Performance Prediction Of High Density Nuclesr Fuel Plate Containing U-7%Mo/Al

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ABSTRACT

PERFORMANCE PREDICTION OF HIGH DENSITY NUCLESR FUEL PLATE CONTAINING U-7%MO/AL. In recent several years, the Center for Nuclear Fuel Technology (PTBN) - BATAN is conducting research and development on new research reactor fuel of U-Mo/Al dispersion containing 7 g U/cm^3 as a subtitute for the actual U_3Si_2 fuel of 2.96 g.U/cm^3. The major advantages of this fuel are higher U content than the U_3Si_2 and easier management, i.e. reprocessing of the spent fuel, while the main drawback is the manufacture of powder that is more difficult because it is more ductile and its thermal conductivity degrade faster during in reactor service. The first difficulties have been solved by hydriding process. Performance prediction should be foreseen in order to obtain permit for irradiation testing of the new fuel. The prediction has been performed on hot spot location by taking into account some effects of fission swelling of fuel particles, formation of interfacial reaction layer, meat densification which feedback to fuel temperature and plate swelling the principal safety parameters of normal operation. The results show that at lower burnup the dominant effect is fission solid swelling but at higher burnup it is replaced by fission gas swelling. At 60% burnup (10.2 x 10^21 fission/cm^3) fuel particle swelling reaches 75.79% and at total burnup swelling rises to 103.1%, which corresponds to 11.6% and 17.2% plate pillowing. The interfacial reaction layer at full burnup is 5.7 µm. Plate pillowing at 60% burnup is below the limit acceptance but plate pillowing at full burnup is beyond the limit acceptance.

Key words: U-Mo powder, hydriding, nuclear fuel, irradiation performance, analysis.

ABSTRAK

PREDIKSI KINERJA PELAT ELEMEN BAHAN BAKAR NUKLIR DENSITAS TINGGI YANG MENGANDUNG U-7%Mo/Al. *Dalam beberapa tahun terakhir, pusat (CNFT/PTBN) melakukan penelitian dan pengembangan baru U-Mo / Al dispersi penelitian bahan bakar reaktor yang mengandung 7 g U/cm^3 untuk pengganti bahan bakar U_3Si_2 yang ada berdensitas 2,96 gU/cm^3. Keuntungan utama dari bahan bakar ini kandungan U lebih tinggi dari dan lebih mudah manajemennya daripada bahan U_3Si_2, yaitu memproses ulang bahan bakar habis pakai. Kelemahan utama adalah pembuatan bubuk yang lebih sulit karena lebih ulet dan lebih cepat degradasi konduktivitas termal selama dalam pelayanan reaktor. Kesulitan pertama telah diselesaikan dengan hidridisasi proses. Prediksi kinerja harus dipersiapkan untuk mendapatkan izin untuk pengujian iradiasi bahan bakar baru. Prediksi telah dilakukan pada lokasi titik-panas dengan memperhatikan beberapa efek fisi pembengkakan partikel bahan bakar, pembentukan*

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reaksi lapisan antarmuka, densifikasi daging yang mengumpan balik untuk suhu bahan bakar dan pembengkakan pelat, yang merupakan parameter keselamatan utama pada operasi normal. Hasil analisis menunjukkan bahwa pada derajat bakar lebih rendah efek dominan adalah pembengkakan hasil fisi padat tetapi pada derajat bakar tinggi itu digantikan oleh pembengkakan gas hasil fisi. Pada derajat bakar 60% (10.2 x 10^{21} fission/cm^3) bahan bakar partikel pembengkakan mencapai 75.79% dan pada derajat bakar sebesar 103,1% pembengkakan, yang sesuai dengan 11,6% dan 17,2% bengkak pelat. Lapisan reaksi antar muka pada derajat bakar penuh adalah 5,7 um. Bengkak pelat pada derajat bakar 60% berada di bawah batas maksimal diperbolehkan untuk keselamatan operasi, jadi diterima.

Kata kunci: *U-Mo bubuk, hidridisasi, bahan bakar nuklir, kinerja iradiasi, analisis.*

INTRODUCTION

In recent several years, the Center (CNFT/PTBN) is conducting research and development of research reactor fuel of higher uranium content than the actual fuel of 2.96 g.U/cm^3 for prolong the life time, easy uses and economic advantage. The plate type fuel bundle consists of fuel plates stacked parallel with space/gap for coolant flow as shown in Fig-1. The plates consist of meat of fuel powder dispersion in Al matrix and Al clad. The earlier step was development of same type fuel of U3Si2 fuel powder dispersed in Al matrix, but with higher fuel fraction to contain 4.2, 4.8, and 5.2 g U/cm^3[1]. The recent development concerning U-7Mo fuel alloy of higher U of 12 g.U/cm^3 which is the fuel for plate element of 7 g.U/cm^3. Fabrication of Fuel bundle prototype of U-7Mo/Al of 7 g.U/cm^3 for irradiation qualification is in progress[2]. RIA and LOFA related to the proposed irradiation test are in progress. This work presents a preliminary analysis for fuel performance related to high burnup during normal operation of reactor. The allowable plate swelling is limited to assure the coolant flow rate is sufficiently to maintain fuel temperature. Figure 2 show a typical metallographic of plate cut perpendicular to plate face experiencing excessive swelling[3], that should be avoided.

The interaction layer need to be quantified in order to obtain good predict of thermal behaviour. The behaviour of new fuel during irradiation qualification in the reactor needs to be well understood in order to obtain permit of irradiation experiment in reactor. The first generation fuel U-Mo dispersion consists of U-Mo fuel particles dispersed in a matrix of aluminium, very similar to the existing research and test reactor fuel U_3Si_2 / Al. The first generation fuel element plates show the problem to an acceptable fuel performance at high power and high burnup, due to the intense interaction between the particle and the matrix alloy, especially at high temperatures and resulting thermal conductivity drops drastically by the interaction layer that is refractory. Further testing showed that the addition of small amounts of silicon (2-5 wt.%) into the matrix fuel restrains the interface interaction [3,5]. The phenomenon of the fuel particle swelling and the formation of aluminide phase from fuel-matrix interaction which is less dense than the original phase enlarge the meat swelling compared to other fuel-matrix system having less reactive. The plate swelling or sometime is called plate - pillowing as the plate edges- which is free fuel zone and does not swell will reduce the coolant channel width between plates. This will reduce the coolant flow then increase its temperature and consequently the fuel peak temperature. The decrease in thermal conductivity has been related to the presence of interface reaction layer of fuel particles and matrix that causes the fuel temperature increase. The fuel temperature is limited to ensure the mechanical strength degradation limited for safety and the plate swelling is limited to assure enough coolant flow in cooling the fuel plates. The plate swelling comes from fuel particles swelling which are originated by by fission gas bubbles and solid fission product. An excessive swelling of meat fuel particles –as shown in Figure 2 and accommodated by thickening the plate need to be avoided.

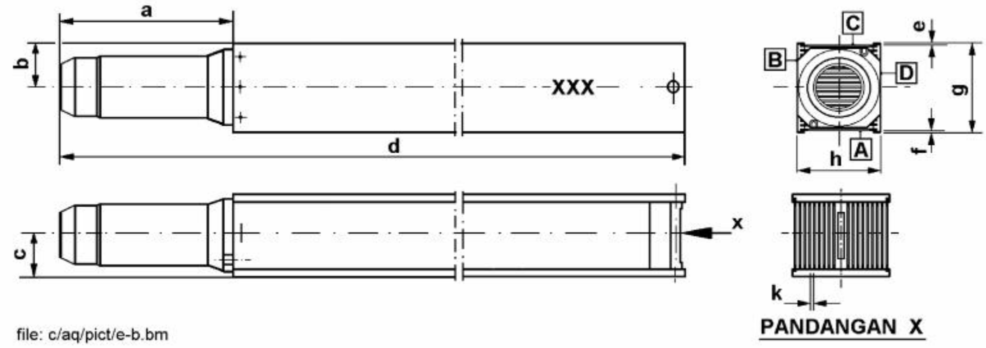

Figure 1. Typical Bundle of 21 flat fuel- plates[1]

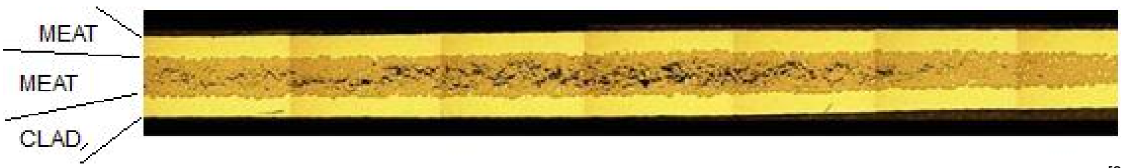

Figure 2. Metallograph of irradiated fuel plate at mid length and across its width and thickness[3].

ANALYSIS PROCEDURE

The analysis was based on these following assumptions: (1) All the bubbles is spherical. (2) The bubbles size (< 0.2 um) is much smaller than the size of fuel particle powder (60 um); the swelling of particles powder are isotropic. (3) The particles powder are much harder than Al matrix. (4) At initial swelling of particle powder cause shrinkage the fabrication pores, then the meat swelling having soft matrix will press the cladding perpendicular to plate surface. (5) The swelling to other directions are neglected because of: (a) the dimension ratio of thickness to with and thickness to length is very small (0.3/65 and 0.3/700); (b) at both ends there are frame of meat of 25 mm and plus rigid frame of plates bundle which are swagged to it; (c) In additional, the swelling in direction of plate length does not impose any safety.

The fuel temperature of a U-Mo/Al dispersion fuel rod was calculated by solving a cylindrical heat transfer equation with the aid of the thermal conductivities of the dispersion fuel meat, Al clad, and oxide film. The thermal conductivity of the U-Mo alloys is expressed as a function of the temperature as follows[6]: where T is the absolute temperature (K). The effect of radiation on the thermal conductivity of the Al matrix was not included in this study. Because the void swelling rate of aluminium is near zero at around 150°C due to a self-annealing or a recombination of the radiation defects [6], only the fission gas bubble in the U-Mo particle was considered as a major degradation mechanism of thermal conductivity.

The thermal conductivity of the dispersion fuel meat was calculated on the basis of a modified Hashin and Shtrikman [8] relation, which was developed by CEA:. Swelling due to fission products is modelled as a sum of swelling due to fission gas and swelling due to solid fission products as a function of the density of fission[8]:

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Equation 1 shows swelling due to gas fuel fission at low densities.

Equation 2 shows the fuel swelling due to fission gas at high fission density.

$$\left(\frac{\Delta V}{V_0}\right)_g = 1.8\times10^{-21}(f_d) \quad \text{for} \quad f_d \le 3\times10^{21}\ \text{f/cm}^3, \tag{1}$$

$$\left(\frac{\Delta V}{V_0}\right)_g = 5.4 + 2.2\times10^{-21}\left(f_d - 3\times10^{21}\right) + 0.51\times10^{-42}\left(f_d - 3\times10^{21}\right)^2, \quad f_d \le 3\times10^{21}\ \text{f/cm}^3, \tag{2}$$

Equation 3 shows the fuel swelling due to solid fission products.

$$\left(\frac{\Delta V}{V_0}\right)_s = 3.5\times10^{-21} f_d \tag{3}$$

The thickness of interfacial reactions layer growth is calculated using the equation 4 as follows[6, 9]

$$Y^2 = A\ F_r^{0.5}\ \exp\left(-\frac{Q}{RT}\right) t \tag{4}$$

Where:
Y = thick interaction layer (cm)
A = pre-exponential factor
Fr = fission rate (f/cm^3-s)
T = temperature (K)
T = time (s)
Q = 8000 (cal / mol), the activation energy.

Equation 4 shows the interaction layer growth as a function of the labelled variable.

In a thorough application, the rate of cleavage of the data obtained by neutronical calculation operation and burnup history and the concentration of nuclides by nuclear fission reactions and other nuclear transformation.

Fuel cladding surface temperature calculated from the heat balance. For steady-state thermal conditions (steady-state), coolant temperature along the channel is calculated from the heat balance between the air and fuel generation as a function of the axial position or transverse (width direction of the plate). Convective transfer coefficient h is calculated based on the phenomenon of the Thermal Hydraulics at each interface location-cooling plate.

$$T_s = T_{coolant} + q''\left(\frac{1}{h}\right) \tag{5}$$

With the notation T coolant is bulk coolant temperature, q" heat flux per unit area of the plates, and h is the convective thermal transfer coefficient between the plate and the air.

Temperature between phases Al cladding and corrosion product (boehmite / bayerite) is calculated with the equation.

$$T_{ik} = T_{coolant} + q''\left(\frac{c}{k_b} + \frac{1}{h}\right) \tag{6}$$

With the notation kb is the effective thermal conductivity of the boehmite/ bayerite layer. Temperature as a function of the thickness of the plate is calculated from the diffusion equation with the existing records in the fuel heat source nuclear reactions. Cladding temperature in the heat balance is calculated by diffusion. Statement to the temperature at the cladding interface - namely Tam core fuel is as follows [10]:

$$T_{am} = T_{coolant} + q''\left(\frac{b}{k_c} + \frac{c}{k_b} + \frac{1}{h}\right) \tag{7}$$

With the notation kc is the thermal conductivity of the fuel cladding.Cladding temperature in the heat balance is calculated by diffusion.

The temperature in the middle of the field plate can be calculated simply by the formula,

$$T_m = T_{coolant} + q''\left(\frac{a}{2k_f} + \frac{b}{k_c} + \frac{c}{k_b} + \frac{1}{h}\right) \tag{8}$$

With the notation kf is the effective thermal conductivity of the fuel meat.

RESULTS AND DISCUSSION

The input data for the analysis is presented in Table 1 to Table. The Table 4 shows an example of the calculation to the data with the mean temperature distribution of the cooling rate of fission fuel element entrance slit 51 °C. The temperature of the coolant out ratio obtained overall heat balance equation at steady state, i.e., the power generated in a plate equals to the heat leaving the fuel by coolant flow. Data distribution of power in the axial and transverse plate (thermal and neutronical calculation) has been used to compute the highest temperature on the surface of the plate by convection heat transfer. It is presented in Table 4.

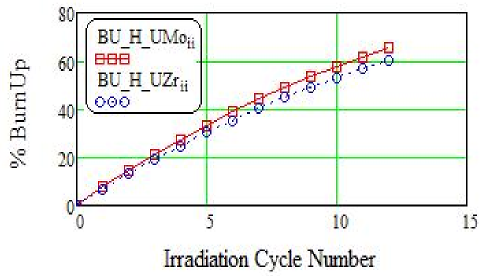
Table-1. The RSG-GAS Core Parameter[1].

Core Parameter	Value
Thermal Power, MW	17,1
Coolant Pressure , kg/cm^2	2,036
Inlet Coolant Temperature, °C	44,5
Minimum Coolant Rate, m^3/hr	3,6
Radial Peak Factor, FR	2,122
Fcool	1,167
Ffilm	1,200
Fhflx	1,200
Fclad, Fbond, Fmeat	17,1
Max Coolant Temperature, °C	48,67
Coolant Flow Minimum, kg/s	800
S	3,1
Power Flux, W/cm3	131,1

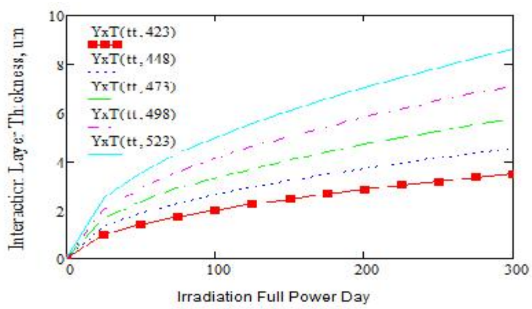
Table-2. Table Plate and Meat Dimension of Licensed U3Si2/Al Fuel Plate[1].

Fuel Plate	
Length, mm	625 ±0,2
Width, mm	70,75 ±0,15
Thickness, mm	1,3 ±0,07
Fuel Meat	
Length, mm	± 150
Width, mm	± 15
Thickness, mm	± 0,631

The Figure 3 (a) shows the burnup history of meat at mid plate for U-Mo/Al fuel and compared to U-Zr/Al fuel. The U-Mo fuel disperse slightly higher burnup history than U-Zr/Al fuel. The difference is related higher U density of U-Mo/Al fuel than that's U-Zr/Al fuel. . The Figure 3 (b) shows the growth of interaction layer thickness for differences location depth which are represented by it's local temperature. The highest curve is at the mid of plate which is temperature reach 525 K. The calculation results of temperature at different depth of plate may used as the initial iteration, to determine the interaction layer thickness, and thermal-mechanical properties depending on temperature. The fuel particle swelling increase significantly as burnup reaches the medium range. From this analysis one can deduce that the experiment needs to pay enough precaution for burnup above 50%.



(a)



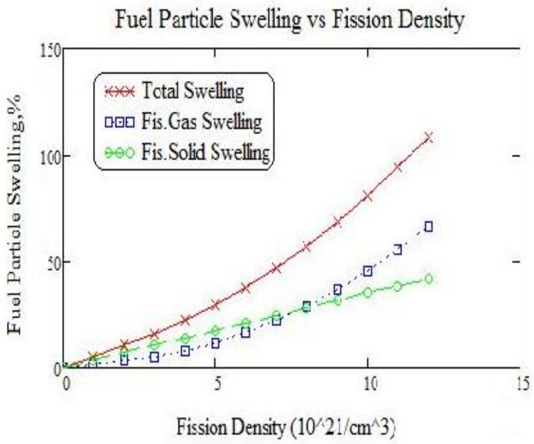
(b)

Figure 3. Fuel Burnup at End of 12 Cycles (a), Interaction layer growth of (U-Mo)Al_x) at different depth of fuel meat, represented by its temperature (b).

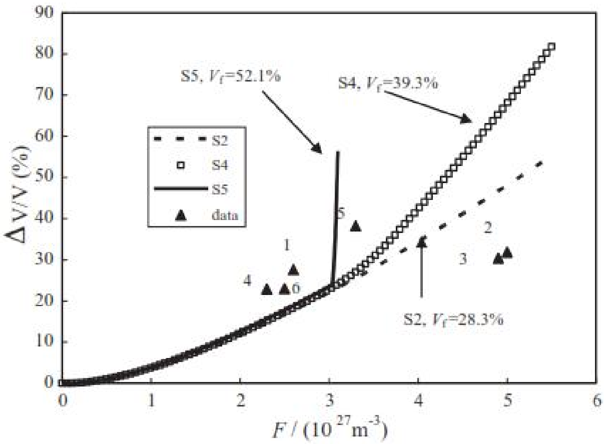
The result of swelling calculations are presented in Table-1. The model analysis covers parameters such as input and output between heat flux, peak temperature, temperature profile, swelling of the fuel particles, the thickness of the interaction layer, swelling of the plate thickness and the thickness of the corrosion layer.

At the application stage, the model is required to support the safety analysis report (SAR) of irradiation experiments, which is required to obtain a permit for irradiation test. It is very important because BATAN have not a loop or lead assembly irradiation test, therefore the plate will be directly related to the safety of the reactor coolant causing irradiation test needs more reliable. In the next stage of the analysis results can guide further testing of post-irradiation test results can be validated by comparison to the results of the analysis of post-irradiation.

Figure 4 (a) shows the fuel particles swelling versus fission density. The contribution of solid swelling is important at lower burnup and it is linear to burnup. The fission gas swelling is important at high burnup because the formation of gas bubbles retained in inner grains of fuel particles. Both solid and gasses swelling have been considered in uni-direction, parallel to the minimum dimension. Because the ratio of both thickness/width and the ratio of thickness/length the assumption of one direction perpendicular to plate extension is justified both for computational and for conservative safety. The fresh meat thickness of 0.65 cm and 2 faces clad thickness of 0.65 cm then the equivalent thickness ratio of cladding / matrix / fuel equal to 50 / 25 / 25. The thickness ratio at 80% fuel particle swelling of fresh plate with 10% pore will be 50: (25-5) : (25 x 1.75)= 50 : 20 : 43.75. Then the swelling or pillowing of the plate = (50+20+43.75) – 100 = 13.75%. At full burnup, the plate reach 18.9% is higher than allowable; it will reduce too much the coolant flow.



(a)



(b)

Figure 4. Prediction of Particle swelling from fission gas, fission solids, and total of them (a), Meat swelling measurement and calculation by fuel-particle induction swelling (FPIS) model [10](b).

By considering swelling direction distributed equally to all direction (3 principal direction), the thickness ratio at 80% fuel particle swelling of fresh plate with 10% pore will be: 50 : (25-5/3) : 25 x(1 +0.8/3) , and swelling of the plate equals 11.6%.

The thickening of fuel plate during irradiation is not resulting from irradiation swelling, but also originated from thermal swelling here is formation fuel-matrix interaction layer and thermal expansion of plate.

CONCLUSION

U-7Mo alloy fuel dispersion in the matrix Al of 7 g.U/cm^3 which is corresponding to the CNFT development by hydriding technique for plate type fuel of material testing reactor allows prolong the life time in service than the actual fuel of 2.96 g.U/cm^3. The prediction of fuel performance in reactor has been performed on hot spot area. The performance prediction should be prepared in order to obtain permit for irradiation testing of the new fuel. The prediction has been performed on hot spot location by taking into account some effects of fission swelling of fuel particles, formation of interfacial reaction layer, meat densification which feedback to fuel temperature and plate swelling the principal safety parameters of normal operation. The results show at lower burnup the dominant effect is fission solid swelling but at at higher burnup it is replaced by fission gas swelling. At 60% burnup (10.2 x 10^{21} fission/cm^3) fuel particle swelling reach 75.79% and at total burnup swelling 103.1 %, which corresponding to 11.6% and 17.2% plate pillowing. The interfacial reaction layer at full burnup is 5.7 um. The plate pillowing at 60% burnup is under and full burnup is beyond the limit acceptance.

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Appendix

Table a. Mathematical Expression Notation

A	7.5 × 10-18, pre-exponential factor	T	temperature (K)
b	constant	Tam	the temperature at the cladding interface
c	constant	Tc	Cladding temperature
fd	fd	Tcoo	bulk coolant temperature
Fr	fission rate (f/cm3-s)	Tik	Tik
h	convective thermal transfer coefficient	Ts	cladding surface temperature
kb	the effective thermal conductivity of the layer boehmite / bayerite	V	Volume
kc	the thermal conductivity of the fuel cladding	Vo	Initial Volume
kf	the effective thermal conductivity of the fuel	(dV/Vo)g	fuel swelling due to fission gas
Q	Debit	(dV/Vo)s	fuel swelling due to fission solids
Q"	heat flux per unit area of the plates	X	X
R	Gas Constant	Y	interaction layer thickness (cm)
t	time (s)	T	temperature (K)

Table b. Plate and Meat Dimension of Licensed U3Si2/Al Fuel Plate

Plate			
Long, mm	625 ±0,2	Long, mm	± 150
Width, mm	70,75 ±0,15	Width, mm	± 15
Thickness, mm	1,3 ±0,07	Thickness, mm	± 0,631
Cladding Thickness, mm	> 0,25		