Completion of Jordan Research and Training Reactor Construction Project

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Abstract. In June 2017, a consortium of the Korea Atomic Energy Research Institute (KAERI) and Daewoo E&C handed over the Jordan Research and Training Reactor (JRTR) to the Jordan Atomic Energy Commission, the owner and operator of the JRTR. This official hand-over took place at the end of almost a seven-year long endeavour since the project first launched in August 2010. This paper presents the chronology of the JRTR construction project along with focal points to which the Consortium paid special attention. For the chronology, we divided the whole period of project into three stages: a design stage, a stage of construction in a narrow sense including manufacturing and installation of equipment, and a commissioning stage. The design stage, from the launching of the project to the issuance of the Construction Permit (CP) in August 2013, was three years long. The Consortium focused on the design meeting international safety standards as well as the performance requirements. In practice as agreed upon with the owner, we primarily adopted the Korean regulations, codes, and standards, which conform to international standards including the IAEA guides and requirements. The construction stage, from CP until the start of the Construction Acceptance Tests in July 2015, took about two years. One of the focal points was the minimization of non-conformity to the design. Lastly, the commissioning stage took two years and two months: ten months for the non-nuclear commissioning until the fuel loading in April 2016, and another fourteen months for nuclear commissioning and fulfilment of the contractual obligations until the official hand-over. During the commissioning stage, the Consortium paid attention to not only confirming the completeness of the construction but also enhancing the operation capability of the Jordanian staff. KAERI is proud of the successful completion of the JRTR construction. Furthermore, it is continuing its collaboration with Jordan in the areas of operation and utilization of the JRTR, such as the RI production technique.

1. Overview of the Project

In March 2010, the Jordan Atomic Energy Commission (JAEC) and the Korean consortium, which consists of the Korea Atomic Energy Research Institute (KAERI) and DAEWOO E&C, concluded the EPC turnkey contract for a research and training reactor at the Jordan University of Science and Technology. After fulfillment of the prerequisites for the commencement, the clock started ticking in August 2010. The reactor to be constructed was named the Jordan Research and Training Reactor (JRTR), and the complex comprising all the facilities named the Jordan Center for Nuclear Research (JCNR).

The scope of supply is as follows:

- 5 MW research reactor, which is upgradable up to 10 MW,
- Radioisotope (RI) Production Facility (RIPF),
- Radioactive waste Treatment Facility (RTF) which was added to the scope later on,
- Training center, and
- Education and training of the Jordanian staff

The philosophy of defining the scope of supply is such that, at the taking-over, the JRTR will be operable by the Jordanian staff themselves, produce qualified RIs such as Mo-99, I-131 and Ir-192, and be maintainable for a while without additional supply of consumables.

TABLE I. Specification of JRTR.

Reactor Type	Open-Tank-in-Pool
Thermal Power (MW)	5
Max. Thermal Neutron Flux (n/cm^2s)	$1.5x10^{14}$ in the core $0.4x10^{14}$ in the reflector region
Fuel Type & Material	Plates type, 19.75% enriched U_3Si_2 in Al matrix
Coolant and Moderator	Light water
Cooling Method	Forced downward convection
Reflector	Be and heavy water
I&C system	Full digital
Utilization	Horizontal - 4 beam tubes (2 standard, 1 for n. radiography, and 1 for cold n.) - 1 thermal column Vertical - in the heavy water reflector region: 17 holes including 1 for CN, 3 for NAA, 3 for NTD, and holes for RI production, etc. - in the core region: 3 holes for RI production (2 of them are currently Be plugged) - in the Be reflector region: 12 holes for RI production (10 of them are currently Be plugged.)

It was supposed that the JAEC would install the instruments for the neutron beam application and a cold neutron source by itself later on. In addition, the JAEC had a plan to add a building for the research with cold neutrons and a fuel fabrication facility in the JCNR complex.

TABLE I shows a brief specification of the JRTR. Introducing detailed design is not the purpose of this paper and more information on the design could be found elsewhere.

FIG.1 shows a brief chronology of the JRTR construction, in which several key actual milestones are found. As shown, it took about 7 years from the commencement to the official

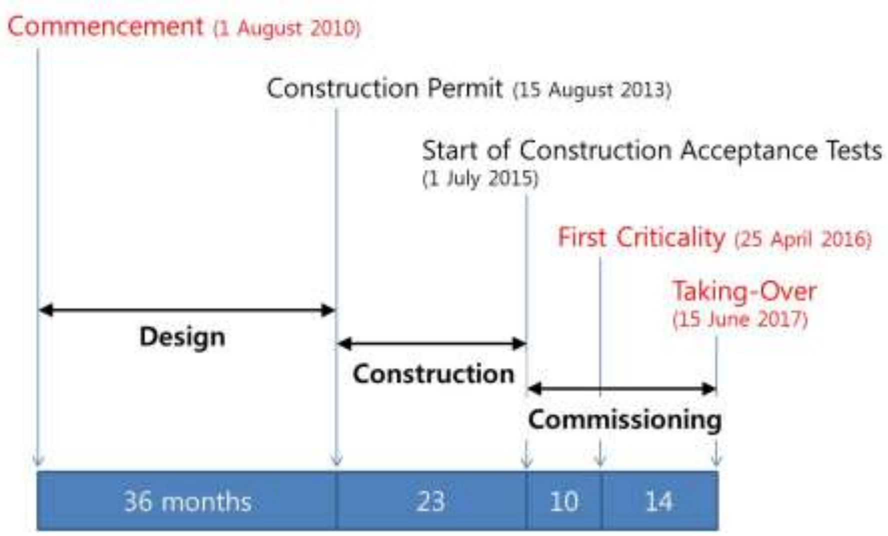

FIG. 1. Major milestones of the JRTR construction and stage division.

taking-over or hand-over, which was about six months longer than the planned period of six years plus a grace period of six months. We schematically divided the whole period of the construction into three stages: a design stage, a stage of construction in a narrow sense, and a commissioning stage. The design stage refers roughly to a stage for the system design and architecture engineering. The component design of most equipment continued during the construction stage. Contrarily however, manufacturing of some long lead items such as the reactor structure assembly and nuclear fuels started during the design stage. Activities during the construction stage included not only construction of buildings and structures but also manufacturing and installation of equipment. The first part of the commissioning stage is the so-called cold commissioning which corresponds to the 'Stage A' commissioning in the IAEA's terminology [1]. It started with the Construction Acceptance Tests (CATs) followed by the System Performance Tests (SPTs) and Integrated System Tests (ISTs) later on. It took about ten months. The later part of the commissioning is the so-called nuclear commissioning, which corresponds to the Stages B and C commissioning in the Agency's terminology. It started with the fuel loading and covered the Reactor Performance Tests (RPTs). Technically, we finished all the RPTs by the end of November 2016; however, we needed another seven months for the owner's inspection, further works agreed with the owner later, and fulfilment of the contractual obligations.

In addition to the JAEC and the KAERI-Daewoo Consortium (KDC) as the contractual parties, many other entities were involved in the JRTR project. FIG. 2 shows those entities. The JAEC is the owner and operator of the JRTR so that it is the licensee and eventually responsible for the safety of the JRTR. It had supports from the IAEA as well as its own consultant, a consortium of French and Jordanian companies. The KDC is the supplier. In the KDC, KAERI was the representative of the KDC and carried out the design of major systems such as the reactor core, fluidic systems connected to the reactor and the I&C system. It was also responsible for the education and training of the Jordanian staff. As an experienced constructor of nuclear power plants, Daewoo was responsible for the EPC as a whole and ran the project. The Energy and Minerals Regulatory Commission (EMRC; former Jordan Nuclear Regulatory Commission) is the nuclear regulatory authority. It had a special agreement with the Korea Institute of Nuclear Safety (KINS), which is one of the technical support organizations (TSOs) of the Nuclear Safety and Security Commission (NSSC) of Korea. The KINS played a role of the co-inspection and co-review of the safety together with

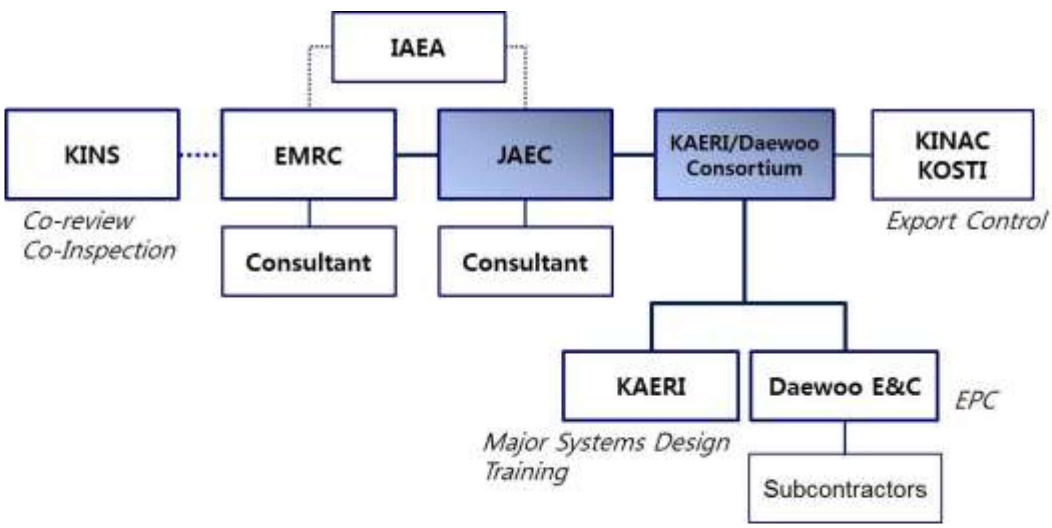

FIG. 2. Entities involved in the JRTR project.

the EMRC. The EMRC also had supports from the IAEA and its own consultant, an American company. The IAEA, mainly the Research Reactor Safety Section, supported both, but separately the EMRC and the JAEC through Technical Cooperation programs. On the other hand, two Korean governmental organizations were involved for the export control - the Korea Institute of Nuclear Nonproliferation and Control (KINAC) for the nuclear materials and the Korea Strategic Trade Institute (KOSTI) for the dual-purpose materials. The KINAC is one of the TSOs of the NSSC. In short, the involved entities were multi-national rather than bi-national, so that a harmonization of their different bases of knowledge and experiences was important.

2. Design Stage

This section describes the focal points that the KDC paid special attention during the design stage. The goal was to develop a design that would meet all the safety requirements as well as the performance requirements. Of particular, the JRTR was supposed to meet international safety standards including IAEA's.

Upon the request of the owner, adopted were two documents as the basis of the safety requirements: the IAEA's NS-R-4 [2][1] and US NRC's NUREG 1537 [3][2]. The contents of the Korean guidelines for the safety review of research reactors were based on the US's NUREG 1537. Therefore, there was no essential difficulty in applying the Korean regulatory practice for the JRTR safety review. Applying Korean codes and standards was one of the contract philosophies. On the other hand, the licensing scheme was a two-step scheme consisting of the Construction Permit (CP) and Operating License (OL) upon the request of Jordan side. From time to time, however, the EMRC issued temporal permits, sort of, such as a Limited Work Authorization for excavation of the site before the CP issued. This practice helped the work progress, but the supplier should take the risk if something went wrong; for instance, if the excavated site turns out to be inappropriate, the supplier must restore the site at its own cost.

The design verification and validation was one of the key issues during the design stage. In addition to the V&V of computer codes for the neutronics and core thermal-hydraulic calculations, we carried out several experiments for the validation of design or design methodology. Examples are the critical heat flux measurement for the plate-type fuel in the range of JRTR flow condition and a series of siphon breaker experiment. Some details of these experiments could be found elsewhere.

The other serious issue was the adequacy of the classification of structures, systems and components (SSCs). We had three kinds of classification - safety class, quality class, and seismic category – and the other classes for electric and I&C systems. Adopted was the ANSI/ANS-51.1 [5] for identifying the safety class, however, we needed to accommodate different ideas from different people, particularly, after the Fukushima accident. Note that the classification of SSCs has been one of the most controversial issues among experts invited by the IAEA; the IAEA guide SSG-30 [6] needed discussions for more than 6 years until the final publication in 2014.

[1] It was superseded by SSR-3 in 2016.
[2] It is worth noting that the JRTR safety analysis reports adopted the format of the IAEA's SSG-20 [4].

The Fukushima accident influenced not only the classification, but it resulted in additional systems such as the automatic seismic trip system instead of the seismic monitoring system in the original design and the air discharge system for extra ventilation and monitoring a contamination of air in case of an accident.

Regarding the performance, a capability of power upgrade was one of the most important issues. The bottom line was such that current 5 MW design should not need any modification of structures for future upgrade of the power level up to 10 MW. In order to meet this requirement, we designed structures assuming a 10 MW reactor. An example is the radiation shielding structure that was designed with the source term of a 10 MW reactor. Another example is the reactor core. It reserves extra space, currently filled with beryllium blocks. The dimension of each block is same to that of a fuel assembly so that additional fuels can replace the blocks if necessary. Concerning systems, a decay tank and pipes of cooling systems are the other examples not replaceable. However, the owner is supposed to replace relatively light equipment such as pumps and heat exchangers when upgrade is needed.

In the meantime, manufacturing of long lead items was one of the works started during the design stage. The items were fuel assemblies, a reactor assembly consisting of a heavy water vessel, reactor internals, the control rod driving mechanisms (CRDMs), etc., and digital I&C systems. We paid a special attention to the tests of CRDMs. For the tests such as endurance tests and drop tests, we manufactured exactly same CRDMs to those to be installed in the JRTR and carried out the tests in a test facility newly built in the same factory.

3. Construction Stage

As soon as granting the CP by the regulatory body, the Daewoo E&C reformulated a site organization for a successful enforcement of installation and construction work with a shadowing supporting group of JAEC. It was also responsible for the coordination of all activities on the site including those of the JAEC, the regulatory body, project contractors and others. KAERI took a role of the technical advisor on the special field works that were important to safety or related to the licensing such as the reactor structure assembly and the man-machine interface system.

The construction stage is usually the longest and most cost-intensive parts of a nuclear project. A well-conceived and executed program could have the potential to make significant reductions in schedule, cost and risk. The construction and installation works generally include some detailed engineering and procurement works in line. A close partnership with the JAEC was essential for the preparation of the Operating License and commissioning activities, and both parties achieved it. The Consortium also operated a well-staffed site office from the very beginning of the construction period to the time of project completion in order to manage all the site-oriented works mentioned above. According to the project man-power input plan that was based on the baseline project schedule, a lot of engineers and project staff, subcontractors, and local labors were mobilized for the site works. About 50 high-quality engineers and 500 workers were staying at the site during the construction period. The headquarters of KAERI and Daewoo dispatched the most of key engineers and supervisors per the work schedule.

The Consortium focused on 1) planning and preparation, 2) coordinating and integrating, and 3) overseeing at and inspecting the construction management activities. The construction works were composed of the following packages:

- 'Architecture' for major building and related structures,
- 'Civil' for excavation/backfill and yard/underground works,
- 'Mechanical' for mechanical, process equipment, HVAC, and so on,
- 'Piping' for piping works and insulation, and
- 'Electrical and I&C' for electrical and I&C equipment, cable trays/supports, etc.

The construction stage started with the excavation and pouring lean concrete[3] and installation of the base mat, which took about 6 months. Soon after, as a critical path, the reactor building structure works and mechanical works followed as of the following sequences:

- External structure work of reactor building to overhead crane line,
- Internal structure work to reactor building operating floor,
- Installation and test of the overhead crane,
- Reactor structure and mechanical/electrical work and tests,
- Installation of the main control room in the auxiliary building and the MMI, and
- Preparation of Construction Acceptance Tests (CATs) for the commissioning.

As a critical turning point of the project, the initial energizing from the Jordanian electricity grid was done on 29th June 2015 after about two years since getting the CP. The supply of the permanent electricity enabled the component-based CAT as a part of the cold function test in parallel with the remaining finishing work of the construction. The installation of the reactor structure assembly was the most important step of the JRTR project. It commenced in September 2015 and completed in three months. Under the witness by the regulatory body, the Consortium finished mechanical alignments and performance demonstration successfully.

During the construction, the risk management would give effects on the cost, schedule and even quality and safety. In this respect, the Consortium's ground rule was to execute the construction works with no accidents, no harm to people and no damage to existing facilities and environment. In order to cope with the objectives, the Consortium set up an efficient and effective project execution and Human-Safety-Environment procedures with a strict quality assurance program in compliance with all applicable laws, rules, guidelines, standards and any other requirements specified by the owner. All the efforts made by the Consortium came to the remarkable success; no accident was recorded through about 4.8 million man-hours achieved by the end of 2016.

On the other hand, fostering of Jordanian operators was the other important work during this timeframe because they were supposed to operate the reactor by themselves from the commissioning stage, not after the taking-over. JAEC dispatched more than 20 young Jordanians to KAERI in 2014-2015 in order to make them to understand the design and operation. Ahead of the training of potential operators, more than 10 young Jordanians had studied in two-year-long, nuclear engineering Master courses in Korea through the JRTR education program. In addition to Master degree holders, those trained and passed the qualifying tests became a part of the major force of the JRTR operation.

[3] Actually it took place under the Limited Work Authorization, ahead of the CP.

4. Commissioning Stage

The goal of the commissioning is to demonstrate that SSCs have been correctly installed and they are safe and ready to operate. The JRTR took a staged approach for the commissioning works in order to minimize the risks associated with bringing a new facility into operation in accordance with the IAEA standard guide, NS-G-4.1 [1]. We categorized the commissioning stages into the non-nuclear tests to be carried out before the fuel loading and the nuclear tests at and after the fuel loading. While the 'Stage A' for the non-nuclear tests included three different sub-stages based on their sequences and the nature of work, the nuclear tests were divided into the 'Stage B' for fuel loading and low power tests and the 'Stage C' for power ascension and full power tests. Each stage could have proceeded in sequence only if the previous stage had been successfully completed as per the design requirements specified in the Final Safety Analysis Report.

The commissioning organization, as an integrated structure, composed of the JAEC operators, KDC engineers and the sub-contractors. As shown in FIG. 3, the JRTR commissioning organization consisted of a number of groups and teams in order to manage and supervise all of the commissioning activities. A safety committee was independent from others, and it is continuing the role thereafter. The commissioning organization should make provisions for the participation of future operating personnel so that they are knowledgeable about the facility. Many personnel from the design, construction, manufacturing, QA, JAEC, regulatory body, and other pertinent organizations, participated in the commissioning activities and they collaborated as appropriate. Note that the JAEC had established the reactor operation group and supporting teams for security, radiation protection and emergency planning for a seamless transfer to the complete operating organization. At the beginning of the project, the Jordanians were supposed to operate the reactor during the commissioning, nevertheless, KDC's supervision was indispensable and, in fact, the KDC was the party who conducted the commissioning.

The Consortium had developed in advance and implemented the process for the preparation, approval and management of lots of commissioning documents including commissioning plan and schedule, commissioning administrative procedures, commissioning procedures, etc.

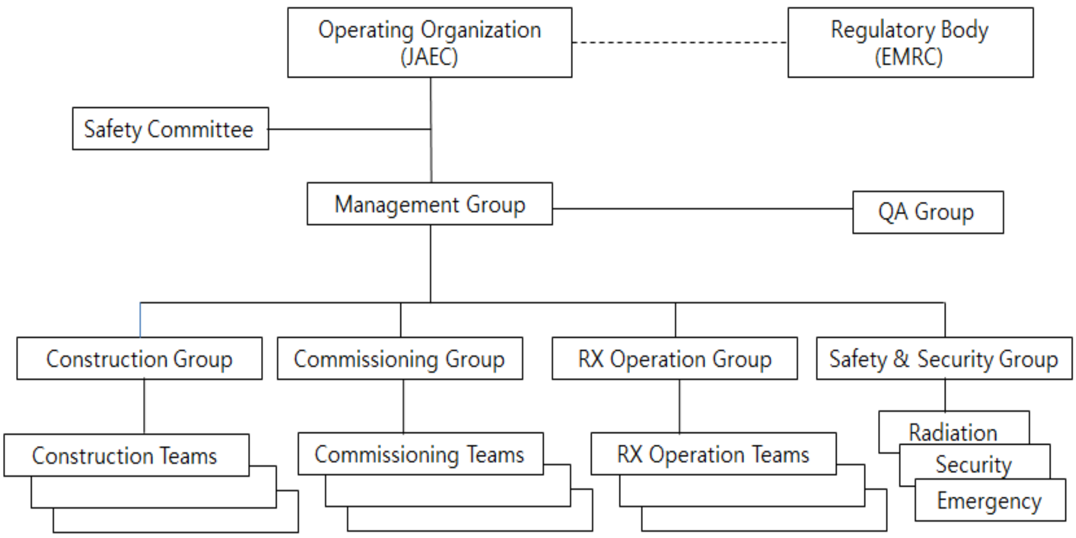

FIG. 3. JRTR commissioning organization.

KDC maintained a live index of all the commissioning documents through the whole course of the commissioning program. It also retained test reports including detailed data taken from the commissioning tests as records, then transferred them to the JAEC for their reference in the future operation.

With the completion of the CATs of the MMIS and main control room facilities, we finished all the construction and installation works by the end of 2015, and then carried out the System Performance Tests (SPTs) for full-dress commissioning. By early 2016, we completed about 46 SPT items and then three Integrated System Tests (ISTs).

As soon as ISTs finished, we started fuel loading on 23rd April 2016. The JRTR historically reached its first criticality on PM 09:05, 25th April 2016. At the very first criticality, the actual control rod position indicated an excellent match with the prediction in +/- 1% of accuracy. A series of zero power and neutronic performance tests continued until the start of power ascension tests. The tests included the measurement of excess reactivity, rod worth, kinetic parameters, void coefficient and flux distribution. The power ascension and full power performance tests of the Stage C commenced at the middle of September 2016, after a precise neutron detector calibration based on the actual thermal power. The JRTR finally came to its rated power of 5 MW on AM 09:55, 15th September 2016. Followed measurements of the reactivity coefficients proved a negative power coefficient, as it should be as one of the contractual safety requirements.

After the full power performance tests such as the I&C function test at power operation, natural circulation, and so on, we checked and proved the performance of the Neutron Activation Analysis (NAA) Facility and RI Production Facility. Those were the last items at the Stage C. As mentioned earlier, a practical capability of NAA and RI production at the hand-over of the JRTR was the one that KDC had guaranteed.

Meanwhile, the Jordanian capability of operation was one of the focal points to which the KDC paid attention. Even though the Consortium had successfully completed the commissioning tests, the Consortium and the owner agreed to re-do the most of Stages B and C tests for six months. The purposes of the tests, called the Initial Operation Test (IOT), were re-confirming the results of the commissioning tests and providing Jordanian operators with an intensive on-the-job training through the operation by themselves in a real world. They completed the IOTs in October 2017 as planned and resulted in fruitful outcomes including satisfying the regulatory body’s requirement on the qualification of the operators.

5. Collaboration after Hand-Over

After the completion of the commissioning tests including the IOTs, JAEC and KAERI tried to find out the best way of how to build up the preparedness for a stable operation and full utilization of the JRTR. As one of the actions, both parties have made an agreement in October 2017 on further technical cooperation between Korea and Jordan. The general purpose of the agreement is to strengthen the technical cooperation for a safe, confident and effective operation of a research reactor as well as a full utilization. Primary areas of interest include the radioisotope production, material irradiation and neutron science. In addition, the cooperation topics are extended to the in-core fuel management, emergency planning and response, radiological protection, maintenance and aging management.

Technical meetings to be organized are going to deal with all the cooperation topics. The other ways of cooperation are an exchange of experts, organizing some joint symposia or workshops in order to share the experiences of operation and maintenance of a research reactor facility. This concept of the cooperation will be further developed towards two sister centres, the JCNR and HANARO, both in name and reality.

6. Remarks

FIG. 4 shows the JRTR at the end of the commissioning stage. It visually testifies to the successful completion of the project, of which the Korean consortium is very proud. It is also worth mentioning that the open-minded cooperation of the JAEC has been one of the indispensable elements for the success.

We would say that a slogan, 'Supply on time, Support forever,' implies something more than just a construction of a research reactor facility. It is much beyond a commercial contract.

7. References

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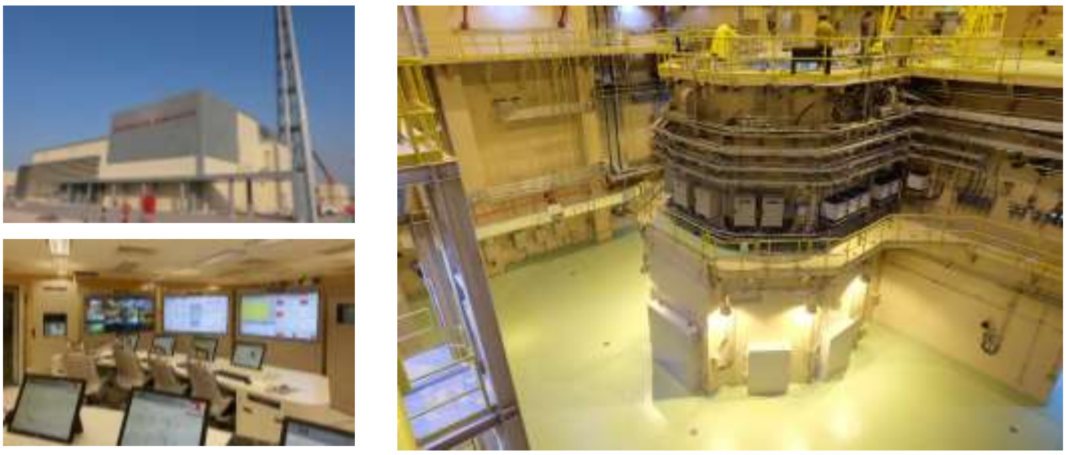

FIG. 4. View of reactor building, main control room and reactor hall of JRTR.