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Development of a Computer Code PADPLAC-UMo for Performance Analysis of Monolithic Uranium Molybdenum Fuel Plate

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1. Introduction

Restrictions related to carbon emissions into the atmosphere have made the development of compact and low power nuclear reactors an attractive alternative to meet the needs of electric power generation in low and medium population density regions. In addition, the implementation of these reactors near the consumption centers has the advantage of implementing less extensive power transmission lines, which leads to lower implementation costs and lower energy losses during operation.
The use of fuel plates in power reactors has been studied as an alternative to traditional fuel rods because they have the following advantages:

- Plant performance:
  a. increase in power density provided by the fuel;
  b. better heat transfer to the refrigerant;
  c. reduction of the operating temperature of the plate when compared to a fuel rod operating at the same power;
  d. Production of more compact cores which leads to lower plant implementation costs.
- Plant Safety:
  a. as it operates at lower temperatures, it has operating conditions that are best suited to the operating limits of the fuel plate materials (fuel and cladding);
  b. greater ability to withstand stresses and external dynamic loading when compared to the strength of the fuel rods.

2 Uranium Molybdenum Fuel Plate

Among the various fuel plate options under development, one that deserves special attention for use in power nuclear reactors is the Zircaloy-cladding uranium-molybdenum monolithic core fuel plates. These plates provide a higher uranium density compared to fuel plates composed of an aluminum-dispersed uranium-molybdenum core, making the reactor core more compact. Additionally, they exhibit better behavior under irradiation (1) and greater mechanical rigidity. Figure 1 schematically illustrates the structure of a monolithic uranium molybdenum fuel plate(2).

Figure 1 - Illustration of a monolithic uranium molybdenum fuel plate (cross section - no scale).

3. Characteristics of the PADPLAC-UMo Computational Program

The PADPLAC-UMo code iteratively calculates the interrelated effects of fuel and cladding temperature, plate internal gas pressure, fuel and cladding deformation, release of fission product gases, fuel swelling, cladding thermal expansion, cladding corrosion, and crud deposition for a given buildup rate as functions of time and fuel-specific power (3).

4. Test cases involving comparison of results obtained by analytical calculations with results provided by PADPLAC-UMo

For the execution of this case, the use of a monolithic uranium molybdenum fuel plate with the dimensions given in Table I will be considered. Regarding the thermohydraulic characteristics adopted for the execution of these tests, values typically found in small reactors. These values are provided in Table II.

For the realization of this test case, the following data were also considered[4]:

- irradiation period: 365 days divided into 20 times increments.
- regarding the power supplied by the fuel plate (38.36 kW), it was considered a progressive increase of this power over time as follows:
    - the 1st time increment 28.00 kW; the 2nd time increment 30.00 kW; the 3rd time increment 32.00 kW; the 4th time increment 34.00 kW; the 5th time increment 35.00 kW
    - the 6th to the 10th time increments 36.00 kW; the 11th to the 15th time increments 37.00 kW; the 16th to the 20th time increments 38.36 kW
- four different power profiles, the first being applied in the first five-time increments, the second being applied from the sixth to the tenth time increment, the third being applied from the eleventh to the fifteenth time increment and the fourth being applied from the sixteenth to the twentieth time frame increment of time. Still with respect to the power profiles, the first two are defined by 12 longitudinal nodes and the third and fourth are defined by 10 nodes.

Table I - Main dimensions of the fuel plate

Symbol	***Description***	***Values***
L (m)	Active width of fuel plate	0.09
H (m)	Active height of fuel plate	1.00
L_c (m)	Width of cooling channel	0.09
e_r (m)	Fuel plate cladding thickness	0.0002
t_m (m)	Fuel plate core thickness	0.002
t_w (m)	Cooling channel thickness	0.003
A_c (cm^2)	Cross-sectional area of a cooling channel	2.70
A_n (cm^2)	Fuel heartwood cross-sectional area	0.90
N_c (dim.)	Number of fuel elements in reactor	21
N_f (dim.)	Number of fuel plates per fuel element	72
N_t (dim.)	Total number of fuel plates in reactor core	1512

5. Results provided by the PADPLAC-UMo program

With the data provided in the previous item, it is possible to elaborate the input data file and to execute the program PADPLAC-UMo. The program provides a lot of information. In this paper, only a small number of results will be analyzed to show the agreement between the data provided by the program when compared to the results obtained by analytical calculation.

For this analysis, the last time increment was used, in which the maximum power is applied. The Figure 3 illustrates the temperatures obtained by the PADPLAC-UMo program.

Table III provides a comparison between the temperatures obtained by analytical calculation and the temperatures obtained by the computer program PADPALC-UMo for longitudinal node 6. As can be seen, the results have an excellent convergence.

Table II - Input thermal and hydraulic data for the cooling channel for the reactor considered.

Description	***Values***
Total rated reactor power (MW)	58
Power generated on fuel plates (MW)	56.6
Peak factor	3.4
Total number of boards in the core	1512

Total power generated on the fuel plate (kW)	38.36
Medium heat flow (W/cm^2)	18.4
Nominal pressure in primary system (bar)	130
Channel flow (m^3/h)	1.26
Reactor design mass flow (kg/s)	427.6
Coolant inlet temperature (°C)	265.0
Cooling channel thickness (mm)	3
Coolant speed in the cooling channel (cm/s)	146.9

Table III - Comparison of temperatures obtained by analytical calculation with the temperatures provided by the PADPLAC-UMo program.

	Temperatures (ºC) Analytical Calculation	***Temperatures (ºC) PADPLAC-UMo***
Coolant temperature	274.40	275.65
Cladding external temperature	298.16	299.72
Cladding internal temperature	331.12	332.31
Fuel externa temperature	333.30	334.08
Center fuel temperature	390.71	391.97

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| Time Step  20 =  365.000 (days)       ----       Average Linear Heat Rate =   38.360 (kW) |
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Node Long.	Coolant Temperature (C)	Clad. Ext. Temperture (C)	Clad. Int. Temperature (C)	Drop Temperature Fuel/Cald Interf. (C)	Fuel Ext. Temperature (C)	Center Fuel Temperature (C)
1	266.12	278.30	295.08	0.89	295.99	325.69
2	267.51	283.46	305.44	1.17	306.60	346.47
3	269.18	291.03	321.13	1.60	322.74	379.27
4	271.46	294.28	325.71	1.68	327.39	384.72
5	273.09	297.16	329.75	1.76	331.51	389.40
6	275.65	299.32	332.31	1.76	334.08	391.97
7	277.40	300.72	331.65	1.68	333.33	390.66
8	279.56	301.54	331.23	1.60	332.98	387.12
9	280.47	297.11	320.19	1.17	320.26	360.89
10	281.35	294.12	311.36	0.89	312.25	342.27

Figure 3 - Main Fuel Plate Temperatures Provided by the PADPLAC-UMo Program

Figure 4 shows the output of the PADPLAC-UMo program with results related to burnup, production and release of fission gas and fuel and cladding stresses. Table IV provides a comparison between the results given in Figure 4 with those obtained by analytical calculation. As can be seen, the results have an excellent convergence(5).

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| Time Step  20 =  365.000 (days)       ----       Average Linear Heat Rate =   38.360 (kW) |

Burnup at the end of the time increment:   10.945 MWd/tU

Fission gas produced (totaled):     0.963E-07 mols
Fission gas released:    0.000E-00 mols
Pressure inside the fuel compartment:    0.000E00 MPa

Thermal Stresses:      Cladding:     -57.942 MPa
                       Fuel:     78.484 MPa

Fuel / Cladding Interface Condition:     Preserved
Cladding deflexion:     0.000E00 mm
Stress in the central edge region (Cladding):    0.000E00 MPa
Stress in the central region of the plate (Cladding):    0.000E00 MPa
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Figure 4 – Results provided by PADPLAC-UMo Code

Table IV - Comparison between the results given by PADPLAC-UMo code with those obtained by analytical calculation

	Analytical Calculation	*PADPLAC-UMo*
Burnup at end of time step (MWd/tU)	10.491	10.945
Fission gas produced (totaled) (mols)	1.065e-06	0.963e-07
Fission gas released (mols)	0.000	0.000
Pressure inside the fuel compartment (MPa)	0.000	0.000
Thermal Stresses - Cladding (MPa)	-59.039	-57.942
Thermal Stresses – Fuel (MPa)	80.876	78.484
Fuel / Cladding Interface Condition	Preserved	Preserved
Cladding deflexion (mm)	0.000	0.000
Stress in the central edge region (MPa)	0.000	0.000
Stress in the central region of the plate (MPa)	0.000	0.000

6. Conclusion

Regarding the models related to the fuel plate thermal analysis, very robust models were obtained through the specialized literature that provided consistent results when compared to the verification tests performed.

The most sensitive and challenging part related to the implementation of the PADPLAC-UMo computer program refers to the one related to the analysis of the fuel plate behavior when considering the effects of fuel burning and their respective influences on the thermal and mechanical behavior of the fuel plate. In this case, the specialized literature provides extremely scarce information, as the Zircaloy coated UMo monolithic fuel plates are still in the embryonic stage of development.

In particular, the task of defining a model that detailed the behavior of the fuel/coating interface along the fuel burn has become extremely complex. The codes used for the performance analysis of fuel rods make use of a large amount of empirically obtained data to perform this type of analysis and such data are practically nonexistent for Zircaloy coated UMo fuel plates.

An important point to consider is that the approximate models used in the code do not invalidate the results obtained but make the results less reliable. As more accurate information can be obtained by experimenting, models already in the code can be improved, so that the program can provide more appropriate results.

Thus, it is considered that the process started in this work is not finished but is a starting point for the proposition of a series of experiments that can provide a better understanding of the behavior under irradiation of monolithic uranium-molybdenum fuel plates making This leads to a natural and joint evolution of the knowledge of the irradiation behavior of this type of fuel plate and the increased accuracy of the results provided by the PADPLAC-UMo computer program.

7. References

1. ROBINSON, A. B. Irradiation Performance of U-Mo Alloy Based ‘Monolithic’ Plate-Type – Design Selection Update. Idaho National Laboratory. INL/EXT-09-16807. 2013. 87 p..

2. WIENCEK, T. C.; PROKOFIEV, I. G. Low-Enriched Uranium-Molybdenum Fuel Plate Development. Argonne National Laboratory. ANL/ET/CP-103084. 2000. 13 p.

3. TONG, J. S.; WEISMAN, J. Thermal Analysis of Pressurized Water Reactors. American Nuclear Society. 1979. 417p.

4. ANDRZEJEWSKI, C. S. Avaliação de Alternativas de Combustível Tipo Placa para Reatores de Pequeno Porte. Dissertação de Mestrado. IPEN. 2005. 83 p.

5. REIS, Regis. Development of a computer code for performance analysis of monolithic uranium-molybdenum fuel plates under irradiation in power reactors. 2018. 111 p. (PhD Tesis – Instituto de Pesquisas Energéticas e Nucleares) – IPEN – CNEN/SP. São Paulo.