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HISTORY, OPERATING, SAFETY AND UTILIZATION OF TAJOURA NUCLEAR RESEARCH REACTOR WITH LOW AND HIGH ENRICHED URANIUM FUELS

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ABSTRACT

This paper describes the operational history and safety and utilization of the Tajoura Nuclear Research Reactor located at the Tajoura Nuclear Research Center near Tajoura (Tripoli) Libya, its uses, and its nuclear safety during its early critical periods, as the reactor was operated at a capacity level of 10 megawatts in September 1981 (the first critical nuclear fission reaction in Lybia). From this date until the end of 2005, the reactor went through five operational life cycles, using highly enriched fuel of the type (IRT-2M), with 80% uranium-235, and an average fuel combustion value estimated at 908 megawatts. daily during these periods. Until the end of 2004, and from the beginning of 2005 to the end of 2006. During this period of time, the work was based on unloading the reactor from the highly enriched fuel and loading it with the new low-enriched fuel, and conducting some practical experiments to measure some of the reactor parameters at zero power using the new fuel. .At the end of 2006, the reactor was commissioned with an initial operating cycle using low-enriched uranium fuel with a content of 19.7% uranium-235 (IRT-4M). This paper included some of the operational characteristics of the Tajoura reactor when it was operated on low-enriched fuel at a power level of 5 MW.

The result of the change from using highly enriched uranium fuel to low enriched uranium fuel was the loss of 2 megawatts of the original capacity of the Tajoura reactor, which was previously 10 megawatts and is now only 8 megawatts.

Due to security reasons to limit the non-peaceful nuclear proliferation imposed by major powers in the United Nations Security Council on the rest of the world's populations in order to maintain their control over these programs by exerting strong pressure on small and oppressed countries (developing countries, especially Arab countries) through their international atomic energy agency.

المستخلص

تصف هذه الورقة التاريخ التشغيلي والسلامة والإستخدام لمفاعل تاجوراء للبحوث النووية الواقع في مركز تاجوراء للبحوث النووية بالقرب من تاجوراء (طرابلس) ليبيا، واستخداماته ، وأمانه النووي خلال فتراته الحرجة المبكرة، حيث تم تشغيل المفاعل في مستوى قدرة 10 ميغاوات في سبتمبر 1981 (أول تفاعل انشطاري نووي حرج في ليبيا). من هذا التاريخ وحتى نهاية عام 2005، مر المفاعل بخمس دورات حياة تشغيلية، باستخدام وقود عالي التخصيب من النوع (IRT-2M)، بنسبة 80% من اليورانيوم-235، وبمتوسط قيمة احتراق للوقود تقدر بنحو 908 ميجاوات. يوميًا خلال هذه الفترات.حتى نهاية عام 2004، وخلال الفترة الزمنية التي بدأت من عام 2005 إلى نهاية عام 2006 كان العمل قائمًا فيها على تفريغ المفاعل من الوقود عالي التخصيب وتحميله بالوقود الجديد منخفض التخصيب وإجراء بعض التجارب العملية لقياس معاملات المفاعل عند صفر قدرة مستخدمًا الوقود الجديد.

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في نهاية عام 2006، بدأ تشغيل المفاعل فعليًا بدورة تشغيلية أولية باستخدام وقود اليورانيوم منخفض التخصيب بنسبة 19.7% من محتوى اليورانيوم -235، من نوع (IRT-4M)، حيث تضمنت هذه الورقة بعض الخصائص التشغيلية لمفاعل تاجوراء عند تشغيله باستخدام وقود منخفض التخصيب عند مستوى قدرة 5 ميجاوات.
وكانت نتيجة التغيير من استعمال وقود اليورانيوم عالي التخصيب إلى وقود اليورانيوم منخفض التخصيب، هي خسران مفاعل تاجوراء ما مقداره 2 ميجاوات من قدرته الأصلية، التي كانت سابقًا تساوي 10 ميجاوات، وأصبحت الآن فقط تساوي 8 ميجاوات، بسبب الدواعي الأمنية للحد من الانتشار النووي غير السلمي الذي فرضته الدول الكبرى في مجلس الأمن الدولي على باقي شعوب العالم لكي تبقى هي المسيطرة على هذه البرامج بفرض ضغوط قوية على الدول الصغيرة والمضطهدة (الدول النامية، وخاصة الدول العربية) باستعمال وكالتها الدولية للطاقة الذرية.
Keywords: Tajoura reactor, IRT-1 reactor, research reactor, reactor safety, IRT-2M fuel, IRT-4M fuel

1. INTRODUCTION

Research reactors comprise a wide range of different reactor types that are not used for power generation. The primary use of research reactors is to provide a neutron source for research and various applications, including education and training. They are small in comparison with power reactors whose primary function is to produce electricity. Research reactor power ratings are designated in megawatts and their output can range from zero (e.g., critical assembly) up to 200 MW_{th}, compared with 3000 MW(th) (i.e., 1000 MW_e) for a typical large power reactor unit.

Research reactors are also simpler than power reactors and operate at lower temperatures. They need far less fuel, and far less fission products build up as the fuel is used. On the other hand, their fuel requires uranium with much higher enrichment, typically up to 20% U-235, than that of power reactors (3-5%). Some unconverted research reactors still use highly enriched uranium (HEU) fuel containing up to ~90% U-235. Research reactors also have a very high power density in the core, which requires special design features. As with power reactors, the core requires cooling, and usually a moderator is required to slow down the neutrons to enhance fission. Many research reactors also use a reflector to reduce neutron loss from the core and to sustain the chain reaction [1].

There is a much wider array of designs in use for research reactors than for power reactors, and they also have different operating modes, which may be steady or pulsed. Common designs are pool-type, tank-type and tank-in-pool reactors. In pool-type reactor the core is a cluster of fuel elements sitting in a large open pool of water. In tank-type reactor the core is contained in a vessel, as it is in nuclear power plants. In tank-in-pool type reactors the core is located in a pool, but enclosed in a tank through which the coolant is pumped. The tank contains the moderator/ reflector, usually different from the coolant. Between the fuel elements are control rods and empty spaces (channels) for experiments. In one particular design, the Material Testing Reactor, a fuel element comprises several aluminum-clad fuel plates in a vertical box. The water moderates and cools the reactor, while graphite or beryllium is typically used for the reflector, although other materials may be employed. Circular or ellipsoidal beam tubes penetrate the reactor shielding, the vessel, and pool to access neutron and gamma beams from the core for experimental uses in the reactor hall [1].

The Tajoura nuclear research reactor is a pool type reactor, moderated and cooled by light water located at the Tajoura Nuclear Research Center (TNRC). 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. Since this date, the program of converting the reactor fuel from highly enriched to low-enriched started through studies and theoretical calculations until the arrival of the new low-enriched fuel was loaded into the reactor and many hydraulic and other experiments were conducted at zero capacity to verify and compare the theoretical results with the practical data obtained Among those experiments, through which the operating parameters of the new reactor were set. One of the most important parameters is the power of the reactor, which became 8 megawatts instead of the old 10 megawatts, and the cooling water flow rate became 1350 cubic meters per hour instead of 1800 cubic meters per hour [2].

This paper presents the history, time of operating; safety features and utilization of the Tajoura Nuclear Reactor during its old life which it loaded with IRT-2M high enriched fuel and IRT-4M low enriched fuel [2] and a comparison will be studied between the theoretical calculations and the laboratory results of the Tajoura nuclear reactor when it was using highly enriched fuel and when it was using the new low-enriched fuel.

2. REACTOR USES AND ORGANIZATION

Research reactors offer a diverse range of applications, such as neutron beam research for material studies and non-destructive examination, neutron activation analysis to measure minute quantities of an element, radioisotope production for medical and industrial use, neutron irradiation for materials testing for fission and fusion reactors, neutron transmutation doping of silicon, gemstone coloration, etc. Another important area where research reactors have a large contribution is education and training in all nuclear technology areas for operators, maintenance and operational staff of nuclear facilities, radiation protection personnel, regulatory personnel, students and researchers. The main areas of Tajoura Nuclear Research Reactor application are as follows:

1. production of radioisotopes,
2. testing of fuel and structural materials for nuclear power engineering,
3. neutron radiography,
4. neutron activation analysis,
5. neutron transmutation doping,
6. Research in neutron physics.

The main activities carried out in Tajoura Nuclear Research Reactor were focused on the following:

1. Irradiation of target materials in vertical channels and in rabbit system;
2. Experiments with utilization of neutron beams from reactor horizontal channels.

To achieve the goals of Tajoura reactor and its facilities, the reactor was organized as shown in Figure (1).

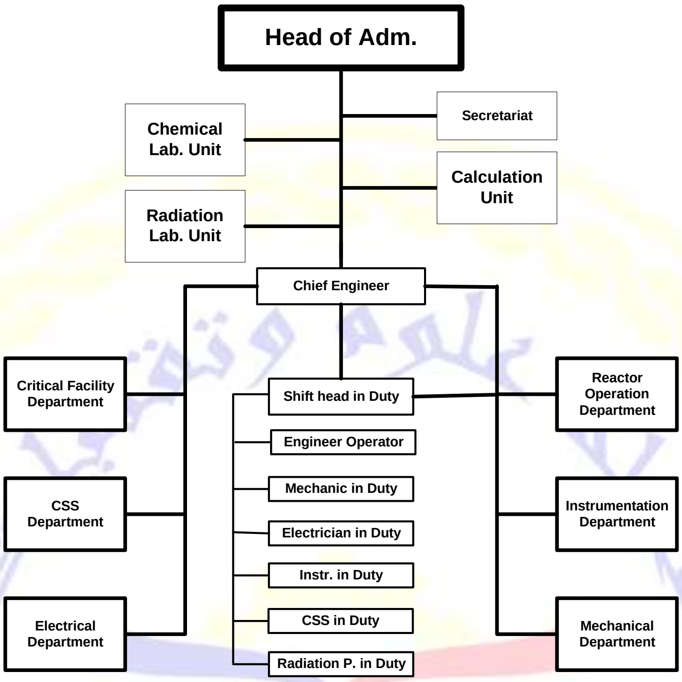

Figure (1): The Reactor Organization Flow Chart.

3. REACTOR AND FUEL DESCRIPTION

In this paragraph, the old, highly enriched, and the new, low-enriched, Tajoura reactor fuel will be explained and described. The Tajoura nuclear reactor main parameters are given in Table (1) and The Tajoura reactor horizontal cross section is shown in Figure (1).

3.1 HEU Fuel Description

Figure (2) shows the horizontal cross section of IRT-2M fuel assemblies. The High Enriched Uranium (HEU, 80% of ^{235}U) fuel assembly type is IRT-2M. There are 16 fuel assemblies; 10 having 3 fuel tubes (3TFA) and 6 having 4 fuel tubes (4TFA). The fuel assemblies are set on a pitch of 71.5 mm. The 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 is 2.25 mm. [4]

The outermost fuel tube has an outer flat-to-flat measurement of 67.0 mm. The outermost three tubes are the same in 3- and 4-tube fuel assemblies (3TFA). The innermost tube in the 3-tube assembly has an inner flat-to-flat dimension of 37.0 mm; the innermost tube in the 4-tube fuel assembly (4TFA) has an inner flat-to-flat dimension of 24.0 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; the radius of the inner surface of a fuel tube corner is 2.0 mm (i.e., same as the tube thickness) less than the radius of the outer surface of the corner. 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 is ignored in the transient calculations. Interior to the innermost fuel tube in the 3-tube assembly is a tube having the same outer dimensions as the innermost tube of the 4-tube assembly.

Table (1):
The Tajoura Research Reactor Main Parameters Data.

Parameter	Fuel Assembly Type	
	IRT-2M (old fuel)	**IRT-4M (new fuel)**
Thermal power, MW	10	8
Moderator / coolant material,	H_2O	H_2O
Fuel Element:		
- Enrichment, %	80	19.7
- fuel shape	3 and 4 concentric tubes	6 and 8 concentric tubes
- Material	U-Al alloy	UO_2-Al alloy
- cladding	Aluminum	Aluminum
- Active length, mm	600	600
Thermal neutron flux, $n/cm^2.s$	2.0×10^{14}	$\sim2.0\times10^{14}$
Cooling system type,	Downward flow	Downward flow

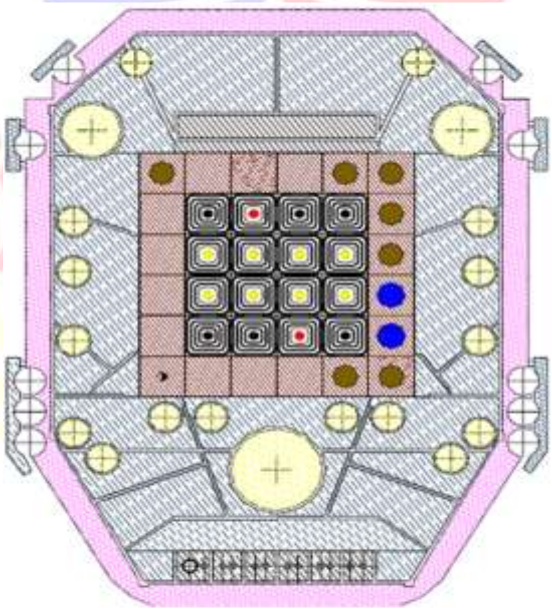

Figure (1): The Tajoura Reactor Horizontal Cross Section with IRT-2M Fuel Assembly.

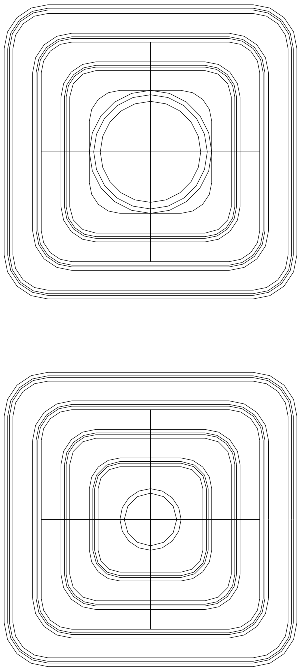

Figure (2): IRT-2M Fuel Assemblies Horizontal Cross Section (3TFA up and 4TFA down).

3.2 LEU Fuel Description

At the end of 2009, the conversion of reactor fuel from highly enriched fuel to low-enriched uranium was completed successfully and without significant technical problems. (LEU, 19.7% of ^{235}U) 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 Figure (3).

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 (Fuel material = UO_2-Al matrix, U Enrichment = 19.7 wt% of ^{235}U, Active length = 60 cm, Uranium density = 2.77 g/cm^3, water gap = 1.8 mm and Mass of ^{235}U/(6TFA and 8TFA) = 263.8 and 300 grams, respectively). 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 [3, 4].

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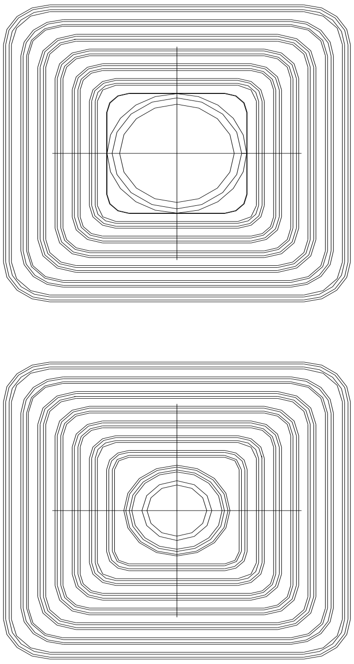

Figure (3): IRT-4M Fuel Assemblies Horizontal Cross Section: (6TFA up and 8TFA down).

4. SHORT HISTORY

The Soviet-designed Tajoura Research Reactor, located at the Tajoura Nuclear Research Center (TNRC) is a 10MW thermal power reactor, although this level of performance was only reached a few times. Construction began in 1977 and end at 1980,10.10, and operations commenced in December 1981.26.08. The reactor is used for isotope production and for fundamental and applied research in nuclear, plasma, radiation physics and chemistry. The research reactor has a high enough neutron flux to produce many useful radioisotopes. The Tajoura Nuclear Research reactor, which houses the reactor, also has a hot cells facility, which is capable of producing Tc-99m (for use in Libya's two nuclear medicine centers) "using the neutron captures reaction on natural molybdenum in the Tajoura reactor and the hot cell facilities. The TNRC has a solvent extraction system for separating Tc-99m from Mo-99 and would like to supply Tc-99m labeled radiopharmaceuticals to local hospitals.

The Tajoura reactor reached its first criticality in December 1981.26.08 with HEU fuels type of IRT-2M. In 1993 the Tajoura reactor was put into operation again. The reactor was in operation until 2006 when it was shut down for fuel conversion program. Normal operation was at 5MW. It is a light water-cooled and moderated, beryllium-reflected reactor.

4.1 Reactor Operation Period

The main history periods of Tajoura reactor from first criticality as follow [4]:

1. **Criticality period (1981 - Sep. 1983)**
    a. Went first critical at 1981

   b. Regular Operation at 1983
   c. Fuel type IRT-2M type (U-Al alloy with 80% ^{235}U)
   d. Thermal power: 10 MW

2. **Operation period (1983 - 2001)**
   a. From criticality time the Tajoura reactor operates on average ≈ 240 hrs/yr (907.914 MWD).
   b. Training and scientific research programs
3. **The period (2001- 2004)**
   a. Some times (operates and/or Shutdown)
4. **The period (2004 - 2006)**
   a. Reactor shutdown and IRT-2M fuel unloading
   b. Return back of fresh IRT-2M fuel to Russia
   c. conversion program (scientific calculations)
   d. Receive the new fuel (IRT-4M)
   e. Loading the new fuel into the reactor
   f. Get the Operating license (≈ 01 Dec. 2006)
5. **Went critical at Dec. 2006**
   a. Fuel type IRT-4M type (UO_2-Al alloy with 19.7% ^{235}U)
   b. Thermal power: 5MW

4.2 Reactor Missions

Tajoura Reactor type is pool-type reactor, moderator and cooled by light water, reflected by Beryllium, and it as a neutron source ... the reactor brief missions as follows:

1. **First Period (1983-2001)**
   a. Establish the nuclear culture (First nuclear facility in Libya)
   b. Support fundamental research on the field of nuclear and neutron physics
   c. Undergraduate education training
   d. Isotope production
2. **Second Period (2006 - 2009)**
   a. Conversion program → complete
   b. Fundamental and applied research → continues
   c. Isotope production (Mo-99 and others isotopes) new goal → continues obligation
   d. Postgraduate and undergraduate education and professional training →appeared
3. **Reactor Utilization**

The Tajoura reactor utilization with the average value of 280 hr/yr with 55MWD/yr

a. **Vertical channels (51 channels)**
   - Isotopes production
   - Pneumatic Rabbit System for Neutron Activation Analysis (NAA).

b. **Horizontal beam ports: 10 pcs.** experimental facilities

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4. Reactor Conversion Program

At the middle of 2006 the all necessary calculations has been done for Tajoura reactor with LEU fuels, such as:

a. **Neutronics Calculations** (critical mass buildup, excess reactivity, flux distribution, control rods critical position, power distribution ……).
b. **Thermal hydraulic Calculations** (temperature distribution, coolant volume flow rate and other critical parameters ...).
c. **Transient scenarios calculations** (cooled water injection, fuel assembly drop, loss of flow, positive reactivity insertion, loss of coolant …)

The some results for Tajoura reactor at steady state with thermal power of 5 MW are shown in Tables (2) through Table (4) [6 - 9].

Table (2):

Tajoura Reactor Main Thermal Hydraulic Parameters with new fuel at 5 MW

Parameter	Value
Reactor core pressure drop, MPa	0.04284
Total mass flow rate in fuel region, kg/sec	114.38
Total volume flow rate in fuel region, m^3/hr	415.85
Primary volume flow rate, m^3/hr	1107.51
Total Thermal power, MW	4.351
Primary inlet temperature, °C	33.53
Primary outlet temperature, °C	36.94
Primary temperature difference, °C	3.41

Table (3):

Tajoura Reactor IRT-4M Fuel Assemblies Coolant Sub-channels Main Thermal Hydraulic Parameters

FA	CH. #	$\dot{m}$ [kg/sec]	V [m/sec]	p_{out} [MPa]	T_{out} [°C]	Heat Flux, MW/m^2		
						CHF	FI	F_{sat}
8TFA	1	0.39	3.45	0.14	33.53	0.00	0.00	0.00
	2	0.25	2.41	0.14	37.37	2.48	1.52	1.90
	3	0.77	2.95	0.14	36.73	2.59	1.89	2.36
	4	0.56	2.48	0.14	40.63	2.49	1.12	1.30
	5	0.69	2.48	0.14	42.20	2.49	1.12	1.30
	6	0.82	2.48	0.14	43.65	2.49	1.13	1.32
	7	0.95	2.49	0.14	45.24	2.49	1.13	1.32
	8	1.08	2.49	0.14	46.87	2.49	1.12	1.31
	9	1.20	2.49	0.14	48.48	2.49	1.12	1.30
	10	0.94	2.77	0.14	44.03	2.51	1.56	1.90
	TOTAL	7.65						
6TFA	1	0.84	2.46	0.14	36.09	2.84	2.45	3.58
	2	0.73	2.63	0.14	40.65	2.51	1.18	1.38
	3	0.87	2.63	0.14	41.86	2.52	1.19	1.40
	4	1.00	2.63	0.14	43.16	2.52	1.19	1.39
	5	1.14	2.63	0.14	44.51	2.52	1.19	1.39
	6	1.27	2.63	0.14	45.91	2.52	1.18	1.38
	7	0.99	2.92	0.14	42.29	2.58	1.65	2.01
	TOTAL	6.85						

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Table (4):
Tajoura Reactor IRT-4M Fuel Assemblies Fuel Elements Main Thermal Hydraulic Parameters

FA	FE	Lift Side		T_{fuel} [°C]	Right Side		DNBR	ONBF	T_{BLG} [°C]	T_{ONB} [°C]	T_{SAT} [°C]
		T_{clad} [°C]	q'' [MW/m^2]		q'' [MW/m^2]	T_{clad} [°C]					
8TFA	1	33.53	0.00	35.45	0.00	37.37	5.06	2.15	124.95	117.30	109.43
	2	49.17	0.17	49.14	0.15	46.72					
	3	49.62	0.20	52.54	0.18	52.55					
	4	56.74	0.25	57.79	0.23	57.09					
	5	61.10	0.30	62.26	0.28	61.31					
	6	65.23	0.35	66.63	0.33	65.57					
	7	69.35	0.40	70.96	0.38	69.74					
	8	73.43	0.45	75.22	0.43	73.83					
	9	77.06	0.49	77.14	0.47	72.13					
6TFA	1	50.75	0.22	53.45	0.21	53.44	5.69	2.47	126.35	116.97	109.43
	2	56.98	0.27	57.97	0.25	57.10					
	3	60.56	0.31	61.74	0.29	60.73					
	4	64.14	0.35	65.50	0.34	64.34					
	5	67.67	0.40	69.21	0.38	67.93					
	6	71.18	0.44	71.25	0.43	66.78					

5. HIGHLIGHT ISSUES

In this section we'll deals with three topics such as safety analysis report, spent fuel return back program and safety aspects of Tajoura reactor, as follows:

5.1 Safety Report Analysis Program

To carry through the safety analysis report of Tajoura research reactor a group (SAR Group) was established (29/04/2007), and from that time the group achieved the following chapters from chapter 1 to chapter 10 [8, 9].

5.2 Spent Fuel Return Back Program

The Tajoura Research Reactor Spent Nuclear Fuel (SNF) Return back Program (Negotiations between U.S DOE/NNSA and TNRC was started in beginning of 2008 and Specific agreement was achieved). To carry though the agreement the main lines should manage parallel [8]:

1. Scientific calculations were achieved.
2. Measurement of radiation level of SNF assemblies was achieved in the beginning of 2009.
3. The SNF assemblies back shipment was achieved at the end of 2009.

5.3 Safety Aspects of Tajoura Reactor

The safety aspects of Tajoura nuclear research reactor during its new life with low enriched fuel are specified in the following categories:

1. Monitoring the new fuel elements performance during irradiation inside the reactor.
2. Tajoura Reactor relicensing the new fission products inventory, reevaluation of accident scenarios on risk analysis and atmospheric dispersion.

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3. Setting the critical and operating conditions for the Tajoura reactor with new compact core loading to operate at 8 MW as maximum level and other power levels.
4. Evaluation of the technical specifications of the new fuel.

6. CONCLUSIONS

From the previous operation of the Tajoura reactor with high-enriched fuel since its first critical state in December 1981.26.08 until the end of 2005, we conclude that no operational problems occurred during the reactor's first lifecycle from a nuclear safety standpoint. Additionally, Libyan operators and engineers gained very good experience in nuclear engineering, including reactor operation, reactor calculations, etc., nuclear physics, and other related areas in reactor operation and design.

Finally, after the reactor conversion program was completed, the reactor obtained a new license to operate using the new fuel (low-enriched fuel) for future reactor operation with a maximum new operational power of 8 megawatts or less using the newly low-enriched fuel.

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