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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 $^{238}PuO_2$ fuel kernels are coated with a strong layer of ZrC designed to fully retain the helium gas generated by the radioactive decay of ^{238}Pu. A recent investigation has concluded that helium retention in large-grain ($\geqslant 200$ μm) granular and polycrystalline fuel kernels is possible even at high-temperatures (> 1700 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 μm) 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 μm) 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 ($N_a = 6.0225 \times 10^{23}$ atoms mol^{-1})
N_o	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_g	perfect gas constant ($R_g = 8.3143$ J mol^{-1} K^{-1})
R_{inner}	inner radius of ZrC coating (m)
$\mathscr{R}$	dimensionless stress factor of a spherical shell
S_p	geometrical surface area of as-fabricated fuel kernel (m^2)
S_R	effective gas release area in fuel kernel (m^2)
T	temperature (K)
t	time (s)
t_{PyC}	thickness of pyrolytic carbon inner layer (m)
t_{ZrC}	thickness of ZrC coating (m)
$T_{1/2}$	radioactive decay half life (s)
VOL	volume (m^3)
Y_{ZrC}	yield strength of ZrC (Pa)

Greek

α	fraction of coarse spheres in a binary mixture at maximum packing
β	maximum packing volume fraction of 2-size spheres in compact
γ	open grain boundary porosity
ε_f	as-fabricated porosity of fuel kernel
$\varepsilon_f^{\text{open}}$	amount of open porosity in fuel kernel
ε_{PyC}	as-fabricated porosity of pyrolytic carbon layer
λ	radioactive decay constant (s^{-1})
η	thermal-to-electric conversion efficiency
ρ	density (kg m^{-3})
σ_T	maximum tangential tensile stress in ZrC coating layer (Pa)
Ψ	thermal power ratio, $q_{\text{CPFC-RHU}}/q_{\text{LWRHU}}$

Subscript/superscript

f	PuO_2 fuel
He	helium gas
m	exponent
max	maximum
Pu	plutonium
TD	theoretical density
1	coarse particles in a binary mixture fuel-compact
2	fine particles in a binary mixture fuel-compact