solid thoria, as recommended by Powell, Ho, and Liley,²³ and high and low thermal conductivity values for helium gas from Massey.²⁴ The 84%-dense bed has a higher thermal conductivity than the 64%-dense bed. The thermal conductivity in helium for both loadings is substantially greater than in argon. A temperature independence of thermal conductivity for the powders and the low values of the 64%-dense material in helium, when compared to helium gas conductivity, indicates that the void size between the particles is limiting the mean free path of the gas molecules. Thus, the conductivity of the gas between the solid microspheres is lowered. For this condition Deissler and Eian²⁵ showed thermal conductivity to be sensitive to pressure changes. This is because the mean free path varies inversely with pressure. The effect of varying the gas pressure on thermal conductivity of the Sphere-Pac beds is shown in Fig. 11. These results are similar to those observed by Deissler and Eian for MgO and by Masamune and Smith²⁶ for glass beads; small solid particles were used in both.

Similar measurements are planned for UO_2 and $(\text{U,Pu})\text{O}_2$ materials derived from the sol-gel process.

Mechanical Properties of Sol-Gel-Derived Fuel Bodies

The ability of a fuel to deform plastically at various temperatures and to support loads is an important parameter in influencing the irradiation performance of a metal-clad fuel body. The strength of the material may influence the formation of fission-gas bubbles and the ability to plastically deform may influence the utilization of included porosity to accommodate solid fission product swelling. The creep of thoria from standard fabrication processes has been investigated at ORNL.^{27,28} More recently C. S. Morgan and L. L. Hall of ORNL have begun

Fig. 10. The Effect of Temperature and Gas on the Thermal Conductivity of Vibratorily Compacted ThO₂ Microsphere Beds.

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Fig. 11. The Effect of Gas Pressure on the Thermal Conductivity of Vibratorily Compacted ThO_2 Microsphere Beds (Bed Density 84% of Theoretical Density for Mixture; 64% of Theoretical Density for 44- μ Particles).

the investigation of the compressive creep of sol-gel-derived thorium pellets. The pellets were fabricated from 400°C calcined powder with isostatic pressing at 60,000 psi. They were sintered in air for 2 hr at 1450°C and then in hydrogen for 0.7 hr at 1750°C. The resulting density of the pellets was 8.8 g/cm³ as determined by mercury porosimetry and 9.1 g/cm³ by water immersion.

Although the studies of compressive creep performance on these pellets are in the preliminary stages, some of the findings to date are of interest. To obtain some information on the compressive strength and plastic deformation characteristics of this material in a relatively short period of time we used an Instron machine with a constant head speed. The ends of the specimen were ground flat and parallel and were supported by thorium disks with tungsten shims to protect the end and keep the specimen and disks from sintering together. This assembly was placed in the center of a tube furnace and the load was applied through alumina rods and graphite supporting members. In Fig. 12 we see the effect of temperature on the mechanical strength and plastic deformation of the sol-gel-derived pellet. Of particular importance in this figure is the high degree of plastic deformation sustained at a relatively low temperature of 650°C. Figure 13 compares pellets from both oxalate-precipitated powder and sol-gel powder; the effect of pellet density is clearly shown by the variation in plastic deformation and strength. We believe that the difference in the shape of the curves for sol-gel pellets at 9.1 g/cm³ and the sintered oxalate powders at 8.87 g/cm³ may result from the porosity distribution established by the fabrication procedure. The low-density oxalate powders were formed by a uniaxial pressing whereas the sol-gel product had been isostatically pressed. Poteat and Yust²⁸ in the previous evaluation of high-density thorium pellets prepared from oxalate powder have shown that with significant strain there is a decrease in density for the pellets. We suspected that the increased porosity in the lower density pellets might lead first to an increase in density followed by a decrease with increasing strain. And indeed, as we see in Fig. 14, in the one test conducted to date this was observed; although this pellet did not fail

Fig. 12. Effect of Temperature on Stress-Strain Relationship for Sol-Gel ThO₂ Pellets of 9.1 g/cm³ Density Tested at a Constant Compressive Strain Rate.

Fig. 13. Effect of Density on Stress-Strain Relationship for ThO₂ Pellets Tested at 1450°C with a Constant Compressive Strain Rate.

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Fig. 14. Change in Density of a Sol-Gel ThO₂ Pellet as a Function of Uniaxial Plastic Strain.

in test, the final point, with the density below the original pellet density, was obtained when the pellet showed a significant number of macroscopic cracks aligned vertically.

To date we have conducted only one typical creep test in which creep was measured under constant load. The results of this test on the 9.1 g/cm^3 -dense sol-gel pellet are compared in Fig. 15. with a high-density thoria pellet fabricated from oxalate-derived powders. Although the load in each of these tests was significantly different, our preliminary conclusions indicate that we are seeing principally a density difference rather than a material difference from processing. This is borne out by the difference in the initial strain rate of the two samples, with the low-density material showing a high strain rate during what we had previously shown to be a densification period, while the final creep rates are quite similar. The test of the low-density pellet was terminated before pellet failure.

Additional work on the investigation of the mechanical properties of sol-gel-derived materials, both ThO_2 and $(\text{U,Pu})\text{O}_2$, is planned.

IRRADIATION TESTING

The irradiation test program on sol-gel-derived fuels can be divided into two basic categories: tests on pyrolytic-carbon-coated particles and tests on metal-clad bulk oxide fuels. The second category can be further subdivided into thoria-base fuels and urania-base fuels.

Since the work on coated-particles and bulk thoria-base fuels has been extensively reported as it progressed, we will only summarize the current status in this report, including the results of tests removed from the reactor since the Second International Thorium Fuel Cycle Conference in May of 1966.

Sol-Gel Oxide Coated Particles

In previous papers the work at ORNL on testing the irradiation behavior of sol-gel-derived oxide fuels with pyrolytic-carbon coatings has been reported.²⁹⁻³¹ The results of the irradiation tests, together with supplemental out-of-reactor testing, has shown that the thermal

Fig. 15. Creep Curves for ThO_2 Pellets With Constant Compressive Loading.

stability of pyrolytic-carbon-coated oxides is remarkably good at temperatures in excess of 2000°C. The high-density outer coatings successfully contained carbon monoxide formed by reaction of the oxides with carbon and thus inhibited further reaction. Much of the testing program has been aimed at establishing the coating parameter requirements for various reactor applications. We have found that coated particles must incorporate at least three features to ensure adequate irradiation stability. (1) The outer coating must be protected from direct fission recoil damage. (2) Adequate void volume in or adjacent to the fuel kernel must be supplied to accommodate swelling. (3) There must be a mechanical decoupling, that is, a distinct physical separation between the inner and outer coating layers. We are currently conducting irradiation tests to establish optimum pyrolytic-carbon-coated particle fuel specifications. A mathematical model for predicting the irradiation performance of coated particles^{32,33} aids in specifying coating parameters. Table 3 lists a variety of sol-gel fuel irradiation tests on coated particles. These tests are planned with the use of the mathematical model, and the results are then compared with the model predictions. The model includes a number of poorly known parameters, such as fuel swelling, fission-gas release, pyrolytic-carbon densification, pyrolytic-carbon mechanical properties, and the effects of fast-neutron damage as manifested in stress-inducing dimensional changes from anisotropic growth and irradiation-induced creep. The test program is designed to help establish more quantitative information for a number of the above parameters. If one considers the uncertainties in these parameters, together with the known particle-to-particle variation in properties of pyrolytic carbon deposits within a single coating batch, the observed agreement between predictions and experimental results is highly gratifying. This is best shown in Fig. 16, in which the results of two noninstrumented irradiation tests, 43-89 and 43-97, have been compared with the model predictions. These two experiments incorporated a large number of coating variations and both sintered UO₂ and UC particles as well as sol-gel UO₂ particles. The experiments have been discussed in some detail previously.^{34,35} Although some questions remain as to the effect of irradiation temperature on the performance of coated particles

Table 3. Summary of Irradiation Tests on Coated-Particle Sol-Gel Fuels

Table 3. Summary of Irradiation Tests on Coated-Particle Sol-Gel Fuels

Experiment	Fuel Varieties	Fuel Kernel Size (μ)	Coated Particle Variations ^a	Type of Experiment ^b	Fuel Irradiation Temperature ($^{\circ}$ C)	Fission Gas Release Rate ^c	Peak Burnup FIMA ^d	Status	Objective
43-89	Sintered WO_2 and UC_2	220	12	1	400, 1000		25	Examined	Compare coated particle model performance characteristics with fuel performance
43-97	Sol gel and sintered UO_2	210	13	1	400, 1400		27	Examined	Compare sol-gel microsphere performance with sintered spheroids
43-98	Sol gel (U,Th) O_2	230	15	1	400, 1400		20	In-reactor	Test fuel particles prepared for irradiation in Dragon; investigate coating optimization and fast-flux effects on particle performance
43-104	Sol gel (U,Th) O_2	230	10	1	400, 1400		25	In-reactor	Determine the effects of the Th/U ratio on fuels with a constant fissile content
43-105	Sol gel (Th,U) O_2	450	11	1	400, 1400		25	In-reactor	Evaluate the performance of fertile fuels and fast-flux effects, including radiation creep on coated-particle behavior
Loop 1-14	Sol gel ThO_2 and (U,Th) O_2	340, 210	2	4	1350, 675	2.5×10^{-5}	2.7	Examined	Evaluate the performance of large beds of loose coated particles and the performance and fission-gas retention of coated sol-gel oxide kernels
Loop 1-15	Sol gel ThO_2 and (U,Th) C_2 Sintered UC_2 and (U,Th) C_2	230, 340							
		380, 180	4	4	1400, 675	2×10^{-6} to 2×10^{-4}	12	Being examined	Same as Loop 1-14, with controlled coolant purity and a preliminary test of a lightly bonded bed of coated particles

Table 3. Continued

Experiment	Fuel Varieties	Fuel Kernel Size (μ)	Coated Particle Variations ^a	Type of Experiment ^b	Fuel Irradiation Temperature ($^{\circ}\text{C}$)	Fission Gas Release Rate ^c	Peak Burnup FIMA ^d	Status	Objective
F9 HIBUP	Sol gel UO_2 Sintered UC_2	150 125	2	3	1400 to 1100	10^{-6} to 10^{-4}	50	Being examined	Evaluate the fission-product retention and irradiation stability of coated particles at extended burnup levels
F9 HIBUP-2	Sol gel UO_2 Sintered UC_2	265, 150	9	3	1400	2×10^{-4}	12	In-reactor	Same as F-9-HIBUP including some SiC coatings
B-9-31	Sol gel UO_2	210	1	3	1400	6×10^{-4}	23	Being examined	Test of Mathematical Model Failure Predictions under monitored gas-release conditions
B-9-32	Sol gel UC_2	280	1	3	1400	1×10^{-4}	25	In-reactor	Evaluate low-temperature performance of pyrolytic carbon coatings
A-9-8	Sol gel UO_2	270	2	3	1400	1×10^{-7}	15	In-reactor	Same as B-9-32
A-9-9	Sol gel UO_2 Sintered UC_2		2	3	1000			In preparation	
Dragon	Sol gel (Th,U) O_2	285	2	5	700 to 1100			In-reactor Dec. 1966 to May 1968	Evaluate sol-gel oxide fuels as coated particles in a fuel element of an operating High-Temperature Gas-Cooled Test Reactor

^aCoating particle variations include both coating parameter and fuel composition variables to make up the different types of coated particles in a test.

^b1. Noninstrumented static-atmosphere capsules. 2. Instrumented static-atmosphere capsules. 3. Instrumented sweep-gas capsules.
4. Instrumented circulated gas loop experiments. 5. Test reactor fuel rods.

^cRelease-to-birth rate ratio for ^{88}Kr .

^dFissions per initial metal atom.

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Predicted Burnup Based on: 30,000 psi Rupture Stress, 100 % Release of Fission Gas from Kernels, 25% of Total Inner Coating Porosity Available as Free Volume (Except 50% for Porous Inner Coatings). Irradiation Creep Rate of 1.5×10^{-7} in./in. - psi- 10^{20} nvt ($E > 0.18$ Mev)

Fig. 16. Comparison of Mathematical Model Predictions and Actual Performance of Coated-Particle Fuels.

and definitely the effect of high fast-neutron doses on their performance, we have shown clearly that sol-gel-derived UO_2 microspheres will perform as well as sintered oxide microspheres or carbide microspheres. The highest burnup attained to date in any sol-gel-derived fuel has been as a coated particle in the F9 HIBUP experiment. Figure 17 is a photograph before and after irradiation of coated particles from this experiment. The burnup attained was approximately 50% FIMA. The operating temperature during this experiment gradually changed from 1350 to 1150°C. The sol-gel UO_2 particles did not develop any grain structure, but all contained the shiny metallic inclusions and pores typical of all UO_2 after appreciable levels of burnup.

Metal-Clad Bulk Oxide Fuels

The irradiation performance of thoria-base bulk oxide fuels has been under examination for some time. We have previously reported on the excellent performance of this type of fuel both from standard processing techniques and sol-gel-derived fuels. In the past we have concentrated on the performance of Vi-Pac fuel rods with sol-gel thoria-base material. We recently began the irradiation of low-energy vibratorily compacted (Sphere-Pac) sol-gel oxide microspheres.

Irradiation tests of thoria-base fuels currently in-reactor or under examination are outlined in Table 4. The fuel rods in Group MTR-II and the pellet rods at very high burnup are currently in the hot cells undergoing examination. To date only dimensional measurements on the cladding are available. The amount of plastic strain in the cladding on these rods tends to substantiate the low swelling predicted³⁵ in thorium-base fuels as a result of contractions by the $\text{Th} \rightarrow \text{U}$ and $\text{Th} \rightarrow \text{Pa}$ conversions compensating for expansion caused by fission. Not shown in the table is the test group MTR-1, which was started in 1961, to compare sol-gel-derived powder fuels with similar arc-cast powder fuels and pelletized fuels. The last rod of this group containing vibratorily compacted sol-gel ThO_2 -4.5 UO_2 has been examined. One striking macro-structural feature has been revealed by these long-duration tests. At the operating conditions of these tests the fuel temperatures were such

Fig. 17. Sol-Gel UO_2 150- μ -diam Microspheres. (a) Unirradiated. (b) Irradiated in coated-particle test F9 HIBUP at about 1250°C to 52% burnup of the heavy metal atoms. No failures were observed.

Table 4. Thoria-Base Fuel Rods Currently Being Irradiated or Examined^a

Designation	Number of Rods	Type of Oxide	Density (% of Theoretical)	Fuel Rod Dimensions, cm			Linear Heat Rating (w/cm)	Peak Burnup (Mwd/tonne metal)	Objective	Status
				Length	OD	Wall				
MTR-II	2	Sol-Gel ThO ₂ -4.5% UO ₂ Vi-Pac	88 to 89	57	0.8	0.06	600	100,000	Obtain higher heat rating by increasing enrichment	Being examined
MTR-III	6	Sol-Gel ThO ₂ -4.5% UO ₂ Vi-Pac	86 to 89	30	1.1	0.06	820	100,000	Compare oxide calcining atmospheres and higher heat ratings obtained by increasing diameter	In-reactor
ETR-II	6	BNL Sol-Gel ThO ₂ -4% ²³³ UO ₂ Vi-Pac	90	48	1.3	0.09	630	30,000 to 100,000	Study effects of remote fabrication and oxide recalcining	1 being examined 5 in-reactor
ETR-III	4	Sol-Gel ThO ₂	88	48	1.3	0.09	770	10,000 to 70,000	Study ThO ₂ blanket material with gradually increasing heat rating and provide high-protactinium low-fission product material for chemical processing	In-reactor
ETR-IV	6	Sol-Gel ThO ₂ -5% PuO ₂ Sphere-Pac	84	24	1.3	0.9	650 to 1000	20,000 to 100,000	Study sol-gel ThO ₂ -PuO ₂ microsphere performance as vibratorily compacted beds at various heat ratings and burnup levels	In-reactor
Sphere-Pac	4	Sol-Gel ThO ₂ -5% PuO ₂ Sphere-Pac	84	19	0.64	0.025	450	5000	Test sol-gel ThO ₂ -PuO ₂ microspheres with high cladding temperatures	Being examined
Pellet Rods	3	ThO ₂ -4.5% UO ₂	91	11.4	0.79	0.06	400	150,000	Investigate swelling and gas release of ThO ₂ -base fuels at very high burnup	Being examined

^aETR-II, ETR-III, and ETR-IV rods are clad with Zircaloy-2; all other fuel rods are clad with type 304 stainless steel.

that sintering and grain growth occurred initially in the center. In the latest test examined the compacted powder sol-gel fuel had sintered all the way out to the cladding. This condition existed throughout the length of the fuel column from the peak burnup section at 126,000 Mwd/tonne of metal to the low-burnup end at only 24,000 Mwd/tonne of metal. This strongly supports the conclusion that sintering is not influenced significantly by burnup, but it depends strongly on the time at operating temperature. Table 5 compares burnup values and fission-gas release data for these tests. The irradiation performance of all three fuel types was comparable. There are some variations in the fission-gas release rate, which may be associated with variations in the test conditions over the prolonged exposure period. The similarity in performance and the effects of extended burnup have been discussed previously.^{29,30,36}

Two of the rods in the Sphere-Pac group have been examined. These rods are unusual in that they are the first irradiation tests on purely sol-gel-derived (Th,Pu)O₂ fuels. They were irradiated in the noninstrumented capsule shown in Fig. 18. This capsule was designed to irradiate four separate fuel rods with the cladding at temperatures of 400 to 600°C. In the first two capsules in this series, two of the rods in each capsule were of the sol-gel ThO₂-5% PuO₂, while two contained UO₂-PuO₂ fuels and will be discussed later. Although the burnup level was extremely low in these tests, approximately 0.5% FIMA for the Sphere-Pac rods of ThO₂-5% PuO₂, they performed well even at the highest heat rating of 450 w/cm, where only the center portion of the fuel showed any sintering. This can be seen in Fig. 19. It is interesting to note that in slightly less than 20 days of power operation the Sphere-Pac bed has begun to sinter and develop a microstructure similar to that seen in pellets under similar operating conditions. The ETR-IV group is a similar group of fuel rods, in which the 0.50-in.-OD Zircaloy cladding is exposed to the test reactor cooling water. This group will test the effects of various heat ratings and burnups on the performance of the ThO₂-5% PuO₂ Sphere-Pac fuels.

Irradiation testing of urania-base sol-gel-derived bulk oxide fuels is just beginning. We recently began a series of screening irradiation tests using the noninstrumented capsule design just discussed. The

Table 5. Comparative Operating Conditions for Various
ThO₂-UO₂ Fuels (MTR-I Group)

Fuel	Fuel Form	Irradiation Time (Reactor Full Power Days)	Maximum Burnup		Time-Averaged Peak Linear Heat Rating (w/cm)	$\int_{T_o}^{T_c} k d\theta$ (w/cm)	^{85}Kr Release (%)
			(fissions/cm ³)	(% FIMA)			
			$\times 10^{20}$				
Arc-fused ThO ₂ -4.5% UO ₂	Vi-Pac ^a	110	2.5	1.2	299	33.8	2.4
	Vi-Pac	376	8.6	4.2	297	33.7	7.2
	Vi-Pac	707	14.4	7.1	267	31.6	6.4
Sol-gel ThO ₂ -4.5% UO ₂	Vi-Pac	110	2.9	1.4	341	37.8	0.5
	Vi-Pac	375	8.2	4.0	286	32.8	13.2
	Vi-Pac	691	16.5	8.1	311	34.6	17.0
	Vi-Pac	1107	26.4	12.5	303	34.2	2.6
Pressed and sintered ThO ₂ -4.5% UO ₂	Pellet ^b	905	26.4	12.0	420	44.8	22.8
	Pellet	660	21.1	9.6	461	48.2	12.4
	Pellet	497	8.1	3.7	270	31.5	c
	Pellet	406	11.0	5.0	394	42.6	c

^aVibratorily compacted to a density 85 to 87% of theoretical.

^bPellets pressed from coprecipitated powders and sintered to 93% of theoretical density.

^cGas samples diluted with air in sampling and partially lost.

IRRADIATION CAPSULE ASSEMBLY

FUEL ELEMENT

Fig. 18. Experimental Test Reactor Irradiation Capsule for Screening Irradiations.

R-38553

Fig. 19. Section of $(\text{Th}-5\% \text{ Pu})\text{O}_2$ Fuel Rod Fabricated by Sphere-Pac and Irradiated to 0.5% FIMA at 450 w/cm with a Cladding Temperature of 450°C .

purpose of these tests is to obtain comparative irradiation performance characteristics for sol-gel-derived fuels fabricated by Sphere-Pac, extrusion, Vi-Pac, and pelletizing. In addition we will obtain some information on the effects of sol-gel process variations on fuel performance and provide irradiated sol-gel fuel material for fuel recycle dissolution studies. To date we have fabricated and irradiated five such capsules, all with fuel rods fabricated by the Sphere-Pac technique. A brief description of these capsules is given in Table 6 together with the proposed operating conditions. We emphasize that these are proposed operating conditions. Experience with the first two capsules in this series indicated that the actual operating conditions may be quite different. The heat generation rates in the fuel rods in these capsules were originally calculated by use of diffusion theory to predict the flux perturbation in the fuel. This type of calculation has worked well with the thorium-base fuel irradiations. Both of these capsules had failures in the $(U,Pu)O_2$ fuel rods. We have since developed a technique for using a reactor computer code³⁷ (ANISN) based on a modified transport analysis that predicts an entirely different flux perturbation and consequently a different linear heat rating. The results of the two calculational procedures are compared in Fig. 20. The integrated fissioning rate for the ANISN calculations is 2.3 times that calculated by diffusion theory and agrees quite well with the rate determined by burnup analyses of the fuel in capsules 43-99 and 43-100.

Although these rods were not tested under the conditions intended, they have provided some information on the performance of Sphere-Pac fuel rods for conditions of overpowering. Figures 21 and 22 are transverse and longitudinal sections of the unfailed $(U,Pu)O_2$ fuel rod in capsule 43-99. The linear heat rating at the transverse section was 1040 w/cm based on the ANISN calculations and burnup analyses, and the linear heat rating at the fuel- ThO_2 insulator interface was 570 w/cm. At these heat ratings and with the steep temperature gradients associated with thermal flux perturbation, we see sintering of the low-density fuel to form a dense annular fuel body. There has also been some dissolution of the low-density sol-gel extruded ThO_2 insulator at the fuel center.

Table 6. Noninstrumented Irradiation Screening Tests of Sol-Gel-Derived Urania-Base Bulk Oxide Fuels

Experiment	Fuel		Number of Rods	Peak Target Burnup (% FIMA)	Peak Linear Heat Rating (w/cm)	Test Objective
	Form	Composition				
43-99	Sphere-Pac	(80% ^{235}U , 20% Pu)O ₂	2	5 ^a	650 ^a	Thermal-reactor test of fast-reactor test fuel
43-100	Sphere-Pac	(80% ^{235}U , 20% Pu)O ₂	2	10 ^a	650 ^a	Same as 43-99
43-103	Sphere-Pac	UO ₂ (20% ^{235}U)	3	2	640	Test Sphere-Pac fabrication with low-density microspheres
	Pellet	UO ₂ (20% ^{235}U)	1			
43-112	Sphere-Pac	(85% ^{238}U , 15% Pu)O ₂	3	0.5	650	Compare mixed-oxide performance with UO ₂
		UO ₂ (20% ^{235}U)	1			
43-113	Sphere-Pac	(85% ^{238}U , 15% Pu)O ₂	3	10	650	Same as 43-112 with high burnup

^aThese are preirradiation calculated values. Rods failed in reactor from overpowering at a peak burnup of 1.5% FIMA.

Fig. 20. Radial Fission Rate Distribution for a 75% of Theoretical Density (0.8% ^{235}U -0.2% Pu) O_2 Fuel Calculated by Both Diffusion and Transport Theories.

R-38557

Fig. 21. Transverse Section of Sphere-Pac Fuel Rod Containing (80% ^{235}U -20% Pu) O_2 From Irradiation Experiment 43-99.

R-38568

Fig. 22. Longitudinal Section of Sphere-Pac Fuel Rod From Irradiation Experiment 43-99.

The heat ratings listed in the table for the other three capsules currently in-reactor are those calculated by the ANISN code. Only post-irradiation burnup analysis can confirm the accuracy of the new calculational technique.

Additional experiments at lower heat ratings are planned, using the noninstrumented capsule to test (U,Pu)O₂ fuels fabricated by pelletizing and extrusion of the sol-gel-processed materials.

We also have an instrumented capsule being designed to investigate thermal conductivity and fuel microstructural changes as a function of operating temperature in-reactor. The first of these tests is not scheduled to go in-reactor until late next spring.

CONCLUSIONS

To summarize our current development status the following statements can be made.

1. The versatile sol-gel process will yield a variety of fuel compositions containing any combination of thorium, uranium, and plutonium in a form suitable for a variety of fabrication techniques.
2. Sol-gel products can be fabricated into fuel forms such as microspheres, angular particles, extrusions, and pellets; experimental quantities of each have been produced.
3. Fuel-rod fabrication techniques using the four forms and suitable for both direct and remote operation are under development. The Vi-Pac technique has been established by semiremote pilot plant operation. The Sphere-Pac technique is routinely used in glove-box operations. Both pelletizing and extrusion fabrication technique developments are less advanced, but the results are encouraging.
4. Mechanical property determinations on sol-gel-derived fuels in out-of-reactor tests have started. To date no unusual characteristics have been established that can be attributed to the sol-gel material.
5. The thermal conductivity of 84%-dense Sphere-Pac beds in helium at 1 atm is low ($0.012 \text{ w cm}^{-1} \text{ }^{\circ}\text{C}^{-1}$), in agreement with other high-porosity oxide compacts, but preliminary irradiation test results indicate such beds densify radially under typical fuel operating conditions.

6. Sol-gel-derived UO_2 microspheres with pyrolytic carbon coatings have performed satisfactorily in irradiation tests at particle bed temperatures above 1100°C to burnup levels of approximately 50% FIMA.

7. Metal-clad bulk oxide thoria-base fuels fabricated by Vi-Pac techniques have been successfully tested in-reactor to burnup levels of approximately 15% FIMA with moderate fission-gas release rates and low swelling rates.

8. Fabrication technique development for all sol-gel product forms will be extended to $(\text{U,Pu})\text{O}_2$ fuels soon. The development of all techniques will continue until either economic analyses or irradiation performance tests define a preferred technique.

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