Performance analysis of coated plutonia particle fuel compact for radioisotope heater units

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Abstract

Coated plutonia particle fuel has been proposed recently for use in radioisotope power systems and radioisotope heater units for a variety of space missions requiring power levels from milliwatts to tens or even hundreds of watts. The $^{238}\text{PuO}_2$ fuel kernels are coated with a strong layer of ZrC designed to fully retain the helium gas generated by the radioactive decay of $^{238}\text{Pu}$. A recent investigation has concluded that helium retention in large-grain ($\geq 200 \mu\text{m}$) granular and polycrystalline fuel kernels is possible even at high-temperatures ($> 1700 \text{ K}$). Results of performance analysis showed that this fuel form could increase by 2.3–2.4 times the thermal power output of a light weight radioisotope heater unit. These figures are for a single-size (500 $\mu\text{m}$) particles compact, assuming 10% and 5% helium gas release respectively, and a fuel temperature of 1723 K, following 10 years of storage. A binary-size (300 and 1200 $\mu\text{m}$) particles compact increases the thermal power output of the RHU by an additional 15%. © 2001 Elsevier Science B.V. All rights reserved.

Nomenclature

- $a$: average fuel grain radius (m)
- $b$: coefficient (Eq. (11)), $b = 1.5121 \times 10^{-2}$ (m$^3$ kg$^{-1}$)
- $D$: gas mass diffusion coefficient in fuel matrix (m$^2$ s$^{-1}$)
- $D'$: effective gas diffusion coefficient in fuel, $D' = D/a^2$ (s$^{-1}$)
- $D_f$: diameter of fuel kernel (m)
- $D_g$: average diameter of fuel grain (m)
- $D_p$: outer diameter of coated fuel particle (m)
- $F$: fraction of helium gas released from the fuel matrix that exerts pressure on outer coating

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\( F^* \) release-to-birth rate ratio of radioisotope
\( M \) molecular weight (kg mol\(^{-1}\))
\( n \) number of moles (moles)
\( N_a \) Avogadro number \((N_a = 6.0225 \times 10^{23} \text{ atoms mol}^{-1})\)
\( N_{\text{Pu}} \) Pu-238 atom density of as-fabricated plutonia fuel kernel (atoms kg\(^{-1}\))
\( P \) pressure (Pa)
\( q \) thermal power (W\(_{th}\))
\( q'' \) volumetric thermal power (W\(_{th}\) m\(^{-3}\))
\( R_{\text{g}} \) perfect gas constant \((R_g = 8.3143 \text{ J mol}^{-1} \text{ K}^{-1})\)
\( R_{\text{inner}} \) inner radius of ZrC coating (m)
\( \mathcal{R} \) dimensionless stress factor of a spherical shell
\( S_{\text{p}} \) geometrical surface area of as-fabricated fuel kernel (m\(^2\))
\( S_{\text{eq}} \) effective gas release area in fuel kernel (m\(^2\))
\( T \) temperature (K)
\( t \) time (s)
\( t_{\text{PyC}} \) thickness of pyrolytic carbon inner layer (m)
\( t_{\text{ZrC}} \) thickness of ZrC coating (m)
\( T_{1/2} \) radioactive decay half life (s)
\( \text{VOL} \) volume (m\(^3\))
\( Y_{\text{ZrC}} \) yield strength of ZrC (Pa)

**Greek**
\( \varkappa \) fraction of coarse spheres in a binary mixture at maximum packing
\( \beta \) maximum packing volume fraction of 2-size spheres in compact
\( \gamma \) open grain boundary porosity
\( e_{\text{open}} \) as-fabricated porosity of fuel kernel
\( e_{\text{open}}^{\text{open}} \) amount of open porosity in fuel kernel
\( e_{\text{PyC}} \) as-fabricated porosity of pyrolytic carbon layer
\( \lambda \) radioactive decay constant (s\(^{-1}\))
\( \eta \) thermal-to-electric conversion efficiency
\( \rho \) density (kg m\(^{-3}\))
\( \sigma_{T} \) maximum tangential tensile stress in ZrC coating layer (Pa)
\( \Psi \) thermal power ratio, \( q_{\text{CPFC-RHU}}/q_{LWRHU} \)

**Subscript/superscript**
\( f \) PuO\(_2\) fuel
\( \text{He} \) helium gas
\( m \) exponent
\( \text{max} \) maximum
\( \text{Pu} \) plutonium
\( \text{TD} \) theoretical density
\( l \) coarse particles in a binary mixture fuel-compact
\( 2 \) fine particles in a binary mixture fuel-compact
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