Commissioning of the Jordan Research and Training Reactor (JRTR)

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Abstract. The Jordan Research and Training Reactor (JRTR) is an open tank-in-pool type reactor with a downward core flow during normal operation. JRTR is built on the campus of the Jordan University of Science and Technology (JUST) to be a hub for excellence in nuclear sciences and technology in the region. JRTR is a multipurpose, 5 MWth upgradable to 10 MWth reactor. Currently, the JRTR is in the operational phase. Prior to the start of JRTR operation, a set of commissioning tests have been performed. The normal purpose of the commissioning process is to verify that systems and components of research reactors and fuel cycle facilities, after they have been constructed, are made operational and meet the required safety and performance criteria.

In the commissioning process of the JRTR, the IAEA safety guides NS-G-4.1 has been followed. As recommended in the IAEA safety guide, JRTR commissioning process was divided into three main stages with hold points at the end of each stage. These stages are; tests prior to fuel loading, fuel loading tests and initial criticality tests which include low power tests; and the last stage constitutes power ascension tests and power tests up to rated full power. These stages have also been divided into sub stages. The performed tests have proved that all design and performance parameters have been achieved. For instance, the thermal power of 5 MW, maximum thermal neutron flux of 1.5 ×1024 (n/cm2·s) and negative reactivity feedback have been achieved. This paper describes each commissioning stage of the JRTR and the final results and conclusions.

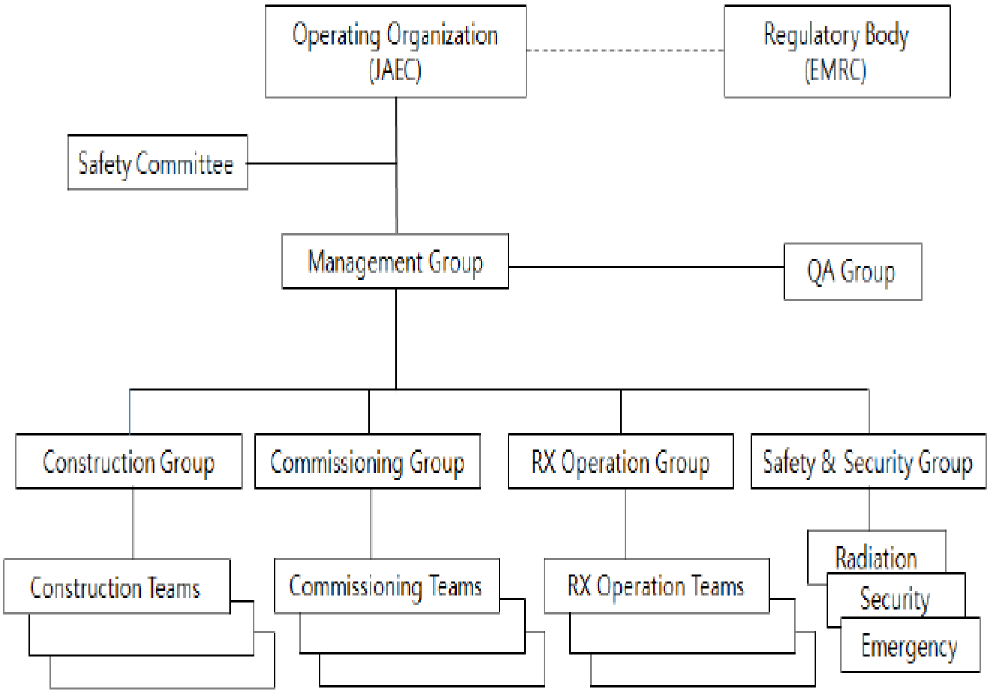
1. **Introduction.** Similar to the goals of commissioning process for all research reactors, the objectives of commissioning of the JRTR are clear and definitive. These include: verifying that the SSCs are commensurate with their importance to safety, demonstrating that the design requirements are met as stated in the Safety Analysis Report [1], providing basic data for safe and reliable operation, verifying that documentation is adequate for full facility operation, providing operation staff with the chance of education for the validity of the reactor operation procedures, and providing the end-users with clear idea about the facility characteristics [2]. It is needless to say that one of the most important objectives of reactor commissioning is to verify the adequacy of facility operation under all anticipated operational modes. The implementation of commissioning activities is the responsibility of the commissioning group including the safe operation of the facility during commissioning.

2. **Commissioning Plan.** Based on the guidelines of research reactor commissioning in Ref. [2], the commissioning plan of the JRTR has been envisaged to address the objectives of commissioning [3]. The main chapters of the plan shed light on commissioning organization, stages, schedule, management, quality assurance, operational limits and conditions, radiation protection and emergency and security management during commissioning.

   For the purpose of conducting commissioning activities, the commissioning organization structure has been designed following the commissioning plan. The structure clearly defines the commissioning groups, the functional responsibilities, levels of authority, approval channels, and interfaces between the participating groups.

   The organization chart is presented in Figure 1. It is mainly composed of the management group, commissioning group, reactor operation group, construction group, quality assurance group, safety & security group and safety committee. The functions and duties of each group are defined in the commissioning plan. For example, the management group, which is chaired by the JAEC Project Manager (PM) consists of KAERI PM who chairs the commissioning safety group, DAWEOO site PM, and JAEC reactor manager. The responsibility of this group is to provide strategic oversight & resources for commissioning, which includes: authorize the official start of commissioning & declare the acceptance of commissioning results, review the commissioning plan and monitor its implementation, follow the NCRs and the appropriate corrective actions, and coordinate between the commissioning groups. The group also plays vital role in providing resources and making lines of communication between all relevant groups and parties. For details on the functions and responsibilities, the reader may refer to Ref. [3].

Figure 1. JRTR commissioning organization structure



3. **Commissioning Experiments and Results.** Following the commissioning plan described in [3], the commissioning activities have been divided into several stages. Preloading commissioning, Stage A: consists of three main stages. This stage is also divided to three sub-stages: Stage A1, Construction Acceptance Tests (CAT), which consists of 5563 tests distributed over the mechanical, electrical and I&C tests [4]. Stage A2, Flushing and System Performance Tests (SPT), consists of flushing of 15 fluid systems and SPT for 43 systems [5], and finally Stage A3 [6] that consists of Integrated System Tests (IST). This latter A3 stage focuses on simulation of the reactor operation during power and training modes. These two modes have been tested using simulated reactor power signals. A loss of power scenario also was simulated in this stage A3.

   The hot commissioning experiments as presented in Ref. [7] start as soon as the process of Fuel Assembly (FA) loading on the core starts. Table 1 presents the major planned hot commissioning experiments. Some of these experiments belong to the fuel loading and low power tests (B1 and B2 stages). Other experiments have been planned for the power ascension and full power tests (C1 and C2 stage). The initial JRTR core constitutes of 18 FAs with various densities distributed around the core as shown in Figure 2.
   In this report summary results of the most important tests are presented.

Figure 2. Sketch diagram represents the JRTR core. Fuel Assemblies, in-core irradiation locations and control absorbing rods are illustrated.

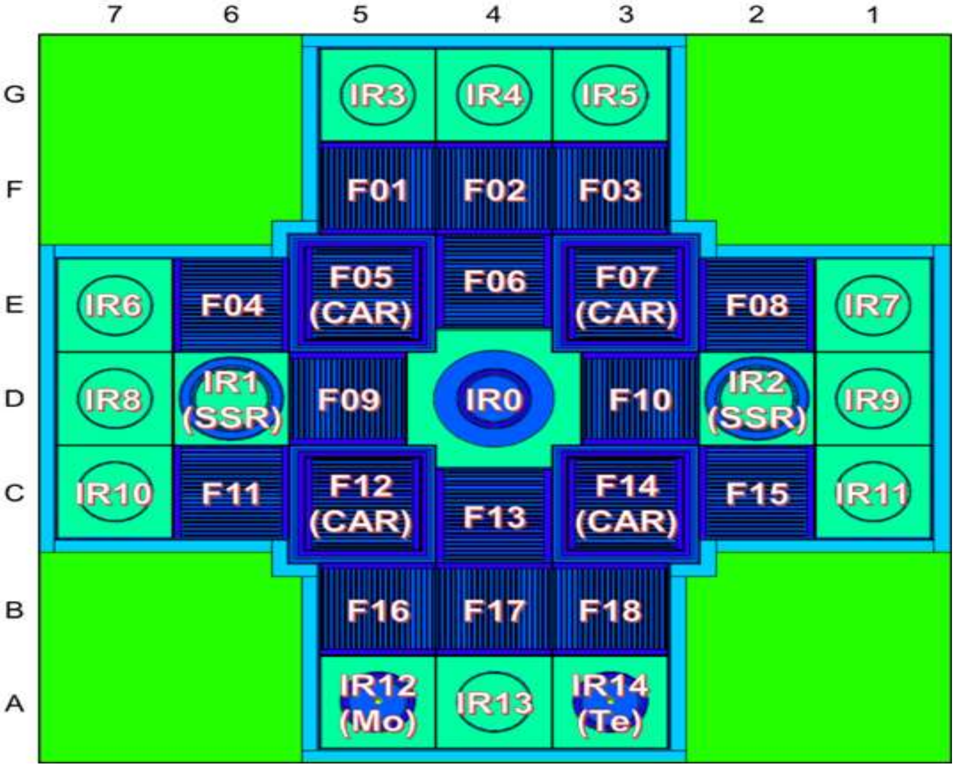


Table 1. Partial list of the JRTR hot commissioning tests and experiments

Test	Stage
Fuel loading and approach to criticality	B1
Excess reactivity measurement	B1
CAR/SSR rod worth measurement	B2
Measurement of kinetic parameters	B2
Measurement of void reactivity coefficient	B2
Measurement of flux distribution	B2
Measurement of isothermal temperature reactivity coefficient	B2
Training mode operation	B2
Natural circulation test	C1
Neutron power calibration	C1
Measurement of power reactivity coefficient	C2
Measurement of xenon reactivity	C2
Shutdown and monitoring capability of the SCR	C2
Cooling performance test of PCS and HWS heat exchangers	C2

Cooling tower capacity test	C2
Thermal neutron flux at IR0	C2
NAAF performance test	C2
RI production test	C2
Loss of primary flow test	C2
Loss of normal electric power test	C2
Radiation surveys to determine shielding effectiveness	C1,C2
I&C function tests during operation	C2

3.1 Fuel Loading and Approach to Criticality. The test aims at reaching the initial critical core using the 1/M (inverse multiplication) method by insertion of external neutron source in the subcritical core and replacing aluminum dummy fuel assemblies in the core with actual fuel assemblies one by one. For details on the process, the reader can refer to Ref. [8]. The initial critical core is the core having minimum number of fuel assemblies necessary for reaching criticality. This initial critical core will be expanded to the first cycle operation core by loading additional fuel assemblies at the next test "Excess measurement". The order of insertion of fuel assemblies in the initial core is presented in Table 2. The uranium density in each Fuel Assembly (FA) is also presented in the table. The test checks whether the initial criticality can be achieved at the initial critical core predicted by calculation.

The results of the test are shown in Figure 3 in which the count rate of the BF3 detector (counts per second) is presented as a function of time (second) for the CAR position at 570.1 mm for initial core of 14 fuel assemblies. The reactivity (ρ) is defined in connection with the effective neutron multiplication factor (k_{eff}):

$$\rho = \frac{(k_{eff} - 1)}{k_{eff}}$$

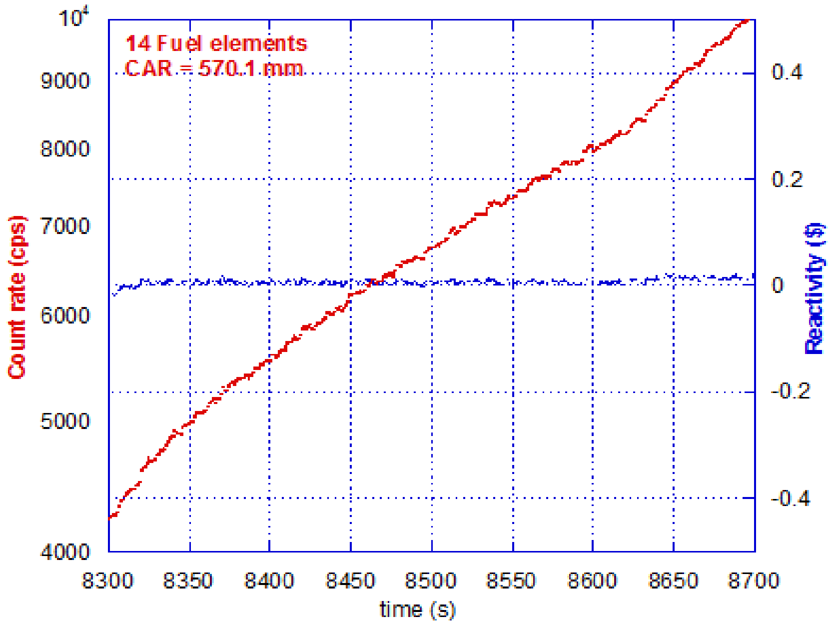
The reactivity must approach to zero for this critical situation. The reactivity ($) is also shown in the Figure 3. It is worth mentioning that the calculations predict the minimum critical core consists of 14 or 15 fuel assemblies and the critical CAR position is 575 mm. Therefore, it can be said that there is excellent agreement between the calculation and the measurement on the number of fuel assemblies and the CAR position for the initial critical core.

Table 2. Fuel assemblies including the uranium density (gm/cm^3) and order of insertion for the initial critical core

Fuel assembly	**Uranium density (g/cm3)**	**Order of insertion**
F07	2.6	1
F12	2.6	2
F14	2.6	3
F05	2.6	4

F13	1.9	5
F06	1.9	6
F10	1.9	7
F09	1.9	8
F02	4.8	9
F17	4.8	10
F03	4	11
F16	4	12
F01	4	13
F18	4	14

Figure 1. Count rate of the BF3 detector (cps) as a function of time (s) for the CAR position at 570.1 mm for initial core of 14 fuel assemblies. The reactivity ($) is also shown in the figure.



3.2 Measurement of Excess Reactivity.

The main objectives of the test are to measure the inserted reactivity to the first initial operational core by loading additional fuel assemblies from the minimum critical core [9]. In addition, this test confirms that the shutdown margin for the first cycle operational core satisfies the requirement.

The fuel assemblies are added to the minimum critical core one by one according to the predetermined fuel loading sequence until the core is fully loaded. Whenever a fuel assembly is added into the core, CARs are withdrawn step by step to approach criticality and 1/M is measured when all CARs are at the same height. The CAR worth is measured from the critical CAR position of the current core to the previous one, and hence the excess reactivity of the new core is determined. The results of this test are presented in Table 3.

Table 3. Measured CAR critical position and total worth by adding FA after reaching the initial criticality. The last column presents the percentage difference between the measured and the simulated CAR worth.

Additional FA, sequence	**Measured CAR position (mm)**	**Total CAR worth ($)**	**% Diff. from the calculated**
Critical core, 14	566.6	0.8958	16.09
FA15,1	454.8	2.4866	14.62
FA16,2	399.4	2.150	13.40
FA17,3	346.1	2.8473	13.09
FA18,4	311.5	2.167	11.85

3.3. Measurement of Power Reactivity Coefficient. The objectives of the test are to evaluate power coefficient of reactivity by measuring the reactivity variation in response to the reactor power change from zero to full power, and during the inverse case also [10].

When the reactor power is varied, the reactivity change in response is compensated by the change of critical CAR position. Therefore, the power defect can be determined by the reactivity change, which is measured from the change of critical CAR position. Among other factors, if the power is rapidly raised and then descended after a short time of operation at full power, the change of core temperature with fixed core inlet temperature is the major factor determining the power defect because the core temperature is directly affected by the change of the inlet temperature. To minimize the effect of other factors, the reactor power is raised from zero to full power, and during the reverse case also as fast as possible. The reactivity change in response to the reactor power variation can be measured by adjusting the inlet temperature [10].

The power reactivity coefficient is defined as the reactivity variation per unit power. For the JRTR case, it can be found from:

$$\frac{\partial \rho}{\partial P}\Delta P = (\rho - \rho_0) - \frac{\partial \rho}{\partial C}\Delta C - \frac{\partial \rho}{\partial X}\Delta X - \frac{\partial \rho}{\partial T}\Delta T$$

where: ρ, ρ0, P, C, X, T are reactivity, initial reactivity, power, CAR position, Xenon concentration, inlet coolant temperature, respectively.

Figure 4. Qualitative description of the measured power defect at selected power values during the indicated power values for the ascending and descending of power

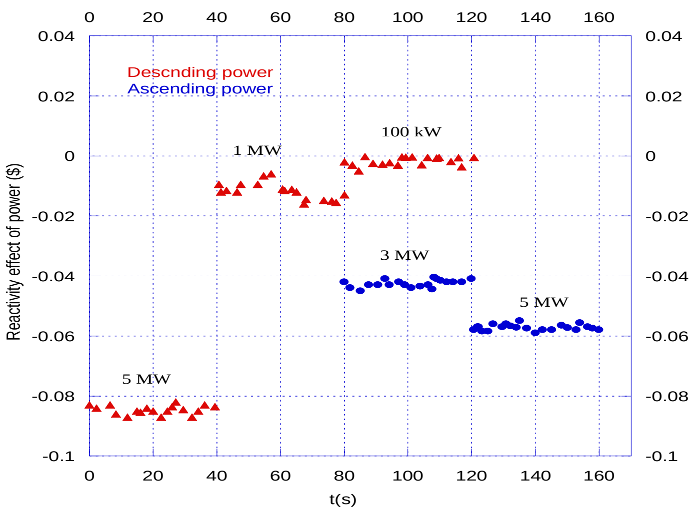


Figure 4 qualitatively shows the measured power defect at selected power values at the indicated power values during the ascending and descending of power. The 10 kW is the reference power defect at zero. These plots have been qualitatively constructed based on the experimental plots in graphs 6 and 7 in ref. [11]. As the figures indicate, power defects measured during power descent are larger than those of power ascension; the relatively rapid rise of core inlet temperature during the 5 MW operation can be one of the reasons [11]. The isothermal temperature effect from 31-34 ^{o}C is relatively large compared to the power defect. Therefore, the uncertainty in the compensation of core inlet temperature effect would be larger during the power descent. In addition, the power defect becomes larger as well at the higher core inlet temperature [11]. However, during this experiment, the measured power coefficients are confirmed negative for all power range.

3.4. Thermal Neutron Flux Measurement at IR0. This test is to measure the peak thermal neutron flux at the central irradiation location (IR0) of the JRTR core in order to verify the design criteria.

Thermal neutron flux is measured through the neutron activation of cobalt wire [12]. To perform the irradiation, the capsule that contains the Cobalt wires is inserted to the expected highest thermal flux position in the IR0 irradiation location. The wire is irradiated for around half an hour when the reactor is operated at the highest nominal power of 5 MW [9]. After the irradiation is completed, the reactor is shut down by cutting the electric power for the “Loss of normal electric power test” [13].

The irradiated rig is moved to the hot cell to cool off for around one day. The Cobalt wires are taken out of the capsules to measure the absolute induced gamma-ray radioactivity. The wires have been cut to smaller pieces in order to measure the activity of each piece separately.

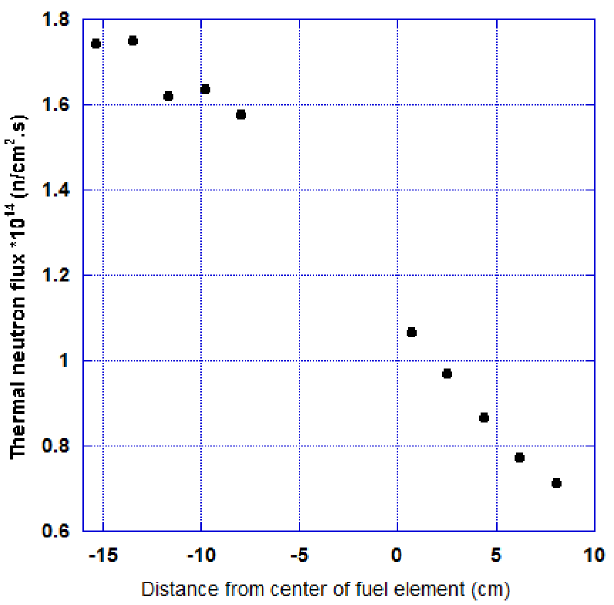
The number of activated nuclei (Co^{60}) N(ti) can be calculated from:

$$N(t_i) = e^{-\lambda t_i} \int_0^{t_i} R(t) e^{\lambda t} dt$$

where R(t) is the measured reaction rate, which is proportional to the reactor power.

For the determination of Co^{60} activity, the 1332.501 keV peak areas have been used. Figure 5 presents the measured thermal neutron flux as a function of distance from the center of fuel element. As it is evident, the measured flux at the center of the radioisotope production rig is ~1.72×10^{14} n/cm2.s, which is higher than the designed flux of 1.45×10^{14} n/cm2.s [12].

Figure 5. Measured thermal neutron flux (n/cm2.s) at the central irradiation location (IR0) as a function of distance from the center of fuel element.



3.5. Neutron Activation Analysis Facility (NAAF) Performance Test. The JRTR was designed as a multipurpose research reactor that can be used for elemental analysis using the neutron activation technique in addition to several other utilization aspects. The purpose of this NAAF performance test is to check the performance when the reactor is operating at full power. The test is to verify that the performance of the Pneumatic Transfer Systems (PTS) and to verify that the performance of the $\gamma-$spectrometer meet the design requirements. Also the test generates key data for the operation of the NAAF, and demonstrates that actual NAA can be carried out [14]. It should be noted that NAA1 location provides a high neutron flux with relatively hard spectrum. NAA2 and 3 locations provide well thermalized neutron spectrum with reasonable flux level for the NAA.

Appropriate weight of Standard Reference Material (SRM) samples have been irradiated for sufficient times in the NAA1, NAA2 and NAA3 locations. The analysis was carried using Ge-based spectroscopy system looking for short, medium and long-lived radioisotopes. The measurement results have been compared with certified/reference values.

The conclusion of this test can be summarized by all three PTS lines function as designed. The gamma spectrometry system also functions well. The JRTR Facility can be used for NAA in acceptable accuracy [14].

3.6. Radioisotope Production Test. The Purpose of this test is to check the performance of radioisotope production at the full power operation. This test verifies the maximum radioactivities of a target capsule for Ir^{192}, I^{131}, and Mo^{99} that can be produced at JRTR as proposed [15].

The Radioisotope production facility of the JRTR has been designed to be capable to produce more than 2000 Ci of Ir^{192} every two weeks, 10 Ci of I^{131} a week and 5 Ci of Mo^{99} a week when the reactor is operating in full power. The neutron activation was carried on Ir^{192} discs of 3 mm in diameter and 0.25 mm in thickness. For the production of I^{131}, TeO_2 with purity higher than 99.9% was irradiated, and for the production of Mo^{99}, MoO_3 targets were used. The details of material, preparation and irradiation procedures are presented in Ref. [16].

During the test, it was possible to produce more than 2716 Ci of Ir^{192}, 14.54 Ci of I^{131} and more than 8 Ci for Mo^{99}. The results of these tests demonstrate that the RI Facility works as designed

4. **Conclusions.** The JRTR commissioning plan included three main stages. The tests prior to fuel loading, fuel loading tests and initial criticality tests which include low power tests; and the last stage constitutes power ascension tests and power tests up to rated full power. All planned experiments have been conducted successfully. These experiments verified the design parameters of the reactor. Particularly, the nominal power, the reactivity feedback, the thermal neutron flux, the radioisotope production facility capability and the performance of the neutron activation analysis facility have been verified to function as designed. In some cases, like the thermal neutron flux peak, the radioisotope production capability has exceeded the design prediction. Therefore, the JRTR has been successfully commissioned and is ready to be utilized.

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5. **References:**

[1] Final Safety Analysis Report, Dec.-201

[2] Safety Guide No. NS-G-4.1, Commissioning of Research Reactors, IAEA, 2006

[3] JR-060-KA-443-001Commissioning-Plan-R9

[4] Summary of CAT Results Stage A1-201604012 and references therein

[5] Summary of SPT Results Stage A2-20160420 and references therein

[6] Summary of IST Results Stage A3-20160420 and references therein

[7] JR-066-KC-443-001Overall Plan for Reactor Performance

[8] JR-066-KC-443-003 R2 Fuel Loading and Approach to Criticality

[9] JR-066-KC-443-004 Excess Reactivity Measurement R3 and references therein

[10] JR-066-KC-443-013 Measurement of Power Reactivity Coefficient and references thein

[11] Summary of RPT Results (Commissioning Stage C2 for the JRTR)

[12] JR-066-KC-443-015 Thermal Neutron Flux Measurement at IR0_R1 and references therein

[13] JR-066-KS-443-002 Loss of Electric Power Test and references therein

[14] JR-066-KP-443-001 R0 NAAF Performance Test

[15] JR-066-KP-443-002 RI Production Test_Rev.2 and the references therein

[16] RA-RR-PRC-002 Target material pre-preparation and target capsule fabrication