NOVEL COMPOSITE MATERIALS FOR PRIMARY CONTAINMENT OF RADIOISOTOPE FUEL IN SPACECRAFT ENERGY SYSTEMS.

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Introduction: A programme of research and development has been initiated within the European aerospace and nuclear industries to investigate four key technological areas in the development of radioisotope power systems. These areas are radioisotope fuel production, thermoelectric conversion, Stirling-cycle conversion and containment of the radioisotope in the event of launcher failure or unscheduled spacecraft re-entry [1]. The latter activity includes parallel study of a traditional containment approach based on Iridium or Platinum-Rhodium alloys, and a novel approach based on a metal-matrix composite fuel. The production of a metal-matrix composite material containing a surrogate for the radioisotope is the subject of this paper.

The reduced availability of ^{238}Pu fuel now that routine production has ceased is well-documented, and in Europe isotope selection studies have identified ^{241}Am as the most promising alternative. Although the specific power output is only around 20% of ^{238}Pu, ^{241}Am fuel can be produced much more economically -and at high isotopic purity- by separation from stored separated Pu produced during reprocessing of civil fuel [2].

Whilst the launch safety framework and standards developed for US systems provide an excellent basis for design of new systems, significant qualification effort will be required for a new fuel, and for launch on European launchers and from European sites. There is some flexibility to explore novel alternative approaches in this context. Previous studies [3] have proposed that a tungsten-matrix composite fuel region, surrounded by a pure tungsten containment layer, could replace the traditional, multilayer containment system of the General Purpose Heat Source (GPHS). In this paper, a preliminary re-entry analysis is used to assess the feasibility of eliminating the traditional aeroshell, an initial material selection for the matrix is reported, and processing and mechanical testing of the novel fuel composite is outlined.

Re-entry thermal modelling: The radioisotope containment system must be capable of containing the radioisotope through the thermal environment of re-entry. A number of re-entry conditions were assessed as part of the GPHS development, one of the most severe for peak fuel temperature was an entry at 5.1 deg and 11 km/s, with the spacecraft break up assumed to release the individual GPHS modules at 100km [4]. A thermal model was developed to undertake a comparative study of a traditional aeroshell and one comprising a refractory material alone, as proposed by previous studies [e.g. 3].

Method. A module of GPHS-form was simplified into 1D spherical coordinates as a 'quarter-brick sphere', as illustrated schematically in Figure 1. The fuel power output and thickness of each layer match the GPHS [4]. 1D models were developed for convective heat flux into the spherical module due to re-entry heating and transient conduction within the module; these were coupled to allow the temperature variations with time and location within the idealised module to be calculated as a function of the entry parameters.

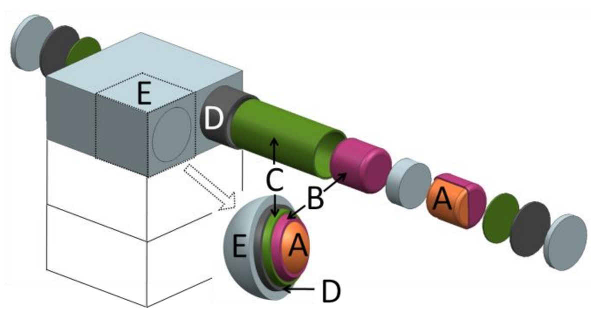

Figure 1 – Schematic representation of 'quarter-brick-sphere' model. A- Radioisotope, B – Clad, C – Graphite Impact Shell, D – Insulation, E – Aeroshell.

Re-entry trajectory was assumed one-dimensional (altitude); with gravity, atmospheric angular velocity and Coriolis acceleration were neglected. The ballistic coefficient of the quarter-brick-sphere was very similar to that of the complete module. A semi-empirical expression was used to estimate the convective heat flux at the stagnation point of a blunt entry body at hypersonic free steam velocity [5-7] with no attempt to vary the thermal input flux over the surface of the module: this assumption maintains 1D conduction throughout.

Within the fuel module, an explicit finite (forward) difference numerical transient model was used to model the conduction. This is a stepwise numerical simulation where temperatures at each node are calculated from those nodal temperatures in the previous time step allowing for conduction through the module, heat generation, non-linear convective heating input from the re-entry modelling and heat loss by radiation from the surface. The initial temperature distribution was obtained by imposing a fixed temperature boundary condition on the surface of the sphere.

This approach is inevitably a very significant simplification of the complexities of the hypersonic aerothermal regime; however it is a practical approach for preliminary design. No attempt has been made to model dissociation, reaction kinetic and deviation from ideal behaviour of gaseous species at high temperatures or surface ablation of the fuel module material.

Results. Simulations for the quarter-brick sphere were compared to reported values for the GPHS [4] and reasonable agreement was noted. The simulation was then repeated for Am_2O_3 fuel in both a GPHS-type containment and a novel containment consisting of varying thicknesses of a refractory material alone. Results are shown in Figure 2, showing that common refractory metals yield unfeasibly large fuel temperatures (note that the model did not include phase-change or ablation) or require significant mass to achieve equivalent performance.

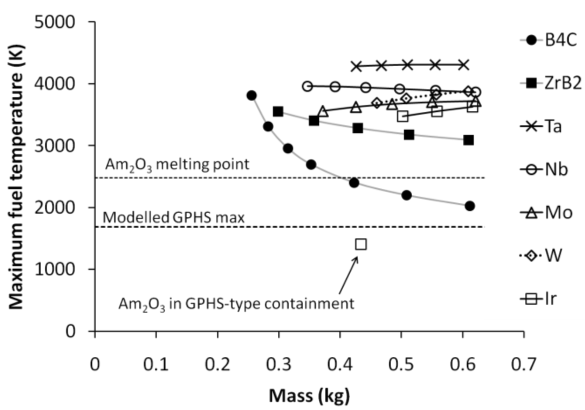

Figure 2 – Maximum fuel temperature in conventional and novel containment approaches.

Novel primary containment concept: The preceding analysis indicates that common refractory materials alone cannot completely replace the traditional insulation and aeroshell approach for radioisotope systems. The design drivers for space reactor systems are different, which means such an approach may still be possible for fission systems. A novel composite may, however still yield a number of benefits as an alternative to the primary containment (cladding) including reduced manufacturing stages, reduced requirement for ball-milling and the elimination of welds.

Material selection. The matrix of the fuel composite was selected on the basis of higher melting temperature than Am_2O_3, low density, capability for plastic deformation and oxidation resistance. On the basis of these factors, niobium scored highest on the trade-off. Neodymium (III) oxide, Nd_2O_3 was selected as the most appropriate stable surrogate for Am_2O_3 on account of similar ionic radii and therefore coefficient of thermal expansion and sintering behaviour.

Material processing and characterisation. Neodymium (III) oxide – niobium composite materials were successfully produced in mass fractions (Nd_2O_3:Nb) of 100:0, 30:70, 50:50, 70:30 and 0:100 by Spark Plasma Sintering (SPS) at high relative densities of >95%. Overall mass efficiency a spacecraft power system drives a high mass fraction of radioisotope fuel in the composite, so 50:50 and 70:30 wt% compositions were selected for optimisation of the sintering parameters and mechanical testing.

Mechanical testing in equibiaxial flexure: An initial indication of the mechanical properties of the composite is required to develop impact models and prepare a more detail test programme. Due to the high mass fraction of ceramic, a ceramic flexural strength standard was selected: ASTM C1499 [8], which will allow basic mechanical properties for the composite at room temperature and in the 'as-sintered' condition to be measured. This test programme is in progress at the time of writing and results will be reported.

Conclusions: Whilst it appears unlikely a sintered matrix can replace the insulation and aeroshell of a radioisotope power system, a novel composite containment may offer advantages in comparison to traditional approaches. Niobium was selected as the matrix material and a composite material developed using a non-radioactive Nd_2O_3 surrogate, characterisation of this new material is in progress.

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