BERYLLIUM IMPREGNATION OF URANIUM FUEL: THERMAL MODELING OF CYLINDRICAL OBJECTS FOR EFFICIENCY EVALUATION

A Senior Scholars Thesis

by

NICHOLAS MORGAN LYNN

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

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Major: Nuclear Engineering

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ABSTRACT

Beryllium Impregnation of Uranium Fuel: Thermal Modeling of Cylindrical Objects for Efficiency Evaluation. (April 2009)

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With active research projects related to nuclear waste immobilization and high conductivity nuclear fuels, a thermal model has been developed to simulate the temperature profile within a heat generating cylinder in order to imitate the behavior of each design. This work is being done so that it may be used in future research projects to represent how heat is being stored or dissipated in a material that has a uniformly distributed heat source from fission or radiation deposition. The model has been built to have a 2-D visual representation of the temperature distribution. A nodal system is employed for this model so that the user chooses the size of the mesh that will develop an accurate reading for their purposes. The model uses fundamental heat transfer equations and heat conduction properties for different metals. The heat transfer equations that will be used are fundamental and used at each point in the mesh developed by the user to ensure accuracy of the calculation. Below is such an example of an equation that will be used to model the temperature distribution in the cylindrical samples. By choosing the thermal properties associated with the material that is being

researched, certain parameters are imposed in the equations automatically. This provides an easy method to see changes in the temperature distribution due to the improvements that have been made. Such parameters are the thermal conductivity and the thermal diffusivity along with others such as the material specific heat. The model will incorporate color variations in the display in order to allow larger meshes to be used while not diminishing the appearance of the results. The color variation will be due to a gradient from red to blue to represent hot to cold.

DEDICATION

To my parents and family and those that tell the students that we can do anything.

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Sean McDeavitt, and graduate student Michael Naramore for their extensive help on this project. I would also like to thank the Nuclear Department for allowing me to go to the student conference at the University of Florida to present the findings of this research and for their funding the assistance from the Undergraduate Research Program.

NOMENCLATURE

Δx	Change in the x-direction
Δy	Change in the y-direction
BeO	Beryllium Oxide
k	Thermal Conductivity
m	Mesh Point Coordinate in x-direction
n	Mesh Point Coordinate in y-direction
$\dot{q}$	Rate of Energy Generation
q"	Surface Heat Flux
q	Heat Generation
T	Temperature
TD	True Density
UO_2	Uranium Dioxide

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CHAPTER I

INTRODUCTION

Nuclear reactors today use Uranium Dioxide(UO_2) fuel that has a low thermal conductivity. This leads to the temperature of the fuel to increase in order to produce the same power output as a higher thermal conductivity material. The Beryllium Oxide(BeO) that is to be used in this experiment is such a material that can raise the initial thermal conductivity of the fuel.

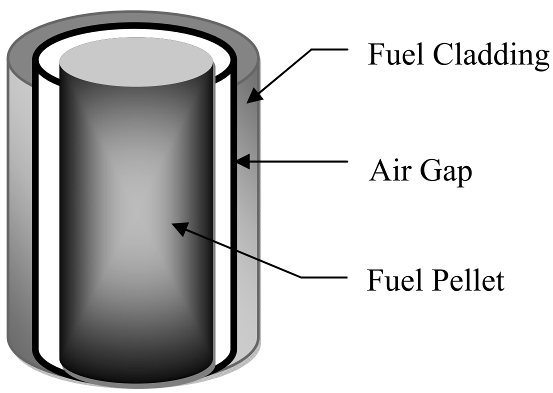

Fig. 1.1. Depiction of a nuclear fuel element in nuclear reactors.

A fuel element is depicted above in Figure 1.1 and is constructed with a fuel pellet, the air gap, and the fuel cladding. The cladding is the structural container for the fuel which keeps the fuel from mixing with the coolant. The air gap is necessary to retain the structure of the cladding as the fuel pellet gets restructured due to burnup. The fuel pellet is composed of a mixture of fissionable and fissile material. The difference between

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This thesis follows the style of Journal of Nuclear Materials.

fissionable and fissile material is that fissionable material needs an extra amount of energy in order to undergo fission, while fissile material is able to fission on its own. Energy within the fuel pellet is created by the fission process of the Uranium and stored as heat. This heat is then transferred through the fuel, across the air gap, through the cladding and finally into the coolant.

The ability of the material to transfer the heat through the fuel is known as the thermal conductivity. The research is trying to improve the total burnup of the nuclear fuels used nationwide. As stated earlier, the higher thermal conductivity allows nuclear plants to operate at lower temperatures. The impregnation of the Uranium by the Beryllium will lead to heightened safety measures related to the core and lower operating cost.

The goal of this work will be to recreate the research done at Purdue University, by T.J., Solomon, A.A., Revankar, and a graduate student. I will be working with Michael Naramore, a Nuclear Engineering graduate student, on this project.

CHAPTER II

THEORY OF THERMAL MODEL

In order to get a valid model of the temperature profile within the fabricated Beryllium Oxide infused Uranium fuel pellet, a nodal system must be established. The system will have each node referencing the four nodes that border the central node, according to Figure 2.1. This nodal system will be used to iteratively solve for the temperature at each point in the system. In the following figure, *m* and *n* are the horizontal and vertical locations, respectively, on the grid used in the thermal model.

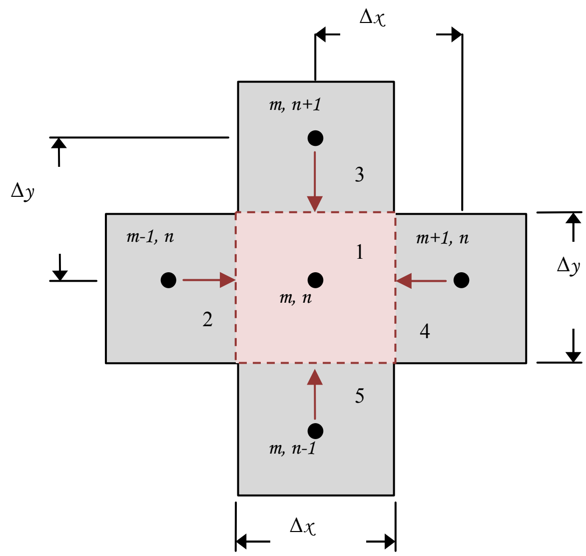

Fig. 2.1. Conduction of adjoining nodes to the reference node. [1])

The model uses two different equations to calculate the temperature at the different nodal points because the central axis of the fuel pellet stays at a constant temperature according to the linear power density. This linear power density is associated with the material that is in consideration for the manufactured pellet. Most of the pellet uses a method called conduction, described above to calculate the temperature at the referenced nodal point. The outside of the pellet is in contact with a gas gap, followed by the cladding, and then the reactor coolant. For this purpose of this study, the pellet will only be in contact with a gas environment, meaning convection. Convection can be visualized by taking away the fourth cell above and replacing it with a heat transfer coefficient and the corresponding heat flux term, that will be discussed later.

Equations that will be used are composed of data that is temperature dependent. By solving iteratively and using calculation methods that recall data at temperature, a more precise and more accurate temperature profile can be found. Smaller parts of the larger equation can be calculated using multiple equations [1]) to calculate the heat flux using the temperatures at the reference node and an adjoining node, thermal conductivity, and cell thickness. Notice that there is no Δz term in the two equations below. This is because the model is based on a two-dimensional scheme instead of three.

$$q_i = k(\Delta x \cdot 1)(T_i - T_1), i = 2,5$$

$$\sum_{i=2}^{5} q_i + \dot{q}(\Delta x \cdot \Delta y \cdot 1) = 0$$

Making the assumption that Δx and Δy are equal, simplifies most of the equations needed for the model to a simple Δx^2 term.

The second equation shown above can then be transformed into different equations depending on the system requirements. As stated above, there are two main equations that are used for the thermal model; one for the inside of the pellet, and the other for the outer surface of the pellet. The two equations are easily distinguishable by looking at the content in the equation. The equation that has a heat flux term, q'', is the equation that is used to solve for the temperature on the outer surface of the rim. This heat flux term denotes the heat that is either lost or absorbed by the fuel. For this model the heat flux is taking heat away from the pellet, and thus will be a negative number. The other equation will be used for the conduction portion of the pellet other than the center axis temperature.

$$4T_1 = \sum_{i=2}^{5} T_i + \frac{\dot{q}}{k(T_1)} \Delta x^2 \text{, Conduction}$$

$$4T_1 = 2T_2 + T_3 + T_5 + \frac{q'' \cdot \Delta x}{k(T_1)} + \frac{\dot{q}}{k(T_1)} \Delta x^2 \text{, Convection}$$

With these two equations, a thermal model can be created to compare the effectiveness of the Beryllium Oxide additive to the Uranium fuel pellet to that of the unmodified fuel pellet.

The thermal conductivities for UO_2 will be found using the following equation that uses the material's temperature to solve for a thermal conductivity.

$$k = \frac{100}{6.548 + 23.533t} + \frac{6400}{t^{5/2}} \exp\left(\frac{-16.35}{t}\right), \ t = T/1000$$

The thermal conductivities for BeO impregnated UO_2 pellets was found using the following plot, figure 2.2, that was found in an earlier report. The plot was put into a grid in which an accurate estimate of values could be determined for use in the thermal model.

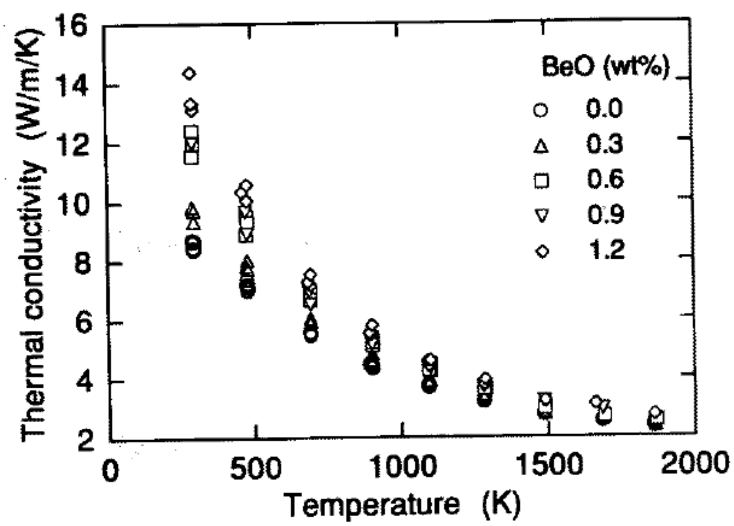

Fig 2.2. Thermal conductivity of BeO infused pellets. [2])

CHAPTER III

RESULTS

Utilizing the methods presented earlier, the model can be created to see the thermal distributions of different additives in fuel. Figure 3.1 below shows a depiction of a normal temperature distribution in a regular nuclear fuel pellet with UO_2.

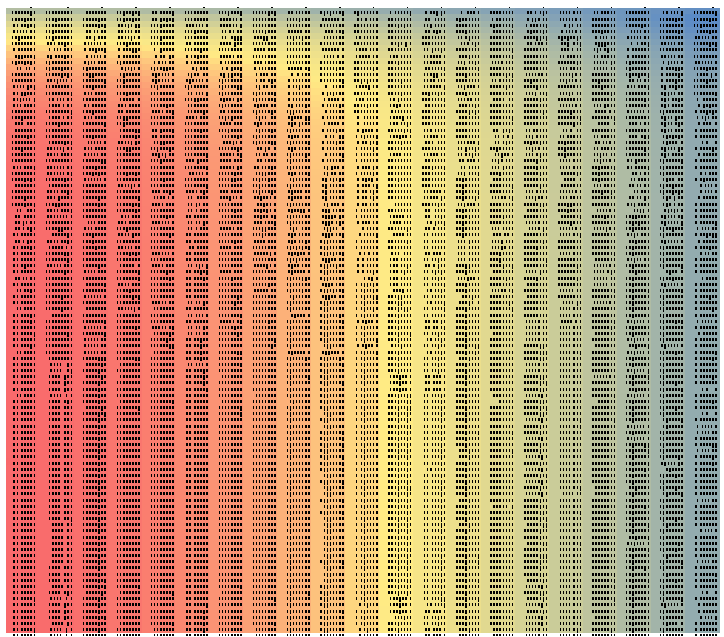

Fig. 3.1. Display of the program's output after convergence iteration.

The hot and cold cells of the fuel pellet can be determined by the color-coding that has been used. Notice the color-coding as it fades from red to cold, illustrating the temperature change across the fuel element. Using the iteration process, the user can visually see the way that the heat propagates through the pellet.

In order to see the change between two different fuel arrangements, the graphs created need to be compared as shown below in figure 3.2. The goal of the new additive is to have a better heat conductivity throughout the fuel pellet in a reactor core leading to more power output from the fuel and better burnup. To see this on the graphs that are created, a lower temperature at the fuel centerline is sought while the temperature at the outside of the fuel is similar to the unaltered fuel. The solid line below shows the temperature profile of a fuel pellet with just the UO_2 fuel while the dashed line is the profile of the BeO impregnated fuel.

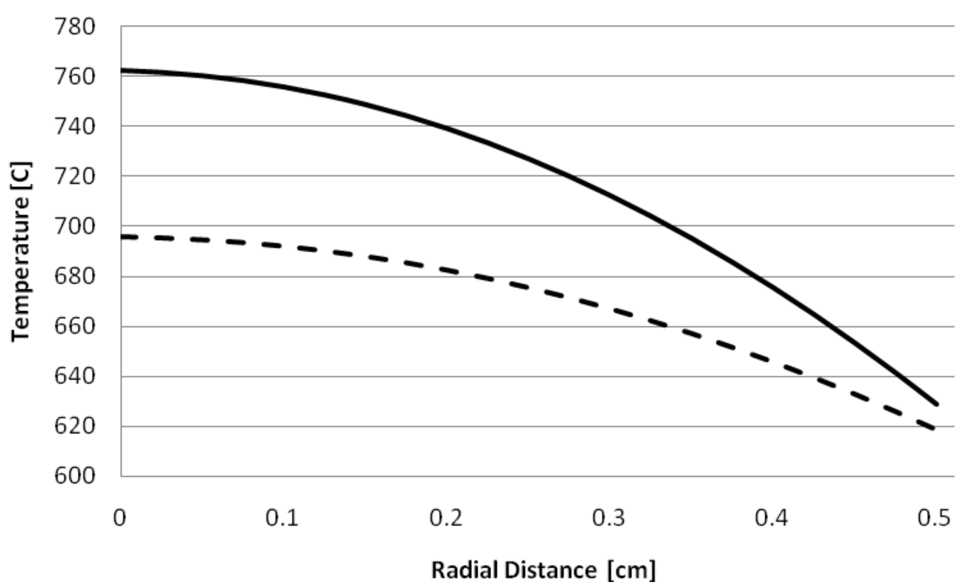

Fig. 3.2. Comparison of UO_2 fuel to that of UO_2 with BeO infused pellets.

In fuel pellets for pressurized water reactors (PWR) today there is a temperature drop of 350°F. This is for fuel pellets that consist of UO_2 with no additives such as Beryllium. If a temperature drop value is found to be less than this, then the Beryllium Oxide additive is a success for increasing the thermal conductivity in the fuel pellet that is currently in use.

Through the use of the model, a temperature drop of 120 °C is found without the BeO enhanced fuel and an 80 °C drop with the BeO enhancement. This shows that the addition of BeO in the UO_2 fuel matrix is an improvement that is worth making to current fuel elements. Furthermore the difference between central temperatures is around 60 degrees and on the outer rim of the fuel there is a temperature difference of only 7 degrees. This again shows the practicality of the Beryllium Oxide fuel enhancement on current fuel elements.

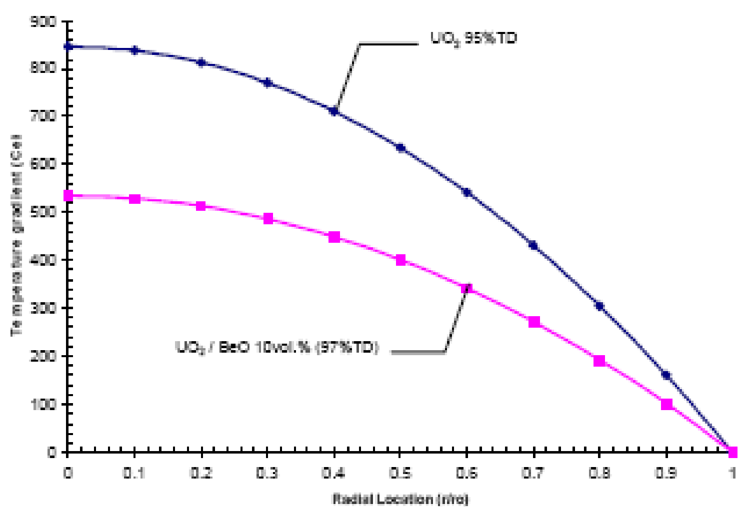

Fig. 3.3. Results from a Purdue study according to a surface temperature of 576 °C. [3])

Comparing figures 3.2 and 3.3, the trends between the two graphs are very similar. The discrepancies between the models can be attributed to the differences in boundary conditions and plotting method. Figure 3.3 is plotted with temperature gradient on the ordinate and the relation of the radial location to the radius is located on the abscissa.

Other discrepancies can be argued by the use of different sets of data for the thermal conductivities for the different types of material. Thermal conductivities of UO_2 were calculated according to temperature using an equation instead of real data due to the availability of the material to do the testing for raw data. The same is true for the BeO infused fuel pellet in the instance that a plot was used to gather the thermal conductivities as an alternative to the data that could not be measured due to the lack of material.

The use of different boundary conditions could lead to the difference between figures 3.2 and 3.3 as well. The thermal model uses a constant volumetric heat generation term which could vary from the term that the group at Purdue University had used.

CHAPTER IV

SUMMARY AND CONCLUSION

As stated earlier, if a material that has a high conductivity is impregnated into the UO_2 fuel matrix and in turn increases the overall efficiency of the fuel, then the enhancement should be made on a grand scale. This will lower operating costs by flattening the power profile and increasing the burnup of the core and increase safety in the plant with the ability to produce the same amount of power at a lower temperature.

The thermal model that has been developed to determine the effectiveness of the addition of BeO to the Uranium fuel pellet demonstrates that there is a thermal conductivity increase. This is shown by figure 3.2 and described in Chapter III. The results are similar to that of the data from Purdue University and thus the thermal model is valid for the use of this exercise.

On a business point-of-view the addition of BeO will increase the overall revenue from the operation of the plant because the lower temperature needed in the center of the fuel. It could even operate at the same central temperature and transfer more heat to the coolant, which leads to more power and more money made.

With the development of innovative and unique ideas more and more efficient systems can be created to be used in everyday operations. The implementation of BeO-UO_2 fuel pellets is a bold step with this mentality. Who knows what the next bold step in fuel additives will be?

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