Design and Nuclear-Safety Related Simulations of Bare-Pellet Test Irradiations for the Production of Pu-238 in the High Flux Isotope Reactor Using COMSOL

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Abstract

The Oak Ridge National Laboratory (ORNL) is developing technology to produce plutonium-238 for the National Aeronautics and Space Administration (NASA) as a power source material for powering vehicles while in deep-space. The High Flux Isotope Reactor (HFIR) of ORNL will be utilized to perform test irradiations of in-capsulated neptunium oxide (NpO2) and aluminum powder bare pellets for purposes of understanding the performance of the pellets during irradiation. Post irradiation examinations (PIE) will be performed to assess the effect of temperature, thermal expansion, swelling due to gas production, fission products, and other phenomena that were caused by irradiation over a period of 1-2 full-power HFIR fuel cycles. In order to properly design and assess the nuclear-safety implications of the Np-O2 pellets used to produce Pu-238, COMSOL Multiphysics 4.2a has recently been qualified to perform nuclear-safety-related calculations at HFIR. The present design and safety analysis simulates the bare-pellet test capsule assembly in full three dimensions (3D) over the entire capsule. The simulation fully couples the heat transfer and structural-thermal mechanics physics, and incorporates a best-estimate representation including nonlinear gap conductance modeling. The results show that the design should produce the desired results provided that the proper pellet side gap size is chosen (on the order of .001"-.0025"radial gap). The nuclear-safety goal is to demonstrate that the maximum pellet temperature during the entire irradiation cycle will not exceed the pellet melting temperature (taken to be 650°C). The results shown herein demonstrate that credit must be taken for pellet side-gap closure due to thermal expansion in order to sufficiently cool the pellet and prevent melting. Therefore, the model correlations used for gap conductance are vitally important to demonstrate adequate cooling. The developed COMSOL model includes several features that may be of interest to the COMSOL user including: 1) CAD geometry input and subsequent manipulation, 2) mesh design considerations, 3) heat transfer of both solid and fluid, 4) elastic structural mechanics including thermal expansion, 5) application of complex thin-film resistance, 6) feedback upon the gas-gap conductance as a result of the surface pressure created by the thermally-expanding contact pairs upon the pellet surfaces, 7) complex variable and function structure embedded directly into the COMSOL model to create a best-estimate of the gas-gap conductance incorporated into the thin-film resistance, and 8) completely non-linear variable properties including conservative estimates of the pellet properties. The resulting solution is highly nonlinear and difficult to obtain; particularly after the pellet surfaces were pressed against the side walls of the in-capsulation.

Reference

1. C. V. Madhusudana, Thermal Contact Conductance, 1996, ISBN 0-387-94534-2, Springer-Verlag, New York, Inc.
2. Plutonium-238 Production Project, http://www.ne.doe.gov/pdfFiles/factSheets/2012_Pu-238_Factsheet_final.pdf.
3. http://blogs.knoxnews.com/munger/2012/03/plutonium-project-at-ornl.html.

Figures used in the abstract

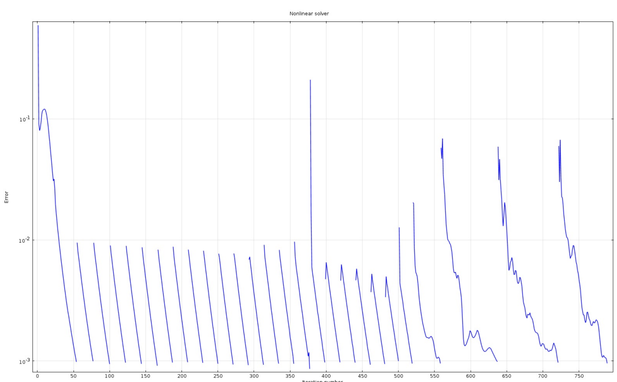

Figure 1: Iteration Sequence for the Design-Basis Results. Each convergence curve represents a 5% increment in reactor power starting at zero (left) to 130% (right) power. The pellet is pressing against the side wall starting at 115% power.

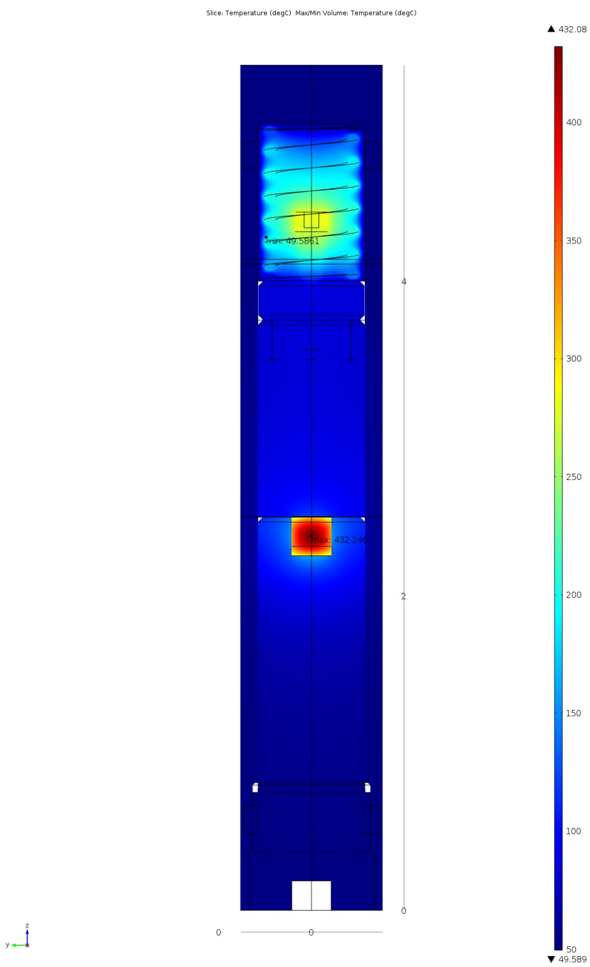

Figure 2: Temperature Slice (C) for the Design Basis Case at 100% Power. The bare-pellet is shown as the hottest region, and the helium-enclosed region about the spring is also highlighted.

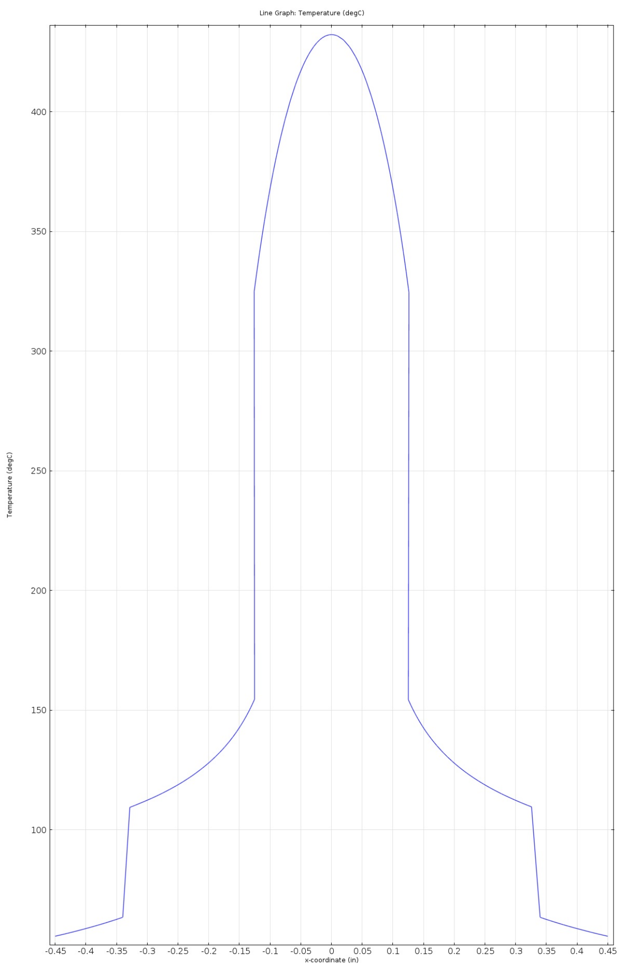

Figure 3: Temperature Cut Line in the Radial Direction at the Elevation of Maximum Temperature. The large step-changes correspond to the gas-gap locations.

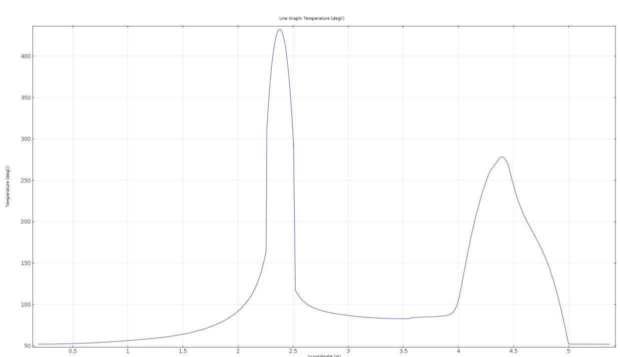

Figure 4: Temperature Cut Line in the Axial Direction at the Capsule Centerline.