INITIAL OPERATION EXPERIENCE AND NEAR FUTURE UTILIZATION PLANS AT THE JORDAN RESEARCH AND TRAINING REACTOR

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ABSTRACT

Towards safe and smooth operation of the Jordan Research and Training Reactor (JRTR), supplementary training and qualification of reactor personnel was attained through conducting a set of extensive reactor performance tests during the initial operation phase. Results of selected tests and overall outcomes of the initial operation phase are presented herein. Measurement results are compared against calculations based on a JRTR core model that takes into account fuel burn-up/depletion due to about 18 full power days of intermittent operation during the reactor's hot commissioning period.

In general, the level of confidence among JRTR personnel to safely operate the reactor increased significantly, and the expected outcomes from these tests were achieved successfully. Finally, beyond the initial operation phase, near-future operation and utilization plans at the JRTR are summarized.

1.0 Introduction

1.1. Briefing

The Jordan Research and Training Reactor (JRTR) is a tank-in-pool research reactor, employing flat-plate MTR-type fuel, with a rated power of 5MW (upgradeable to 10MW). In addition to supplying regional markets with radioisotopes for medical, research and industrial applications, the JRTR is intended to serve as a training facility and research hub for emerging engineers and scientists in the region.

From fuel loading followed by first criticality, on April 25th 2016, the contractor commenced with conducting an extensive set of reactor performance tests as part of the hot-commissioning phase (stage B and C according to IAEA) [1]. The tests were aimed at satisfying a set of pre-set test acceptance criteria to demonstrate that the reactor and its associated facilities are as safe and as effective as described in the design and safety analysis documents. During hot-commissioning phase, design and review of test procedures, handling of materials, reactor operation, data analysis, simulations, and report issuing were *mainly* undertaken by the contractor.

Almost all results satisfied acceptance criteria, which positively contributed towards the taking over process from a contractual point of view. However, additional work was still needed in order to build-up self-confidence required to take over the first nuclear reactor at Jordan from an ownership and operation point of view. Therefore, it was proposed that the operator, Jordan Atomic Energy Commission (JAEC), dedicate the initial operation phase to repeat the hot-commissioning reactor performance tests conducted earlier by the contractor; hence the name, Initial Operation Tests (IOTs). The main objective of the IOTs was to consolidate the operator expertise and build self-confidence required to operate the reactor safely and, eventually, smoothly and effectively.

1.2. Brief Description of JRTR Core

The JRTR core consists of 18 plate-type fuel assemblies (FAs), cooled and moderated by light water, and surrounded by two reflectors, namely Beryllium and heavy water. Reactivity is controlled through four Hafnium control absorber rods (CARs) surrounding FAs 05, 07, 12 and 14 (**Fig 1**). In addition, two secondary hollow cylindrical, Boron Carbide absorber rods, which can be either fully inserted or fully withdrawn, are present to provide additional shutdown capability. **Fig 1** illustrates core fuel assemblies (shades of grey), reflectors (green and light blue for Beryllium and heavy water, respectively) and control rods.

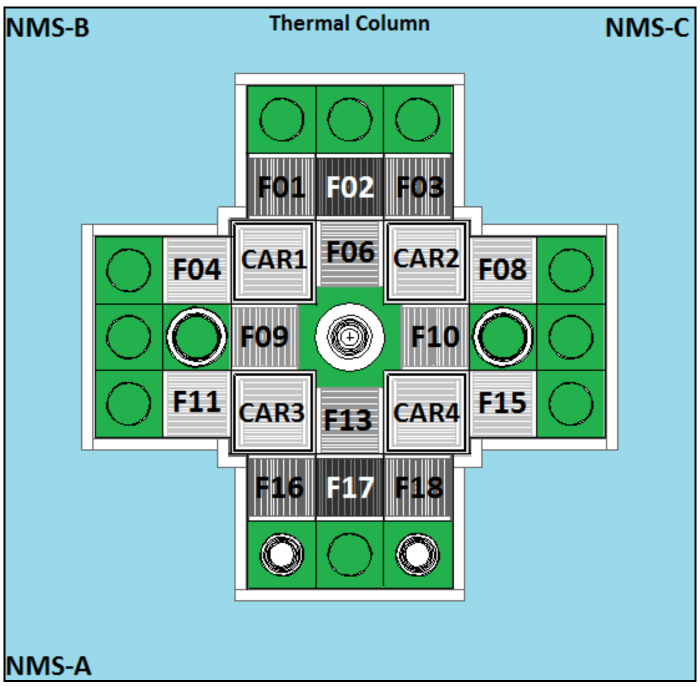

Fig 1. JRTR Core Configuration

2.0 Preparation for the Initial Operation Tests

2.1. Briefing

Hot-commissioning tests procedures had to be redesigned and adapted so as to take into account the change in the reactor core condition due to considerable full power operation during the hot-commissioning period. The chance was employed to involve all related departments in a comprehensive review process not only for tests procedures, but also for related operation and technical administration procedures. Operations team had the chance to practice the procedures hands-on, and provide practical feedback for further improvement.

The JRTR was intermittently operated for about 18 Full Power Days (FPDs) during the hot-commissioning phase. The fresh fuel core model [2], provided and verified by the contractor and validated by the results of the hot commissioning tests, was updated by performing burn-up/depletion calculations using MCNP6 code [3].

Partial list of tests conducted during initial operation phase and their acceptance criteria is given in the table below. Results of selected tests are to be discussed in this paper.

Category	Test	Acceptance Criteria
Reactor Core Performance Tests	Approach to Criticality	NA
	Excess Reactivity Measurement	20% agreement with calculation
	Control Rod Worth Measurement (3 methods)	For each CAR, at least one method can predict its integral reactivity worth to within 15%
	Xenon Worth Measurement	NA
	Power Coefficient of Reactivity Measurement	Negative Power Coefficient of Reactivity
	Cadmium Ratio and Neutron Spectrum Measurement	NA
Systems and Facilities Performance Tests	Neutron power calibration	Deviation less than 150 KW between thermal and NMS
	Cooling Performance of PCS and HWS Heat Exchangers	Demonstration of sufficient cooling capability
	Loss of Flow and Loss of Electric Power	All safety parameters within limits, and fuel integrity maintained
	Radioisotope Production Test	NA
	NAA Spectrum Measurement	NA

Tab 1: Partial list of Conducted Tests

2.2. Fuel Burn-up (Depletion) Estimation

In order to take into account control rods (CARs) position adjustments and consequent flux distribution changes during reactor power operation, operation history was obtained, analysed and segmented into 16 calculation steps. Results of burn-up calculation are presented in terms of normalized U^{235} consumption distributions (Fig. 2). As expected these distributions look very similar to the fission rate distributions at the beginning-of-cycle of the fresh-fuelled reactor core [4]. These results were utilized to perform *neutronic* calculations needed during the initial operation phase. It is worth mentioning that methodology and results of performed burn-up calculations are not considered final and are still going through further investigations.

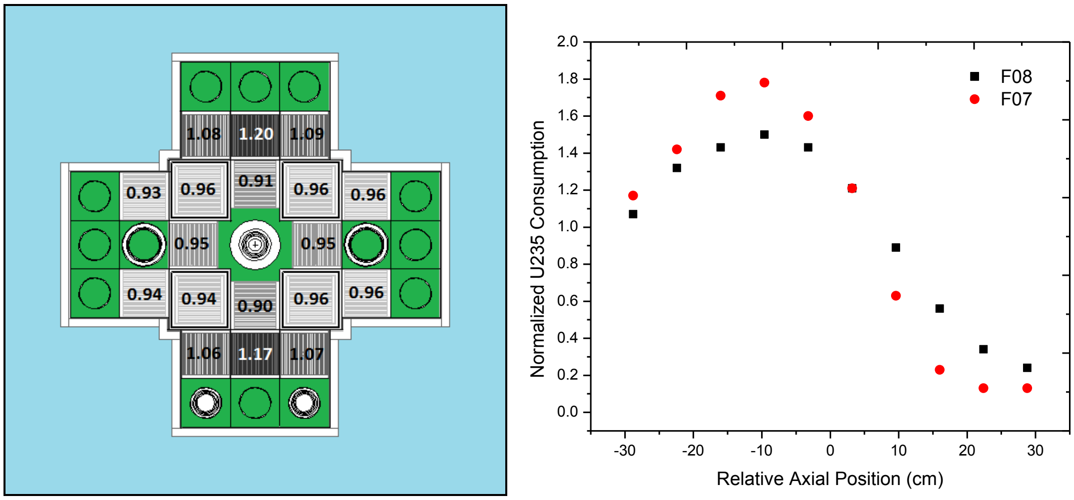

Fig 2. Normalized U^{235} Consumption Distributions

3.0 Reactor Core Performance Tests

3.1. Minimum critical core and approach to criticality

So as to predict the minimum number of fuel assemblies required to bring the reactor core to criticality, criticality eigenvalues were calculated for different core configurations (**Tab 2**). Based on these results, it was decided to perform the approach to criticality test starting with 15 fuel assemblies and 0 dummy assemblies. Criticality for the minimum core was approached through the conventional *inverse multiplication method* [5]. At that configuration, the critical position of CARs was judged (by the operator at the MCR) to be 539.6mm. It is worth mentioning that the total travel span of CARs is 650mm and their positions are measured with reference to the bottom of the core.

# of FA	**# of DA**	**k_{eff} (ACRO*)**	**Std. (pcm)**
14	0	0.98674	11
14	4	0.99258	11
15	0	1.01557	11
15	3	1.02066	11

Tab 2: Calculated criticality eigenvalues for multiple configurations

3.2. Excess Reactivity Measurement

Critical CARs positions were measured for **13** core configurations as part of the excess reactivity measurement test. Before delving into the details and results of excess reactivity measurement and calculations, summary of measured against predicted CAR critical positions for selected core configurations are presented in **Tab 3**. Critical CAR positions were predicted through fitting criticality eigenvalues (k_{eff}), calculated for multiple CAR positions (around the critical position), to a linear equation. In order to confirm that this methodology of predicting critical CARs position is reliable, k_{eff} was demonstrated to be very close to unity when re-calculated at these predicted critical positions. All calculations for prediction of critical CAR positions were performed at 20^{o}C.

# of FAs	# of DAs	Pool Water Temperature (^{o}C)	Measured Critical Position (mm)	Calculated k_{eff} @ Measured position*	Predicted Critical Position (mm)	Calculated k_{eff} @ Predicted position*
18	**-**	23.7	**345.0**	1.00020	**344.5**	0.99992
17	**1**	24.3	**385.8**	1.00052	**385.4**	1.00023
16	**2**	24.6	**450.6**	1.00011	**449.6**	0.99997
15	**3**	23.7	**521.0**	1.00028	**520.0**	0.99995

*****Standard deviation of quoted values is 0.00011

Tab 3: Predicted vs. Measured Critical Positions

Maximum and average discrepancy between measured and predicted critical positions for all configurations amounted to 1.6mm and 0.2mm, respectively. Again these results are not considered final since the methodology of burn-up calculation is still going through additional investigations. In fact, in order to judge the validity of burn-up calculations one has to compare to the performance (validity) of the initial core model. Anyway, this agreement between measured and predicted critical positoins was still a main source of confidence that burn-up calculation results were sufficiently accurate and, to a great extent, representative of the actual condition of the reactor core.

Back to excess reactivity measurement. Since it is not possible to measure the total excess reactivity by simply fully withdrawing all control rods, excess reactivity had to be estimated by summing measured reactivity insertions induced by limited control rod adjustments performed by a rod-swapping method. Reactivity was measured through inverse point kinetics, with point kinetic parameters calculated through MCNP6 code (ENDF-B/VII.1 cross section library). Value of β_{eff} was estimated to be (737±11pcm), including the contribution of delayed photo neutrons measured to be (~14 pcm). All measured reactivity values are based on the average of the three reactor regulation system neutron measurement system (NMS) signals.

For the minimum core that can achieve criticality (with dummy assemblies), control rods were withdrawn step by step and one by one, from critical position to fully-withdrawn position. After induced reactivity value had been recorded for each withdrawal step, other control rods were inserted accordingly to compensate for the positive reactivity and bring the reactor back to critical state. The sum of measured reactivity values for all steps and for the four rods was assumed to represent the *excess reactivity for the minimum critical core*. Subsequently, an additional fuel assembly was added and its worth was estimated by summing measured reactivity values (for all steps and for all control rods) between the two critical positions of (*n)*-assemblies core and (*n+1)*-assemblies core. Finally, the total (*measured*) excess reactivity of the core is assumed to be the sum of excess reactivity for the minimum core and subsequent reactivity worth values for the 16th, 17th and 18th assemblies.

On the other hand, two methodologies were adopted for calculations; all control rods out (ACRO) results are based on fully withdrawing all CARs simultaneously, while “stepwisemethod” results are based on withdrawing each CAR separately and summing the reactivity worth values induced by each CAR. The “step-wise” method can best be illustrated by **Tab 4** below.

FA+DA	CAR1 (mm)	CAR2 (mm)	CAR3 (mm)	CAR4 (mm)	k_{eff}	Reactivity ($)	
15+3	650	520	520	520	1.00378	0.5103	
	520	650	520	520	1.00574	0.7734	**Excess Reactivity of the Minimum Core**
	520	520	650	520	1.00308	0.4161	
	520	520	520	650	1.00368	0.4969	**2.20**

Tab 4: Excess reactivity calculation for minimum core using step-wise method

Tab 5 summarizes measured and calculated excess reactivity of the minimum core, reactivity worth of the 16^{th}, 17^{th}, 18^{th} assemblies, and total excess reactivity value of the full core. Using ACRO calculation method the total excess reactivity was predicted to be **11.24$**, while using the “step-wise” calculation method the total excess reactivity was predicted to be **10.55$.** As expected due to neutron flux redistribution [6], results imply that the value of reactivity induced due to adjustment of the position of a CAR is dependent on the position of other three CARs. Furthermore, as will be illustrated below (3.4), it can be (preliminarily) concluded from calculation results that withdrawing CARs synchronously (all being at the same height/position) induces a reactivity insertion larger than the sum of reactivity insertions induced by withdrawal of each CAR separately.

Assembly Number	Measured (ENDF-B/VII.1) ($)	Calculated ACRO ($)	(M-C)/(C) % ACRO	Calculated Steps ($)	(M-C)/(C) % Steps
15 + 3	2.01	2.75	-26.8%	2.20	-8.5%
16th	2.34	2.69	-12.9%	2.41	-3.1%
17th	3.10	3.27	-5.2%	3.25	-4.7%
18th	2.44	2.53	-3.7%	2.68	-9.0%
Total	**9.88**	**11.24**	-12.1%	**10.55**	-6.3%
Std.	---	0.17	---	0.07	---

Tab 5: Excess Reactivity Measurement and Calculation Results

3.3. Shutdown Margin Measurement

For the JRTR core, shutdown margin (SDM) is the reactivity of the core when all CARs are inserted except for the CAR with highest worth is fully withdrawn. It was the decision of the JRTR designer not to include the SSR reactivity-worth in the estimation of the JRTR core SDM. In particular, to estimate the SDM the following formula is used: ***0.9*(a – (b+c+d))*** [4], where ***a*** represents the reactivity of the three CARs of minimum worth, ***b*** represents the cooling down reactivity, ***c*** represents maximum possible positive reactivity induced due to removal of all irradiation rigs and finally, ***d***, represents the (Xenon-free) core excess reactivity. The result is multiplied by a factor of 0.9 in order to *exclude the possibility of overestimating the SDM due to uncertainties in calculations or measurements*.

In order for the measurement results to closely resemble situations in which immediate shutdown of the reactor is needed, it was proposed to use CARs worth measured through *rod drop method* for SDM estimation. Each of the four CARs was dropped from fully withdrawn position, while the reactor is critical. Using neutron count rate time-profile, measured at 20Hz by two BF3 detectors located in the thermal column, reactivity was estimated through inverse point kinetics. Results are shown in **Tab 6**.

It can be noticed that measured (rod-drop) reactivity worth are higher for CARs closer to the detectors (installed at the thermal column), i.e. CARs 1 and 2. Confirmed by results from other measurement methods as well as from calculations, these results do not represent the actual reactivity worth of the CARs. On the other hand, the sum of the CARs worth do agree with sum of CARs worth predicted by calculation, as will be shown in the next section. Nevertheless, measured shutdown margin (**15.08$**) is far above the acceptance criteria (~7$).

CAR1 Worth ($)	**CAR2 Worth ($)**	**CAR3 Worth ($)**	**CAR4 Worth ($)**	**Minimum N-1 CAR worth ($)**	**Measured Excess Reactivity($)**	**Shutdown Margin ($)**
13.18	14.33	7.70	7.76	**28.64**	9.88	**15.08**

Tab 6: Shutdown margin measurement test results.

3.4. CARs Worth Measurement Using Inverse Multiplication

For the control rod worth measurement using inverse multiplication method, neutron power was measured at multiple (subcritical) control rod positions. Critical CARs position was sought for three CARs while the fourth one, to be measured, was fully withdrawn. Afterwards, the CAR under measurement is inserted in steps of 50mm, and equilibrium neutron power level is recorded for each step. For each step, insertion of the CAR decreases the (subcritical) multiplication factor which, in turn, reduces the equilibrium neutron power.

In order to convert measured equilibrium neutron power to reactivity, the following equation, derived from inverse point kinetics equation for subcritical steady state, can be used:

$$\rho = -\frac{\Lambda s}{n}$$

However, the following factors had to be considered carefully while applying this simple formula:

1. It requires accurate knowledge of the external neutron source term (s)
2. Reproduction time (Λ) value changes with control rod position

3. Fraction of the neutron power (*n*), measured at ex-core detectors, consists of photo-neutrons generated in the reflectors and scattered directly to the NMS detectors without contributing to the reactor (point) kinetics [7].

With any CAR fully withdrawn, position of the other 3 CARs to achieve criticality was at around 310mm. Measured reactivity was estimated based on the *average of the three NMS signals*. As an example, measured and calculated reactivity worth curves for CAR3 are shown in Fig. 3.

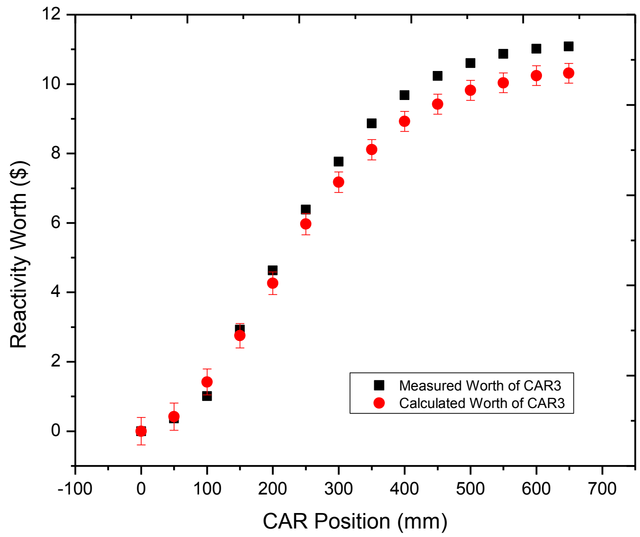

Fig 3. Measured and calculated worth for CAR3

Summary of measurement and calculation results for all four CARs are given in **Tab 7**. Overall, results of inverse multiplication worth measurement satisfied CAR worth measurement acceptance criteria (indicated in **Tab 1**) for all four CARs. It can be noticed that discrepancy between measured and calculated worth is lowest for CAR1 while for CAR4 it is relatively high. Once more, the relative position of CARs with reference to detectors is seemingly affecting reactivity measurement results, similar to what was observed in rod-drop results (3.3). In addition, measured and calculated **sum** of four CARs worth agree very well, and also agree with the **sum** of four CARs worth measured by rod-drop (**~42.97$**) (3.3).

CAR #	**Calculated total Worth ($)**	**Measured total Worth ($)**	**Relative Error (M-C)/C**
CAR 1	10.63	10.78	1.41%
CAR 2	10.95	12.14	10.87%
CAR 3	10.31	11.08	7.47%
CAR 4	10.42	8.91	-14.49%
Sum	**42.31**	**42.91**	**1.42%**
Total Worth when CARs Moved Simultaneously	59.89	---	---

Tab 7: Calculated integral CARs worth for 1/M measurement

Total worth of the four CARs when simultaneously fully withdrawn was also calculated, and turned out to be about 50% higher than the sum of reactivity worth induced by (fully) withdrawing each CAR separately (**Tab 7**). This goes in-line with what was noticed earlier in excess reactivity section 3.2: Total reactivity estimated by indirectly summing induced reactivity worth due to *sub-adjustments* turns out to be smaller than the reactivity induced by the sum of the *sub-adjustments*.

3.5. Power Reactivity Coefficient Measurement

Having negative reactivity coefficients was among the design requirements of the JRTR. This test was conducted to re-demonstrate (what was already demonstrated during the hot-commissioning phase) that during *fast power transients* the reactivity of the core decreases as power increases and that the reactor falls subcritical passively. For *slow power transients*, it is well understood that the core reactivity will decrease due to build-up of neutron poisons; however, slow power transients are - in general - not a safety concern.

To demonstrate negative power coefficient, reactor power was increased step-wise (7 steps shown in **Tab 8**), within 14 minutes, while CARs critical position and core inlet temperature were monitored. During that short period of time, it is estimated that reactivity feedback due to poisons build-up would be smaller than about 0.1 cents, which is negligible compared to the estimated total power defect ~10 cents (~1%). **Tab 8** shows power levels and corresponding critical CARs positions. It is evident that, from 10KW to full power, CARs position had to be withdrawn a little (~1.5mm) in order to maintain criticality.

Ascension		Decent	
Power (KW)	**Critical CARs Pos. (mm)**	**Power (KW)**	**Critical CARs Pos. (mm)**
10	351.39	**5000**	352.86
400	351.45	**1000**	351.65
3000	352.27	**100**	351.67
5000	352.86	**10**	350.94

Tab 8: Power and critical CAR position history

4.0 Reactor Systems and Facilities Performance Tests

4.1. Neutron Power Calibration

Among the signals monitored to make sure that the reactor power is within the safe operation range, neutron power, measured by three ex-core fission chambers, is monitored by the reactor protection system (RPS) in order to actuate reactor trip if certain power set-point is exceeded. Hence, calibration of neutron measurement system is not only important from an operability point-of-view, but also from reactor nuclear safety point-of-view.

The calibration is performed periodically during operation of the reactor. The target is to lower the difference between the measured neutron power and the measured thermal power (at thermal steady-state) below 150 KW (3%FP). Measured thermal power, based on the inlet and the outlet temperatures of the reactor core cooling systems, is assumed to accurately represent the true reactor power. Fig 4 below illustrates the level of agreement between power readings of the thermal and the RPS signals before and after (re)calibration. The dotted line illustrates the acceptance bandwidth.

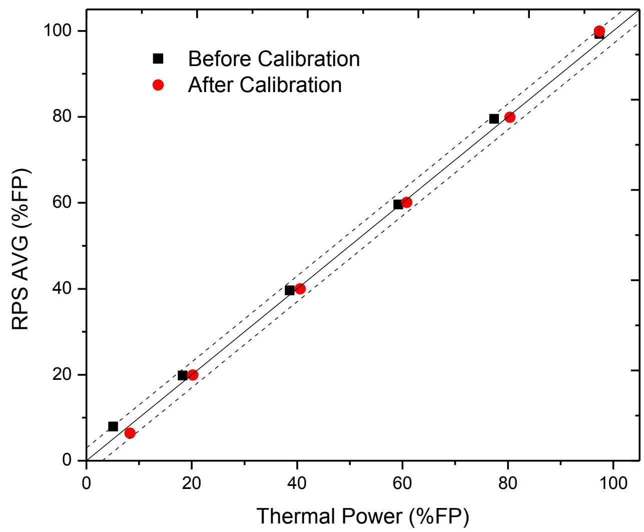

Fig 4. Power readings of the thermal and the RPS signals, before and after (re)calibration.

4.2. PCS and HWS Heat Exchanger Cooling Performance Test

Heat extraction during operation and after shutdown is a primary safety function required to ensure the integrity of the reactor fuel. The cooling performance of the heat exchangers was demonstrated to be sufficient for the energy produced at full power. Measured cooling capacities are presented in **Tab 9**.

Heat Exchanger	**Cooling Tower Outlet Temperature**			
	25~27^{o}C		**30~33.4^{o}C**	
	Cooling Capacity (kW)			
PCS(PCS1/PCS2)	2510	2593	2393	2462
HWS	90		85	

Tab 9: Cooling Capacity of Heat Exchangers

4.3. Loss of Normal Electric Power and Loss of Flow Tests

The Loss of Flow and Loss of Electric Power Tests aimed at demonstrating the intervention of JRTR safety systems in case primary coolant flow or site normal electric power was lost. As of any nuclear safety system, three functions are expected from the JRTR safety system:

1. To control the reactivity of the core (through reactor trip),
2. To maintain sufficient cooling during and after shutdown of the reactor (through primary flow coast-down and opening of flap valves when needed), and
3. To maintain operation of auxiliary systems required to monitor the reactor.

In both tests, initiating event was induced intentionally while the reactor was operating at full power and the reactor parameters were monitored to ensure functions of the safety systems are performing as required. Acceptance criteria for this test were successfully met, and are listed here-in for reference:

1. Safety systems and components achieved the fundamental safety functions as described in the SAR.
2. Proved that power drop and flow coast down profiles used for safety analysis were actually conservative compared to measured power drop and primary flow rate signals after the events.
3. Fuel integrity was maintained during and after the tests.

4.4. RI Production and NAA Performance tests

Additional tests were conducted to demonstrate JRTR utilization capabilities (more on JRTR utilization below). About 4Ci of I-131 (in the form of solution and capsules) and 1Ci of Mo-99 solution were produced at the JRTR hot-cells after in-core irradiation of TeO_2 and MoO_3 powders, respectively. In addition, training on producing *Ir-192 NDT source* assemblies was conducted.

Blind-sample irradiation tests were conducted at the NAAF with cooperation with the IAEA in order to test and demonstrate the readiness of the NAA laboratory at JRTR to produce credible neutron activation analysis.

5.0 Near Future Utilization Plans at the JRTR

Although the JRTR core is designed to accommodate a wide range of neutron applications ranging from radioisotopes production up to cold-neutron applications, its initial implementation (current configuration) is limited to the production of **I^{131}**, **(n,γ) Mo^{99}/Tc^{99m}** and **Ir192**, in addition to neutron activation analysis. The discussion below on JRTR utilization plans is only limited to plans to be implemented within 2 years.

In the field of radioisotope production, a dozen of local nuclear medicine institutions were contacted by the JRTR and agreements to supply I^{131} and Mo^{99} are already on the way. After radioisotope production IOT results confirmed that the RIPF (Radioisotope Production Facility) is capable of producing quality radioisotopes, current efforts at the RIPF are focused towards optimizing a production plan in order to match the expected demands, and towards acquiring required approvals from the FDA (Food and Drugs Administration). In addition, it is planned to expand production to include other radioisotopes, such as Lu^{177} which is gaining popularity in radiotherapy for its favourable decay characteristics. [8] JRTR SAR covers production of the three radioisotopes mentioned earlier only; therefore, safety analysis has already commenced to assess the reactivity worth of Lu^{176} loaded irradiation capsules, and to assess the amount of Lu^{177} that can be handled given the available handling capacity at the current hot cells setup.

A couple of scientific institutions have been contacted and offered NAA services. Accomplished tasks at the NAAF (NAA Facility) include characterizing the neutron spectrum at the NAA irradiation holes through measurements and calculations, and improving procedures in order to incorporate best practices in the field. Current efforts are directed towards raising the expertise level of NAAF operators towards realizing highest quality of produced results.

An NTD facility design for the JRTR is currently being investigated also. It is expected that NTD can be implemented at the JRTR within 2 years, however, before implementation it still has to be confirmed whether this service would realize a level of demand to cover the costs.

Finally, it is worth mentioning aspects of JRTR that qualifies it as a training ground for emerging engineers and scientists. The JRTR can be operated in training mode (at near zero power or up to 50KW) for purposes of conducting experiments and training. A training centre with classrooms, an auditorium and a PC based reactor operation simulator is also available.

6.0 Summary and Outcomes

Overall, initial operation tests at the JRTR were fruitful and their results satisfied predefined acceptance criteria. The operations, radiological protection and safety analysis personnel had an invaluable chance to practice and/or contribute to reactor operation, and as a result gained a decent level of practical experience needed for safe operation of the JRTR. In addition, conducting these activities independently contributed to increasing the sense of ownership among JRTR personnel.

From a technical stand-point, burn-up calculation were conducted and their results gave the JRTR safety analysis team good confidence in the calculation methodology, model and code used for the task of *neutronic* calculations. Results of burn-up calculations enabled performing simulations for the IOTs for the purpose of comparison. In general, measurement results agreed very well with calculation predictions. The main focus of the core performance tests was towards increasing the understanding of reactivity measurements and improving the interpretation of reactivity measurement results in order to explain deviations between measurements and calculations.

Systems and facilities of the JRTR were also demonstrated to perform as required to enable safe operation, and safe utilization activities which are planned to concentrate, for the near future at least, on radioisotope production, NAA, NTD as well as training and education.

7.0 Acknowledgment

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8.0 References

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