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Fuel behavior comparison for a research reactor

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Abstract

The paper presents the behavior and properties analysis of the low enriched uranium fuel, which will be loaded in the Romanian TRIGA 14 MW steady state research reactor compared with the original high enriched uranium fuel. The high and low enriched uranium fuels have similar thermal properties, but different nuclear properties. The research reactor core was modeled with both fuel materials and the reactor behavior was studied during a reactivity insertion accident. The thermal hydraulic analysis results are compared with that obtained from the safety analysis report for high enriched uranium fuel core. The low enriched uranium fuel shows a good behavior during reactivity insertion accident and a revised safety analysis report will be made for the low enriched uranium fuel core.

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1. Introduction

The Romanian TRIGA Steady State Reactor (SSR) research facility, located in Pitesti, at the Institute for Nuclear Research (ICN), was originally loaded with *h*igh *e*nriched *u*ranium (HEU) fuel (93% ^{235}U) and has been operated since 1980. Due to the new international regulations, Romanian authorities, supported by International Atomic Energy Agency (IAEA) have decided to continue the research reactor operation with low enriched uranium (LEU) fuel, with under 20% ^{235}U enrichment. The Romanian TRIGA SSR research facility is involved in the Reduced Enrichment for Research and Test Reactors (RERTR) conversion program from HEU fuel to LEU fuel, supported by the United States government, at Argonne National Laboratory [1,2]. Now the TRIGA SSR research unit operates with a mixed core of HEU and LEU fuels. The data provided by LEU manufacturer [3] shows that there are no differences between HEU and LEU fuel from the thermal properties point of view. The neutron and kinetic analysis show some known differences.

It is necessary to revise the Safety Analysis Report (SAR), to update the data and analysis for LEU fuel core.

Analysis has shown different behavior of LEU fuel compared with HEU fuel from the point of view of prompt negative reactivity coefficient. For that reason, we made some analysis of the TRIGA LEU core behavior during reactivity insertion accidents.

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The TRIGA fuel is a metallic alloy of uranium, zirconium hydride, and erbium. The SSR TRIGA fuel composition is uranium 235, zirconium hydride, ZrH, with H/Zr atomic ratio of 1.6, for moderation purposes and erbium poison to control the reactivity during fuel burn-up.

2. Fuel properties and TRIGA research reactor model

TRIGA LEU manufacturer, General Atomics Company, San Diego, CA, USA, has presented physical properties of this fuel in Refs. [3,4] and HEU physical properties are given in SAR, Ref. [5] The mass proportion are presented in Table 1. The ZrH and U–ZrH systems are essential simple eutectoids with at least four separate hydride phases in addition to the zirconium and uranium allotropes. The effect of uranium addition on ZrH system is to shift all the phase boundaries of the ZrH diagram to slightly lower temperatures. For example, the eutectoid temperature is lowered from 820 to 814 K. All available evidence indicates that the addition of erbium to the U–ZrH will introduce no deleterious effects to the fuel. Erbium has a high boiling point and a relatively low vapor pressure, so that it can be melted into the uranium–zirconium uniformly. Erbium is a metal and forms a metallic solution with uranium–zirconium, and there is no reason to believe that there will be any segregation of the erbium. Erbium also forms a stable hydride (as stable as zirconium hydride), which also indicates that erbium will remain uniformly dispersed through the alloy.

2.1. HEU and LEU fuels physical properties

2.1.1. TRIGA fuel density

The density of zirconium hydride decreases with increase of the hydrogen content [5]. The density change is quite high, up to the delta transition (H/Zr = 1.5), beyond which point the change is slight with further increase in hydrogen. For TRIGA design calculation the hydrogen to zirconium atomic ratio is 1.6 and the formula given to calculate the HZr1.6 density is [3]

$$\rho_{\mathrm{ZrH}} = \frac{10^3}{(0.1706 + 0.042 \times 1.6)} = 5.64 \times 10^3\ \mathrm{kg\ m^{-3}}.$$

For the uranium density the value given by [3] is

$$\rho_{\mathrm{U}} = 19.07 \times 10^3\ \mathrm{kg\ m^{-3}}.$$

The fuel density [3] is given by

$$\rho_{\mathrm{UZrH}} = 1 \bigg/ \left(\frac{w_{\mathrm{U}}}{\rho_{\mathrm{U}}} + \frac{w_{\mathrm{ZrH}}}{\rho_{\mathrm{ZrH}}} \right)\ \mathrm{kg\ m^{-3}}. \qquad (1)$$

Using formula (1) the HEU resulting density is

$$\rho_{\mathrm{UZrH}} = \frac{10^3}{\left(\frac{0.1}{19.07} + \frac{0.872}{5.64}\right)} = 6.255 \times 10^3\ \mathrm{kg\ m^{-3}}.$$

The manufacturer document of HEU fuel bundles gives $6.1255 \times 10^3\ \mathrm{kg\ m^{-3}}$, which corresponds to the computations in good limits. The differences are due to the fact that Erbium was not taken in account for fuel density calculation. With the same formula (1) the LEU fuel density is:

$$\rho_{\mathrm{UZrH}} = \frac{10^3}{\left(\frac{0.45}{19.07} + \frac{0.535}{5.64}\right)} = 8.41 \times 10^3\ \mathrm{kg\ m^{-3}}.$$

The manufacturer document of LEU fuel bundles gives $8.1396 \times 10^3\ \mathrm{kg\ m^{-3}}$ which also corresponds to the computations in good limits. The difference is again as explained before.

2.1.2. The volumetric heat capacity

The volumetric heat capacity C_{p} ($\mathrm{J\ m^{-3}\ K^{-1}}$) is given by the formula

$$C_{\mathrm{p}} = \frac{(C_{\mathrm{pU}} \cdot w_{\mathrm{U}} + C_{\mathrm{pZrH}} \cdot w_{\mathrm{ZrKH}})}{\rho_{\mathrm{UZrH}}}\ \mathrm{J\ m^{-3}\ K^{-1}}. \qquad (2)$$

The uranium specific heat capacity is

$$C_{\mathrm{pU}} = (1.305 \times 10^{-4}\, T + 0.2296265) \times 10^3\ \mathrm{J\ kg^{-1}\ K^{-1}}.$$

The zirconium hydride heat capacity is

$$C_{\mathrm{pZrH}} = (0.06796T + 52.29674) \times 10^3\ \mathrm{J\ kg^{-1}\ K^{-1}}.$$

Volumetric heat capacity is plotted in Fig. 1 as a function of temperature. From Fig. 1, it can be seen that the values of volumetric heat capacity are practically the same for HEU and LEU fuel.

Table 1
TRIGA fuel composition

Fuel type	Composition	Fraction (wt%) in the fuel
HEU	^{235}U enrichment 93.0%	10.0
	$ZrH_{1.6}$	87.2
	Er	2.8
LEU	^{235}U enrichment 20.0%	45.0
	$ZrH_{1.6}$	53.0
	Er	2.3

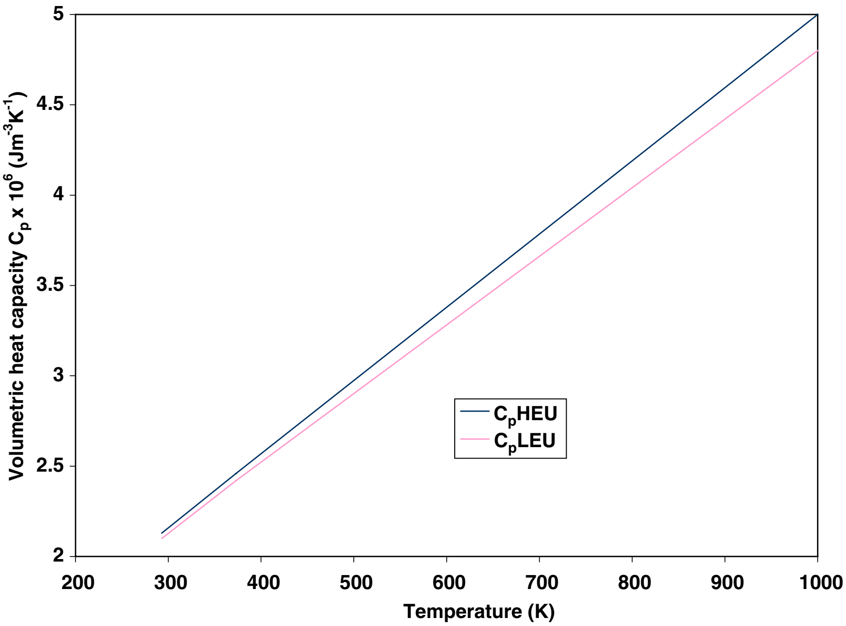

Fig. 1. TRIGA HEU and LEU fuel volumetric heat capacity versus temperature.

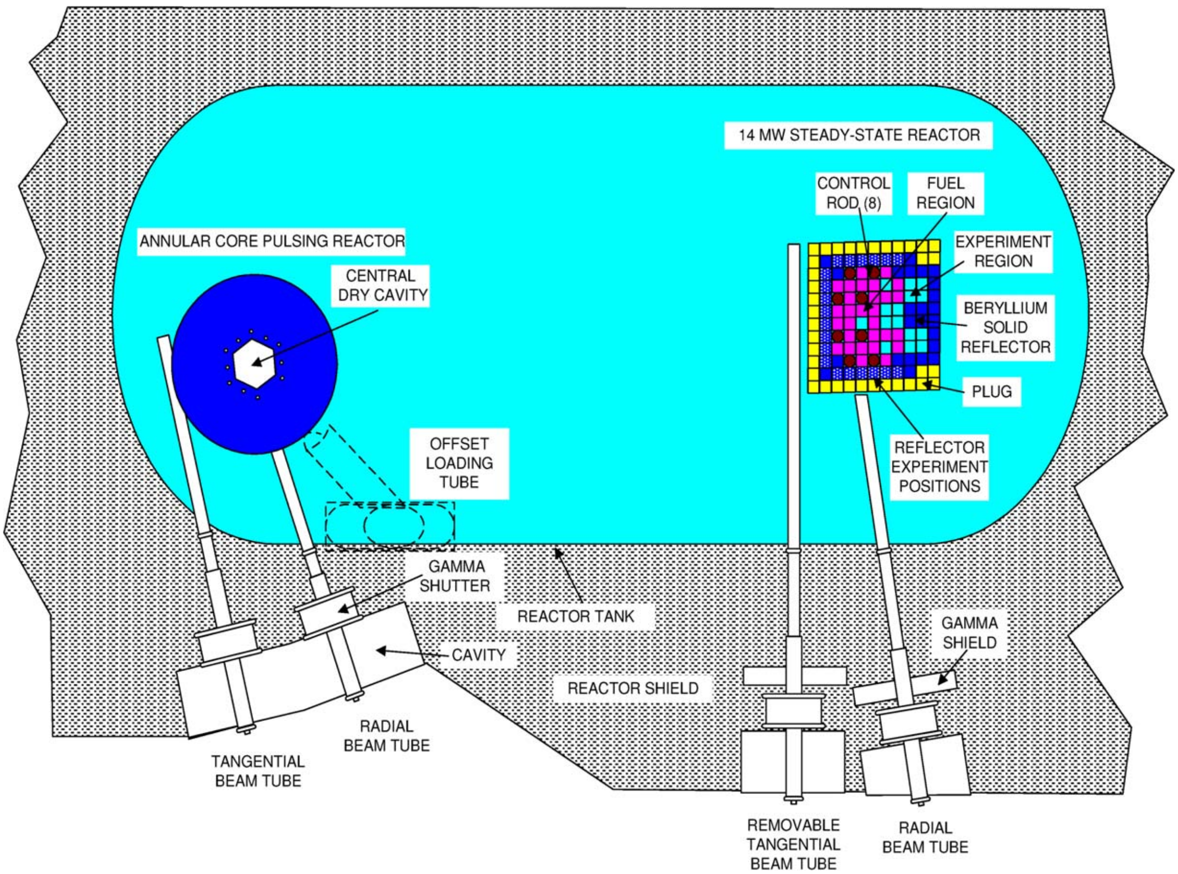

Fig. 2. TRIGA facility layout.

2.1.3. The fuel conductivity

Both HEU and LEU fuel thermal conductivities are similar as in [3]. The TRIGA fuel thermal conductivity value is

$\kappa = 18.0 \pm 0.9\ \mathrm{W\,m^{-1}\,K^{-1}}$.

2.2. Neutron core design parameters

Romania TRIGA research facility comprises two fully independent research reactor cores located in the same open pool. The Steady State Reactor is a material test research reactor with a nominal power of 14 MW. The SSR research reactor is cooled in forced convection by the main pumps and the heat is removed by three heat exchangers to the secondary circuit. In the same pool, an Annular Core Pulse Reactor (ACPR), cooled by natural convection is also placed. The TRIGA facility layout is presented in Fig. 2.

The TRIGA SSR was designed to meet the parameters that are discussed in Table 2, [5].

Table 2
Summary of core design parameters and characteristics

Parameter	Value	Units
Thermal neutron peak flux at core center	$\sim 2.9 \times 10^{14}$	$\mathrm{cm^{-2}\,s^{-1}}$
Reactor power	14.0	MW
Core size	29	fuel bundles
Core lifetime	~7000	MW d
Maximum operational temperature	1023	K
Active core length	0.560	m
Reactivity requirements		
Xenon (equilibrium)	2.7	%
Samarium (equilibrium)	0.8	%
Cold–hot swing[a]	1.5–2.5	%
Total	5.0–6.0	%
Operational swing (samarium not included)	4.2–5.2	%
β_{eff}	0.0070	
l (BOL)	31.0×10^{-6}	s
l (EOL)	39.0×10^{-6}	s
Maximum fuel temperature	1023	K
Recommended excess reactivity at BOL	6.7	%
Control system worth		
All rods	13.4	%
With maximum-worth rods stuck out	8.3	%

Conditions: beginning of live, BOL; end of life, EOL.
[a] Based on peak fuel temperature of 1023 K and an average core temperature of 588 K.

2.3. LEU versus HEU fuel prompt negative coefficient

Generally, the phenomena to be taken into account in the analysis of prompt negative temperature coefficient for the Romanian TRIGA SSR core in the Safety Analysis Report (SAR) [5] are:

- Cell-increased thermal disadvantage factor (ratio of neutron flux in the water to flux in the fuel) with increased fuel temperature leading to a degradation in neutron economy.
- Irregularities in the fuel lattice due to control rod positions. When control rods are in the core, the additional poison increases the capture probability for neutrons, which escape from the fuel-moderator material when it is heated. Thus, the temperature coefficient is more negative when control rods are in the core.
- Doppler broadening of ^{238}U and Er resonances leading to increased resonance capture with increased fuel temperature.
- Leakage – increased loss of thermal neutrons from the core when the fuel is heated.

A comparison of infinite lattices with TRIGA, HEU, and LEU performed with WIMS/D4/ANL code, takes into account only the modification of the cell-increased disadvantage factor and Doppler effect as a result of changing fuel material. Actually, different enrichments determine different control rods configuration and eventually lead to different prompt negative temperature coefficients. Leakage and control rod effect would create additional contributions to the absolute value of the prompt coefficient. Also, the space-independent model predicts lower absolute values than real case, according to [5].

As a result of the above considerations, it is expected that the comparison between HEU and LEU cell coefficient, based on an infinite lattice, is consistent. The temperatures calculated using this coefficient will be conservative in both cases.

A set of calculations were performed at different temperatures for both HEU and LEU cases. In Table 3, the κ_{inf} values corresponding to these temperatures and the calculated prompt negative temperature coefficients α ($\mathrm{K^{-1}}$), constant on each temperature interval are presented.

Fig. 3 presents a histogram representation of the prompt negative temperature coefficient values as a function of temperature (dotted) together with a

Table 3
Neutron multiplication factor κ_{inf} and prompt negative temperature coefficient $\alpha = \Delta k/\Delta T$ (K^{-1}), for HEU and LEU fuels

Fuel	T (K)	296		500		800		1000.0		1200
HEU	κ_{inf}	1.2953		1.2845		1.2564		1.2298		1.1992
	$\alpha \times 10^5$ (K^{-1})		−5.29		−9.36		−13.30		−15.30	
LEU	κ_{inf}	1.3591		1.3451		1.3219		1.3040		1.2848
	$\alpha \times 10^5$ (K^{-1})		−6.86		−7.73		−8.95		−9.60	

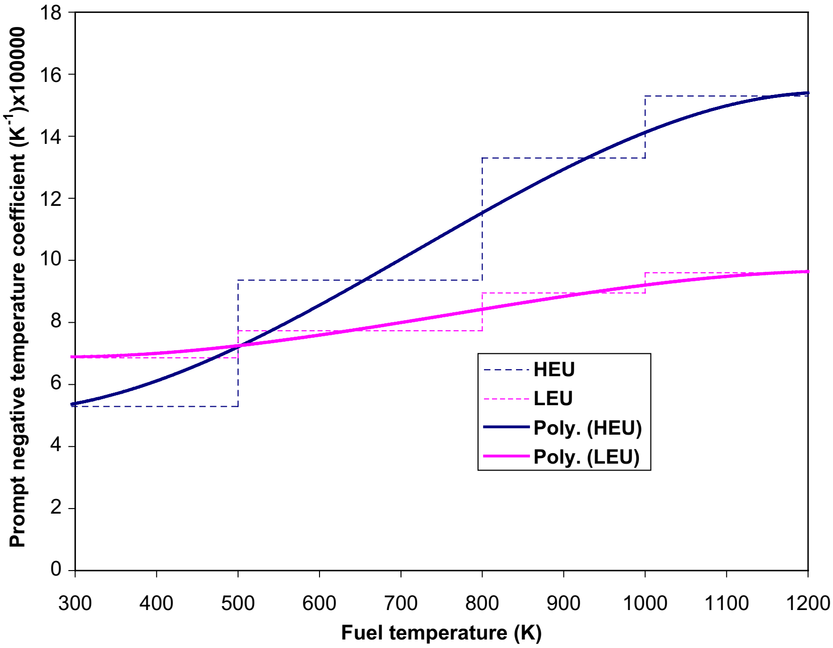

Fig. 3. Prompt negative temperature coefficients for HEU and LEU temperature dependence resulted from cell calculations with WIMS/D4/ANL.

third degree polynomial trend line (continuous). It shows that at lower temperature the LEU coefficient is higher than HEU coefficient, but the LEU curve becomes much lower for higher temperature.

2.4. TRIGA SSR thermal hydraulic and one point kinetic RELAP5 model

The HEU and LEU fuel have similar thermal properties but different nuclear properties. These differences can be proved only in transient situations.

In this view a point kinetic model of the TRIGA core was developed using RELAP5 code [6]. The main features of the model are based on the thermal hydraulic characteristics of the TRIGA SSR 14.0 MW reactor. These are presented in a previous paper, Ref. [7]. TRIGA SSR core was modeled using the data from SAR and the BLOOST7 computer code input data provided by SAR [5]. The RELAP5 TRIGA reactor thermal hydraulic model is presented in Fig. 4.

At a low power level of 1.0 W the heat transfer from the reactor core is driven by natural convection. The coolant flow rises up through the core bundles and the natural convection loop closes through the core openings – the experimental channels, as it is shown in Fig. 4.

Under normal operation conditions, i.e., for 14.0 MW power level, the reactor core is cooled by forced convection. The coolant flows from pool volume down through the core to the outlet pipe. During the reactivity insertion accident the flow rate is constant. To this model it was attached a new model of point kinetic. In the analysis two different models were used: one for a HEU core and one for a LEU core, with different prompt negative

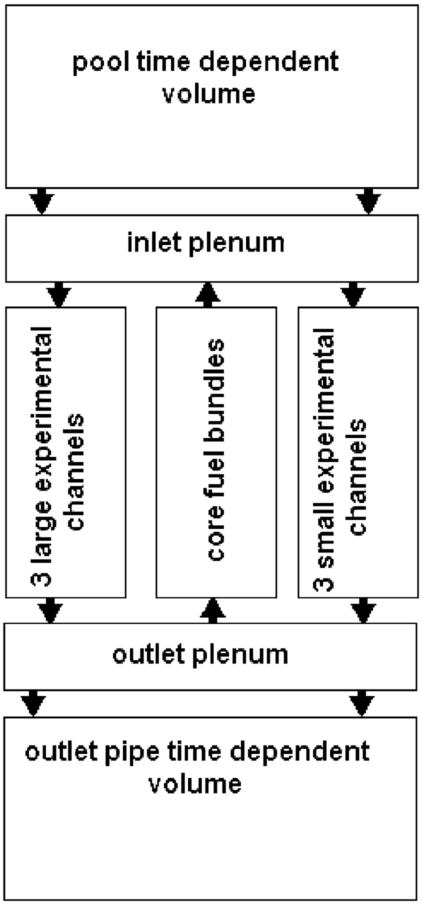

Fig. 4. RELAP model for TRIGA SSR research reactor.

temperature coefficients. The HEU original core has 29 fuel bundles and the LEU core has 35 bundles.

The analysis has been made for the 'Shim Bundle Removal' accident. This accident was analyzed by the SAR [5] which says that it is an initiated reactivity insertion accident, where an equivalent of 1.0% reactivity insertion in 0.3 s, at 1 W power level is extracted from the reactor core. The reactivity insertion accident analysis was extended, also at 14 MW normal operation level.

3. Results and discussion

3.1. Reactivity insertion accident analysis for steady state 1.0 W power level

In the SAR [5] the accident analysis is done for the TRIGA SSR research reactor at 1 W level prior to the reactivity insertion.

For the analysis two different models were developed: one for HEU fuel with data provided by SAR [5], with 29 fuel bundles and one for LEU fuel core with data provided by SAR [5], which has 35 fuel bundles.

3.1.1. HEU fuel (SAR)

RELAP5 analysis of the 1.0% reactivity insertion accident in 0.3 s leads to 545 MW SSR peak power pulse. The pulse peak power value from the SAR [5] is 550 MW. So, the RELAP5 analysis gives practically the same peak power value as that from SAR.

The fuel central temperature evolution during the reactivity insertion accident was also studied. The SAR gives a value of 1083 K for the central fuel peak temperature of the hottest pin with $P/Pmed = 2.5$ (P – local neutron power, $Pmed$ – core medium neutron power). In the RELAP5 analysis the same peak temperature value is 1075 K. This shows good agreement between the RELAP5 results and the values from SAR.

The RELAP5 peak power, fuel maximum temperature and SAR peak fuel temperature values evolutions during the 1.0% reactivity insertion accident in 0.3 s are compared in Fig. 5.

3.1.2. LEU fuel

The same of 1.0% reactivity insertion in 0.3 s accident analysis, with RELAP5 model, leads to a peak power value of 247 MW. This value is lower compared with HEU fuel core, due to the different prompt negative temperature coefficients. In the lower range of fuel temperatures, LEU has higher temperature coefficients which lead to lower peak power. Consequently, the central fuel peak temperature value is 636 K, which is lower than HEU central fuel peak temperature. This proves that LEU fuel core has a better behavior for this type of accident.

In Fig. 6 the peak power values during the 1.0% reactivity insertion accident in 0.3 s for HEU, LEU analysis with RELAP5 code and SAR results are presented comparatively. The RELAP5 peak power value for HEU fuel of 545 MW and SAR value of 550 MW are practically the same, and the RELAP5 peak power value of 247 MW for LEU fuel is lower.

3.2. Reactivity insertion accident analysis for 14.0 MW steady state normal operation power level

We extended our analysis for the 14 MW normal operation level. In this situation, we made analysis both for HEU and LEU type fuel cores.

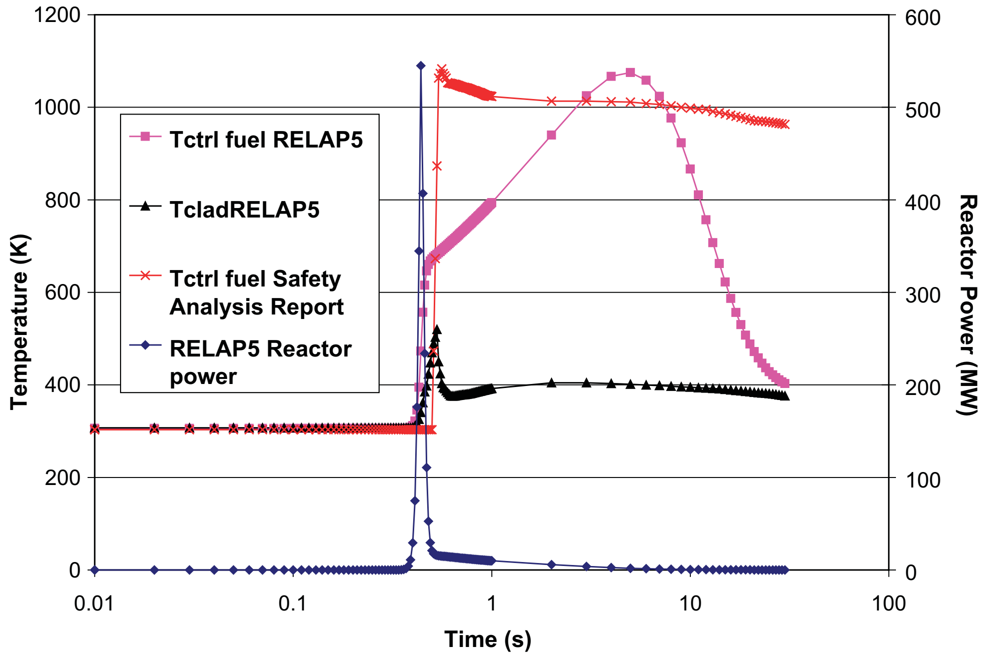

Fig. 5. Fuel temperature and reactor power for 1% reactivity insertion accident for TRIGA SSR reactor with HEU fuel.

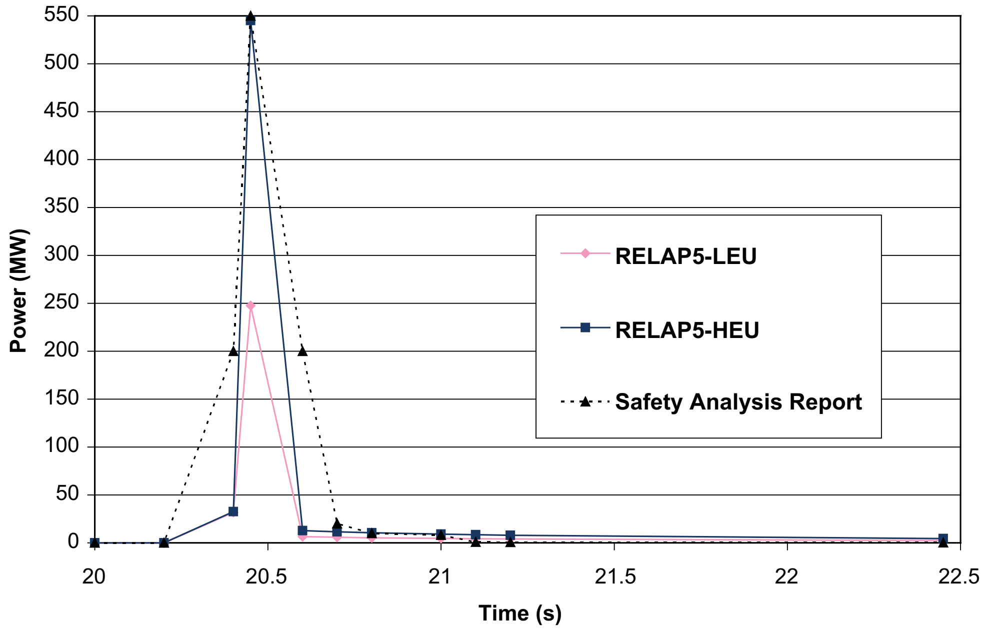

Fig. 6. Comparisons between peak power for 1% reactivity insertion accident for TRIGA SSR reactor with HEU and LEU fuel.

3.2.1. HEU fuel

In this analysis, the RELAP5 peak power value is 70 MW due to the cutoff by prompt negative temperature coefficients and reactor scram. The hottest central fuel temperature reaches 1143 K peak temperature, compared with 1023 K value at normal operation power level of 14 MW. The clad maximum temperature is only 363 K during the transient compared with 360 K clad temperature at normal operation power level of 14 MW. So this accident seems not to affect the fuel integrity.

3.2.2. LEU fuel

The LEU core reactivity insertion accident peak power value of 90 MW, from RELAP5 analysis, is higher compared with the 70 MW HEU fuel core peak power value. This is because the LEU core prompt negative temperature coefficient is lower at high temperature, compared with a higher HEU prompt negative temperature coefficient at high temperature. The hottest central fuel temperature reaches 1178 K peak temperature value for a core of 35 LEU fuel bundles compared with 1143 K peak temperature value for 29 HEU fuel bundles core during reactivity insertion accident. The LEU clad maximum temperature value is only 363 K compared with 360 K clad temperature at normal operation power level of 14 MW. This proves, also, that for LEU core, this reactivity insertion accident seems not to affect the fuel integrity.

4. Conclusions

As it is documented in this paper, the thermal properties of new TRIGA LEU fuel are not significantly different compared with HEU fuel thermal properties, originally used in the TRIGA SSR research reactor. The most significant differences are from the point of view of fuel prompt negative temperature coefficients.

The RELAP5 thermal hydraulic analysis for HEU 29 fuel bundles, originally loaded core, verified the SAR results. The peak power and maximum fuel temperature in the reactivity insertion accident in both cases have very close values.

The LEU fuel behaves better in a reactivity insertion accident at 1.0 W power level, the peak power and maximum fuel temperature values being lower than that in HEU fuel core case.

For the normal operation 14 MW power level reactivity insertion accident, the LEU peak power and maximum fuel temperature values seems to be higher than for the HEU fuel core. This is due to LEU lower temperature coefficients. Anyway, the peak fuel and the clad temperatures values reached during the reactivity insertion accident, obtained by RELAP5 analysis, seems not to affect fuel integrity.

The RELAP5 point kinetic model of the TRIGA 14 MW SSR core proved very useful for these investigations.

This analysis is to be included in the further Safety Analysis Report for the new TRIGA SSR LEU fuel core.

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