REACTIVITY-INDUCED TRANSIENT MODELING FOR TAJOURA NUCLEAR RESEARCH REACTOR WITH HEU AND LEU FUELS

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ABSTRACT

Design information is presented for high enriched uranium (HEU, using IRT-2M fuel) and low enriched uranium (LEU, using IRT-4M fuel) cores in Tajoura (IRT-1) reactor in Libya. Calculated results are presented for several reactivity-induced accident situations. In no case does fuel approach conditions which might lead to damage.

1. Introduction

The Tajoura (IRT-1) reactor [1] is a pool type reactor, moderated and cooled by light water located at the Renewable Energies and Water Desalinization Research Center (REWDRC). The reactor is designated to carry out experiments in field of nuclear physics and nuclear engineering, neutron activation analysis, solid state physics and isotope production. The reactor was put into operation at a power level of 10 MW in September 1983.

The base of the Tajoura core is a square grid plate with 36 identically formed places with a lattice pitch of 71.5 mm. The fuel assemblies (FA), the removable beryllium units, and guide tubes of the control rods (8 shim control rods, 2 safety rods and one automatic regulating rod) can be put into theses places. The compact core loading of Tajoura consists of 16 FAs. The FAs are surrounded by 20 removable beryllium units. Stationary beryllium reflector surrounds the removable core units. The horizontal cross section of the core is shown in Figure 1. The active fuel length is approximately 0.6 m. The fuel is cooled by the pumped flow of water from top to bottom of the core.

The reactor is being converted from High Enriched Uranium (HEU, 80% of ^{235}U) to Low Enriched Uranium (LEU, 19.7% of ^{235}U) [2,3] fuel type. Companion papers [4,5] present the analysis of the Tajoura core for power level (maximum) of 10 MW showing steady-state conditions and response to flow-induced accidents. The present paper shows results from PARET [6] for reactivity-induced transients.

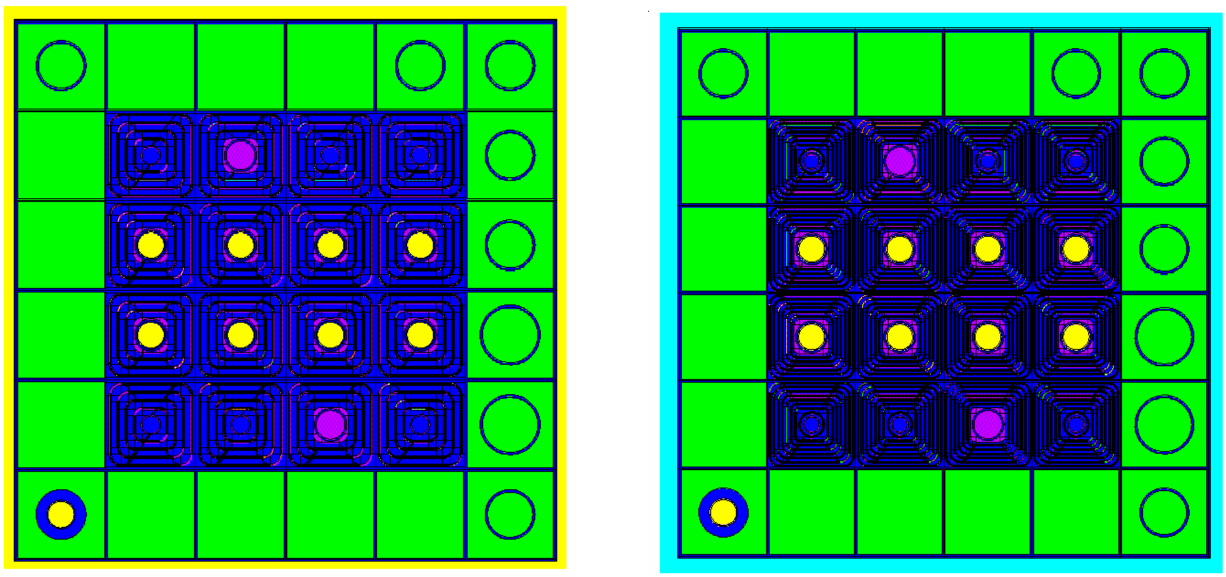

Figure 1 HEU (left) and LEU (right) Compact Core Loading for Tajoura Reactor

1.1. HEU Fuel Description

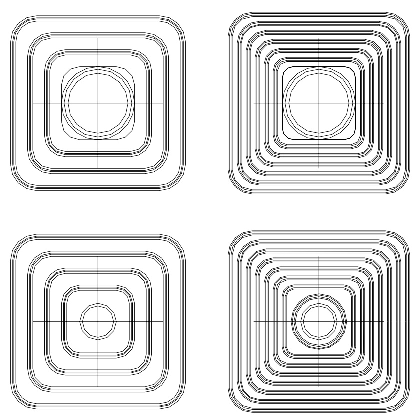

Figure 2 IRT-2M (left) and IRT-4M (right) Fuel Assembly Cross Section

The old HEU fuel of the reactor is of the IRT-2M type: the fuel is an alloy (matrix) of aluminum and uranium-aluminum eutectic (UAl_x–Al) with aluminum cladding. The compact core loading consists of 10 fuel assembles having 3 fuel tubes (3TFA) and 6 fuel assemblies having 4 fuel tubes (4TFA) as shown in left side of Figures 1 and 2. The fuel tubes have four flat sides joined by rounded corners. The coaxial fuel tubes are 2.0 mm thick, which consists of 0.4 mm of fuel between two 0.8 mm thicknesses of cladding. The thickness of the water gap between adjacent fuel tubes is 4.5 mm; the half-thickness of the water space outside of the outermost fuel tube (between fuel assemblies) is 2.25 mm. The radius of the outer surface of the corners of the outermost fuel tube is 10.0 mm; the radius for the outer surface of the corners of an interior fuel tube is 1.0 mm smaller than the next most outer fuel tube. Interior to the innermost fuel tube in the 4-tube assembly is a circular tube having 8.0 mm outer radius; material interior to this tube does not change temperature or contribute to reactivity feedback during the transient calculations. Interior to the innermost fuel tube in the 3-tube assembly is a tube having same outer dimensions as innermost tube of the 4-tube assembly as guide for control rod.

1.2. LEU Fuel Description

The reactor is being converted to LEU fuel of type IRT-4M [2]; the new fuel is an alloy (matrix) of aluminum and uranium-dioxide (UO_2–Al) with aluminum cladding. The compact core loading consists of 10 fuel assemblies having 6 fuel tubes (6TFA) and 6 fuel assemblies having 8 fuel tubes (8TFA) as shown in right side of Figures 1 and 2. The fuel tubes have four flat sides joined by rounded corners. The coaxial fuel tubes are 1.6 mm thick, which consists of 0.7 mm of fuel between two 0.45 mm thicknesses of cladding. The innermost tube in the 8-tube assembly is round rather than square and has an inner diameter of 18.1 mm. The thickness of the water gap between adjacent fuel tubes is 1.85 mm; the half-thickness of the water space outside of the outermost fuel tube (between fuel assemblies) is 0.95 mm. The radius of the outer surface of the corners of the outermost fuel tube is 9.3 mm; the radius for the outer surface of the corners of an interior fuel tube is 0.8 mm smaller than the next most outer fuel tube. Interior to the innermost fuel tube in the 8-tube assembly is a circular tube having 14.0 mm outer diameter.

The design specifications of Tajoura reactor with HEU and LEU fuels type are given in Table 1 [4].

Table 1.

Description of TAJOURA Reactor Core Design Parameters with HEU and LEU Fuel Loading.

Parameters	Values HEU/LEU	Parameters	Values HEU/LEU
Reactor Type	Pool	Coolant inlet Temperature. ^oC	45
Power level (max), MW_{th}	10	Coolant inlet Pressure, *kPa*	169.319
Fuel Positions	16	Total Hydraulic Area/core, m^2	0.05571/0.04541
Irradiation Position (Vertical)	51	Coolant Mass Flux, $kg/m^2 .s$	4950.8/3227.9
Horizontal Beam: Total	11	Coolant Density, kg/m^3	990.15
Radial	8	Total Fuel Volume/core, m^3	0.002294/0.008316
Tangential	3	Volumetric Heat Capacity of Meat, $J/K.\ m^3$	$(2.55/4)\times10^6$
Fuel: Type	IRT-2M/IRT-4M	Meat Thermal Conductivity, *W/m. K*	140.0/137.95
Meat Material (0.4/0.7 mm)	UAl_x-Al/UO_2-Al	Volumetric Heat Capacity of Clad, $J/K.\ m^3$	2.432×10^6
Clad Material (0.8/0.45 mm)	Al (SAV-1)	Clad Thermal Conductivity, *W/m. K*	186.6
Active Length, *mm*	580/600	Prompt Neutron Life Time, *μs*	93 / 80
Lattice Pitch, *mm*	71.5	Delayed Neutron Fraction, β_{eff}	0.00764/0.00769*
Moderator, Coolant	H_2O	Insertion Control Rods rate at Scram, *m/s*	0.6
Reflector	Beryllium	Delay after Trip, *s*	0.1
Control Rod Absorber	(8) B_4C	Over Power Trip, %	115
Safety Rod	(2) B_4C	Total worth of Control Rods, β_{eff}	33 / 29
Automatic Rod	(1) B_4C	Reactivity increasing rate of CR, β_{eff}/s	0.03

* P. Egorenkov, Oral Communication (Tajoura), Feb. 2006

2. Calculation Methodology

Computer code PARET [6] was employed to carry out transient safety analysis calculations. PARET is a coupled neutronics, hydrodynamics, and heat transfer code employing point kinetics, one dimensional hydro-dynamics, and one-dimensional heat transfer.

A two-channel model was utilized in PARET. One channel represents the hottest fuel plate and its associated coolant flow; the other channel represents an average fuel plate and its associated coolant flow. Axial power distribution has been represented by 15 equi-distance mesh points. For the HEU core, the neutronics calculations were performed using MCNP [7], resulting in an axial peaking factor of 1.345 and a "radial" (actually plate-segment to plate-segment laterally) peaking factor of 1.434. For the LEU core, the neutronics calculations were performed using the MTR_PC V3.0 computer package [8], resulting in an axial peaking factor of 1.347 and a "radial" peaking factor of 1.392.

All calculations were performed starting at a power of 10 MW, a coolant inlet temperature of 45°C, and inlet pressure of 169.319 kPa which corresponds to the static pressure of water column from the top of the core to a point of 7.0 m higher at the free surface. The steady-state coolant flow rate in the primary system has been determined [5, 9] to be 1850 m^3/hr total (1044 m^3/hr of this is through the fuel) in HEU core and 1350 m^3/hr total (533 m^3/hr of this is through the fuel) in LEU core.

3. Safety Analysis Scenarios

Four reactivity-induced transients [10] have been considered:

1. Positive reactivity insertion due to the withdrawal of one control rod (KC),
2. Positive reactivity insertion due to the withdrawal of Automatic Regulating Rod (AR),
3. Positive reactivity insertion due to the disengagement of the aluminum follower from the control rod, and
4. Positive reactivity insertion due to cooled water injection.

The settings of the emergency protection system of Tajoura reactor are as follows:

1. All transient calculations were started with the reactor at critical state, i.e., KC3, KC4, KC5, KC6, and AR rods are fully inserted; AZ1 and AZ2 rods are fully withdrawn; and KC1, KC2, KC7, and KC8 rods are at critical position, which has bottom of rods 39 mm above core mid-plane for HEU and 59 mm below core mid-plane for LEU.
2. The overpower trip level is 115% of rated power level. The trip on low period (e.g., less than 20 s) is ignored in the calculations as a conservatism.
3. The delay time is 0.5 s between crossing any trip set point and start of control rod motion into the core.
4. Scram consists of the drop of the two AZ rods from fully withdrawn position and drop of four KC rods from critical position.
5. The control rods fully insert with constant velocity of 0.6 m/s.
6. Pumps continue to run after scram for reactivity-induced transients.

Results calculated for the four transients are presented below for the HEU and LEU cores.

3.1. Control Rod Withdrawal

The transient is defined as the withdrawal of highest worth KC control rod at a constant speed of 3.4 mm/s. This gives a reactivity insertion of 1.25 $ in 87 s for the HEU core and 1.94 $ in 116 s for the LEU core. The critical position of rods differ for the two cores.

The results of this case for the HEU core are shown in Figure 3. (Reactivity insertion begins at 1 s in all of the HEU and LEU cases to be shown.) The reactor core power level increases from 10 MW to 11.5 MW during 4.2 s and the control rods start into the reactor core 0.1 s later at which time the power level has reached 11.55 MW and the net reactivity insertion into the system is 0.089 $. During this time the peak coolant and cladding surface temperatures have reached 63 °C and 118 °C, respectively. The minimum reactor period is 24 s.

The results of this case for the LEU core are shown in Figure 4. The reactor core power level increases from 10 MW to 11.5 MW during 4.5 s and the control rods start into the reactor core 0.1 s later at which time the power level has reached 11.54 MW and the reactivity insertion into the system is 0.085 $. During this time the peak coolant and cladding surface temperatures have reached 90 °C and 120 °C, respectively. The minimum reactor period is 28 s.

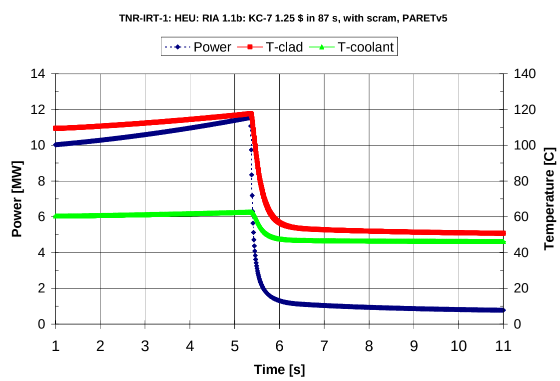

Figure 3 Power, peak clad and coolant temperatures in hot channel in HEU core during KC7 withdrawal at 3.4 mm/s

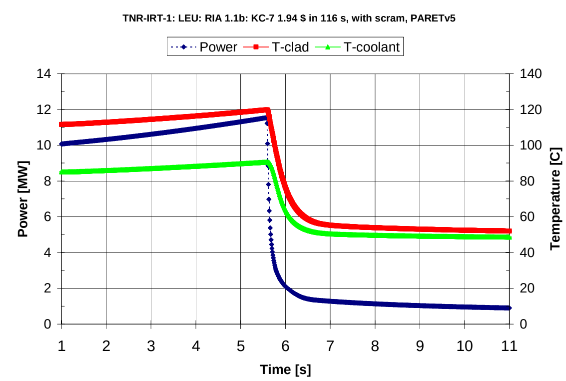

Figure 4 Power, peak clad and coolant temperatures in hot channel in LEU core during KC7 withdrawal at 3.4 mm/s

3.2. Regulating Rod Withdrawal

The transient is defined as the withdrawal of AR automatic regulating rod at a constant speed of 25 mm/s. This gives a reactivity insertion of 0.47 $ in 26 s for the HEU core and 0.54 $ in 26 s for the LEU core.

The results of this case for the HEU core are shown in Figure 5. The reactor core power level increases from 10 MW to 11.5 MW during 7.8 s and the control rods start into the reactor core 0.1 s later at which time the power level has reached 11.55 MW and the net reactivity insertion into the system is 0.085 $. During this time the peak coolant and cladding surface temperatures have reached 63 °C and 118 °C, respectively. The minimum reactor period is 24 s.

The results of this case for the LEU core are shown in Figure 6. The reactor core power level increases from 10 MW to 11.5 MW during 7.9 s and the control rods start into the reactor core 0.1 s later at which time the power level has reached 11.54 MW and the reactivity insertion into the system is 0.082 $. During this time the peak coolant and cladding surface temperatures have reached 91°C and 120°C, respectively. The minimum reactor period is 27 s.

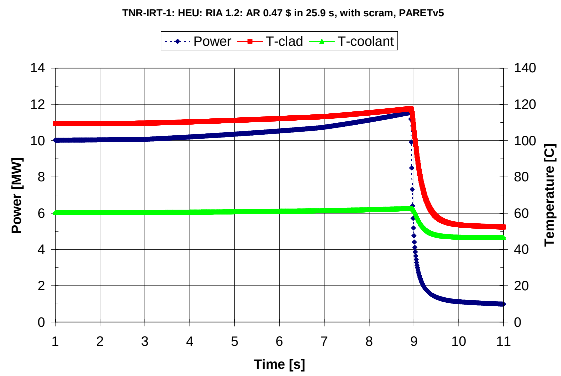

Figure 5 Power, peak clad and coolant temperatures in hot channel in HEU core during AR withdrawal at 25 mm/s

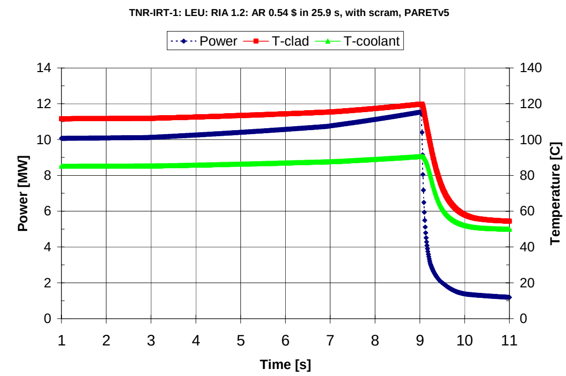

Figure 6 Power, peak clad and coolant temperatures in hot channel in LEU core during AR withdrawal at 25 mm/s

3.3. Control Rod Follower Disengagement

The transient is defined as the detachment and downward motion of the aluminum control rod follower from the bottom end of partially withdrawn control rod KC7. The rod follower falls at the same speed as a control rod moves during scram. This gives a reactivity insertion of 0.12 $ in 0.50 s for the HEU core and 0.15 $ in 0.34 s for the LEU core. The difference in insertion time is due to the difference in rod height at criticality in the two cores.

The results of this case for the HEU core are shown in Figure 7. The reactor core power level increases from 10 MW to 11.5 MW during 1.4 s and the control rods start into the reactor core 0.1 s later at which time the power level has reached 11.52 MW and the net reactivity insertion into the system is 0.100 $. During this time the peak coolant and cladding surface temperatures have reached 63°C and 118°C, respectively. The minimum reactor period is 4 s.

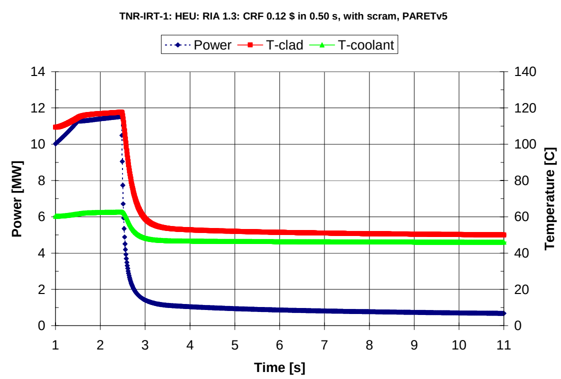

Figure 7 Power, peak clad and coolant temperatures in hot channel in HEU core during KC7 follower drop at 0.6 m/s

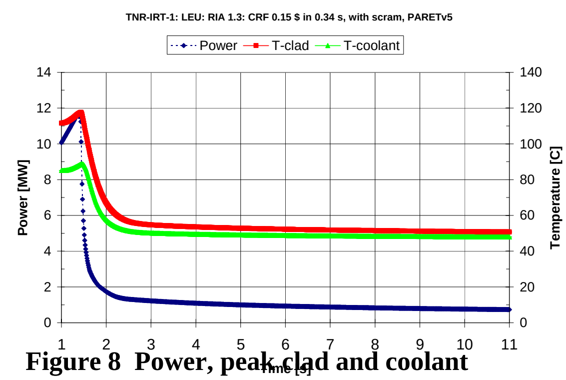

Figure 8 Power, peak clad and coolant temperatures in hot channel in LEU core during KC7 follower drop at 0.61 m/s

The results of this case for the LEU core are shown in Figure 8. The reactor core power level increases from 10 MW to 11.5 MW during 0.3 s and the control rods start into the reactor core 0.1 s later; between these two times the peak power level of 11.57 MW and the peak net reactivity insertion into the system of 0.133 $ have occurred. During this time the peak coolant and cladding surface temperatures have reached 89°C and 118°C, respectively. The minimum reactor period is 2 s.

3.4. Accidental Cooled Water Injection

While the reactor is in operation the flow rates and the operating coolant loops are selected before raising the control rods. The addition of cold water to the reactor while the reactor is in operation is unlikely since the operating conditions are set. However, the reactor coolant inlet temperature can change due to the change in the ambient conditions through the cooling towers in the third circuit of the reactor coolant system, and then it has effect on the secondary circuit; this changing of the large amount of the coolant (400 m^3) in the secondary circuit has an effect on the reactivity of the reactor and the reactivity change can be compensated by the power automatic regulator rod. The Tajoura reactor core has four cooling pumps; during normal operation of the reactor three pumps are in operating mode and one is in standby mode; each pump has maximum coolant flow rate of ~ 650 m^3/hr.

Taking one loop out of operation while the reactor is in operating mode will probably cause a reactor scram based on the pressure drop signal limit; this scram has been ignored in the calculations to be shown below. Putting the reserve pump into operation at full flow rate is done gradually because of the limiting conditions imposed by the electrical motors that drive the head and the bypass valves [9]. The inlet coolant temperature will change from 45°C to 42.28°C after mixing in the cold water from the loop which had been in standby mode. PARET does not allow input of variable inlet temperature; therefore, the effect of the coolant temperature change is simulated as an equivalent reactivity change. The positive reactivity insertion into the reactor core due to this change in the coolant inlet temperature will be 0.060 $ in the HEU core and 0.036 $ in the LEU core; the insertion is assumed to occur over 0.1 s for the both the HEU and LEU cores.

The results of this case for the HEU core are shown in Figure 9. The reactor core power level increases from 10 MW to 11.5 MW during 11.6 s and the control rods start into the reactor core 0.1 s later at which time the power level has reached 11.51 MW and the net reactivity insertion into the system is 0.041 $. During this time the peak coolant and cladding surface temperatures have reached 63°C and 118°C, respectively. The minimum reactor period is 2 s during the initial power rise immediately after the beginning of the transient, and the period is in the range 75 to 200 s during the longer power rise.

The results of this case for the LEU core are shown in Figure 10. The reactor core power level increases from 10 MW to 10.4 MW during 0.1 s and the peak net reactivity is 0.04 $; thereafter, there is a gradual rise to a power of 11.3 MW during 3 minutes, after which the net reactivity is approximately 0 and the power is constant. During this time the peak coolant and cladding surface temperatures have reached 90°C and 119°C, respectively. The minimum reactor period is 3 s during the initial power rise immediately after the beginning of the transient and the period is greater than 200 s during the longer power rise.

The reactivity addition is sufficiently low that the high power trip setting is not passed. Three actions are likely in the reactor that are not included in the PARET model: (1) The control system, if enabled, would be attempting to maintain power at a preset level (e.g., 10.0 MW or lower) rather than the increasing power in the calculation. (2) An increase in power would ultimately lead to an increase in core exit coolant temperature, which could cause a reactor scram. (3) In sufficient time, the increase in core exit coolant temperature would lead to an increase in core inlet coolant temperature which would be a negative reactivity insertion. There are, therefore, several real features of the IRT-1 reactor that would counteract the calculated power increase.

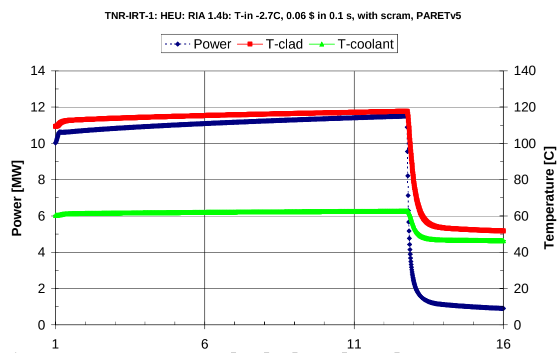

Figure 9 Power, peak clad and coolant temperatures in hot channel in HEU core during 2.7°C inlet temperature decrease

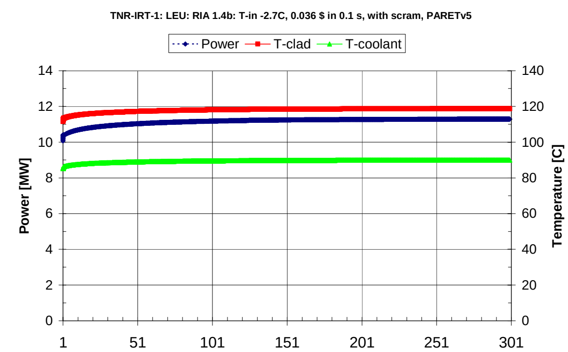

Figure 10 Power, peak clad and coolant temperatures in hot channel in LEU core during 2.7°C inlet temperature decrease

4. Conclusions

Design information has been presented for HEU and LEU cores in Tajoura reactor. Calculated results have been presented for several reactivity-induced accident situations. The power rise in all transients except one is terminated in a few seconds by reactor scram on high power; in the one exception the reactor is calculated to stabilize at 13% higher power than the initial value. In no case does fuel approach conditions which might lead to damage.

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