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Joint Assessment of ETRR-2 Research Reactor Operations Program, Capabilities, and Facilities

M. Bissani, D. S. O'Kelly

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JOINT ASSESSMENT OF ETRR-2 RESEARCH REACTOR OPERATIONS PROGRAM, CAPABILITIES, AND FACILITIES

U.S. DEPARTMENT OF ENERGY
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1.0 Summary

A joint assessment meeting was conducted at the Egyptian Atomic Energy Agency (EAEA) followed by a tour of Egyptian Second Research Reactor (ETRR-2) on March 22 and 23, 2006. The purpose of the visit was to evaluate the capabilities of the new research reactor and its operations under Action Sheet 4 between the U.S. DOE and the EAEA, "Research Reactor Operation," and Action Sheet 6, "Technical assistance in The Production of Radioisotopes." In particular, this assessment reports Task A of Action Sheet 4, *Joint Assessment and Evaluation of Research Reactor Operations Program According to EAEA Requirements* and Task A of Action Sheet 6, *Joint Assessment of Reactor Capabilities and Facilities According to EAEA Requirements*.

Preliminary Recommendations of the joint assessment are as follows:

1. ETRR-2 utilization should be increased by encouraging frequent and sustained operations. This can be accomplished in part by
    a. Improving the supply-chain management for fresh reactor fuel and alleviating the perception that the existing fuel inventory should be conserved due to unreliable fuel supply; and
    b. Promulgating a policy for sample irradiation priority that encourages the use of the reactor and does not leave the decision of when to operate entirely at the discretion of reactor operations staff.

2. Each experimental facility in operation or built for a single purpose should be reevaluated to focus on those that most meet the goals of the EAEA strategic business plan. Temporary or long-term elimination of some experimental programs might be necessary to provide more focused utilization. There may be instances of emerging reactor applications for which no experimental facility is yet designed or envisioned. In some cases, an experimental facility may have a more beneficial use than the purpose for which it was originally designed. For example,
    a. An effective Boron Neutron Capture Therapy (BNCT) program requires nearby high quality medical facilities. These facilities are not available and are unlikely to be constructed near the Inshas site. Further, the BNCT facility is not correctly designed for advanced research and therapy programs using epithermal neutrons.
    b. The ETRR-2 is frequently operated to provide color-enhanced gemstones but is operated infrequently for radioisotope production. Because the two irradiation programs compete by utilizing the same core locations, the issues should be resolved at a high level.
    c. Cobalt-60 production uses the most valuable irradiation location in the ETRR-2 (the high neutron density flux-trap), but there seems to be no potential customer for the Co-60. Further, the low number

of hours the reactor is operated per week precludes ever producing a marketable specific activity of Co-60. Accordingly, Co-60 production should be reevaluated.

d. ETRR-2 staff would benefit from additional training to successfully design new experiment facilities and utilize existing facilities more effectively. This training can include IAEA Fellowships, as well as topical DOE Sister Laboratory visits to gain experience using equipment and research tools at other research reactor facilities.

2.0 Facility Description

The Egypt Second Research Reactor (ETRR-2), also called the MultiPurpose Reactor (MPR), is located at the Inshas Nuclear Center of the Egypt Atomic Energy Authority about 60 km from Cairo. It is a 22 MW, light water moderated and cooled, open-pool reactor designed and manufactured by INVAP, a company in Argentina. The reactor is designed to be used in a wide variety of fields including neutron physics, materials science, and boron capture therapy. The facility was constructed and commissioned through the 1990's with initial criticality on November 27, 1997. Full power (22 MW) operations occurred on March 11, 1998. The reactor was not fully accepted by the EAEA until 2002 due to necessary correction of facility deficiencies.

3.0 Research and Industrial Capabilities of the ETRR-2

The ETRR-2 facility seems to incorporate many lessons learned from previous research reactor designs and utilization programs. INVAP and EAEA had clearly evaluated and envisioned the potential usage of the facility based on experience and several international studies concerning the use of medium flux ($\sim 10^{14}$ nv) reactors. However, it must be emphasized that active research reactor programs in the late 1980s (at the time the majority of the ETRR-2 facility was designed) may no longer represent cutting-edge nuclear analytical research or programs with high growth potential. The key aspect of the ETRR-2 design is its flexibility and potential for modification as new uses for research reactors are realized.

3.1 Silicon Transmutation Facility

Two silicon ingot irradiators have been designed and installed in the reactor thermal column. The purpose is to produce transmutation doped silicon via the (n,γ) reaction with subsequent decay of the activated silicon to phosphorous for homogeneous doping. To avoid contamination of the silicon ingot with higher energy neutron reactions it is desirable to minimize the fast (higher energy) neutron flux. Hence, the NTD facility is located in the neutron thermalizing, graphite column. Each NTD facility will accommodate a 5 inch diameter silicon ingot and slowly turns the ingots while the reactor is operating to produce evenly doped ingots. ETRR-2 reactor operations staff believe they could modify the existing system to accommodate ingots that are 6 inch in diameter. The semiconductor industry has gradually gone to larger ingots (as much as 300 mm) but there may be a physical limit of the NTD silicon ingot because of neutron self-shielding absorption and the original size of the NTD irradiation facility. Because the production of larger diameter wafers (with acceptable spreads in resistivity) could represent a significant market, the ultimate upper diameter limit of NTD silicon should be evaluated by modeling or experiment. The two irradiation areas could be replaced by a single, large-diameter NTD irradiation facility if the self-shielding is acceptable.

The NTD facility provides irradiated-doped silicon ingots that may be fully processed at the ETRR-2 facility. A designated individual is responsible for the quality assurance and production of the doped wafers. The processing includes ultrasonic cleaning, cutting into individual wafers, testing for the resistivity, measuring doping homogeneity of the wafers and packaging for shipment. All the apparent necessary equipment is available for use, however, no market has been identified for the wafers and there is no current customer.

Recommendation: Immediately begin commercialization of the doping service and product for customers and markets. The NTD irradiation and processing facility represents a significant and under-utilized investment that can be marketed aggressively. A formal evaluation for the potential to irradiate larger-diameter wafers with acceptable dopant gradients should be undertaken.

3.2 Radiation Color Enhancement of Gemstones

The ETRR-2 reactor seems to operate primarily to irradiate topaz for a European customer. This is done because it generally fills all available irradiation locations in the reactor (apparent maximum utilization). In the process, the reactor operators have control of the final product and determine when the reactor will be run. The commercial user requires the operation of the reactor for up to 12 hours a day at full power once a week. It would seem that topaz irradiation should have remuneration, but the facility has yet to ship large quantities of stones to the customer for billing. Many U.S. reactors are no longer involved in the irradiation of topaz because of the liability and legal difficulties.

Gemstone irradiation is a technique where a raw, variable-impurity target material (a natural stone) is irradiated to a high fluence in a nuclear reactor, thus producing relatively high radioactivity. The stones are allowed to decay but the trace impurity radioisotopes may remain significant for weeks or months. Each gemstone must be evaluated for radioactivity before release to the customer, making the post-irradiation processing potentially time consuming. ETRR-2 plans to develop an automatic counting system to evaluate the radiation levels of each stone before shipment. The design of this counting system could be funded entirely by the user because the investment would enable relatively rapid return of the stones to the customer. This funding could be a single, one-time payment based on estimated costs or a surcharge per stone shipment, eventually paying for the original counting system installation and long-term maintenance.

This evaluator was involved in large-scale topaz irradiation and processing for several years in the early 1990s. Gemstone irradiation can be a relatively simple source of additional revenue. However, it does not promote broad reactor utilization and is likely discouraging use if all reactor locations are monopolized by gemstones during operations.

Recommendation: ETRR-2 management should reevaluate the gemstone irradiation program and determine if the reactor has become essentially a single-use facility. Correspondingly, EAEA management should determine if local (Egypt) researchers or customers take precedence over external users when reactor operations are scheduled.

3.3 Cobalt Irradiation

A designed use of the ETRR-2 reactor facility is the production of Cobalt-60 for medical or industrial gamma irradiators. A single loading of cobalt target material is currently in the high flux area (flux-trap) of the reactor (2E14 nv). Unfortunately, there is no apparent customer for the Co-60 currently in production. The EAEA has a separate Cobalt-60 irradiator facility with high use (samples are staged with a backlog of materials for the sterilization of food and other materials) but this was purchased directly from INVAP very recently. To produce useful quantities of Co-60 over a reasonable period the reactor would have to operate perhaps 24 hours a day for 5 to 7 days a week. Long periods of reactor operation are not currently performed at the reactor facility due to fuel availability concerns and staff overtime issues. With no potential use for the Co-60 in production, the conclusion is that a valuable irradiation position is unavailable for more marketable products or services such as medical-isotopes or materials irradiations. Irradiation of a long-lived material with no end-customer or expected use represents the direct production of radioactive waste.

Recommendation: EAEA management should determine if there is a customer (even internally) for the Co-60 in production. A price per Becquerel should be determined and compared to market price to assess if the production of Co-60 by ETRR-2 is profitable or if production costs are partially recovered. Management should then reconsider the best use of the flux-trap.

3.4 Medical Radioisotope Production

The production of medical isotopes is a primary strategic focus for the ETRR-2 and the EAEA. The domestic production of isotopes for medical therapy and diagnostics would provide a steady, if not increasing, income as well as the very real benefit of positive public and government perception of the nuclear reactor facility. The potential local market for medical isotopes was discussed in a meeting with nuclear medical professionals on March 21. There is clearly interest in Cairo and in Egypt for the local production and sale of radioisotopes, but the EAEA has not become a source of materials primarily due to reliability issues. The staff and management of the ETRR-2 have not developed an internal "Service Culture" necessary to instill confidence for outside users that their needs will be met in terms of cost and schedule.

Two hot cells are currently used for the production of medical isotopes: one cell for Iodine-131 and the other for Molybdenum-99 (Tc-99m) processing. Additional space is available to install new hot cells, and these should be considered to develop new isotope production lines (e.g., P-32, Cr-51).

Currently, the reactor is not operated for one or two samples in a few locations because of perceived excessive uranium fuel burnup. This is counter-productive because the reactor is best run frequently for small-scale production until processes are error-free and customer supply chains are well developed. Large-scale production and distribution of short-lived medical radioisotopes will require significantly more experience by the ETRR-2 staff in routine isotope production. Increased production will require that the reactor operate for small batch samples and perform extended irradiation for the efficient production of high-specific activity radioisotopes. In order to achieve the strategic goal of high facility utilization, EAEA management will need to fully support the reliable and extended operation of the reactor for the production of medical and commercial radioisotopes.

Recommendation: Management should oversee the development of a customer oriented Service Culture program for the reactor operations and radiochemistry departments together. Frequent (once a week initially) meetings should be planned and led by a member of EAEA management to determine if the needs of the customers are being met. A managerial focus should be on the goal of operating the reactor at least 50 hours a week within 6 months for radioisotope production.

3.5 Neutron Beamport Areas

The ETRR-2 has been designed with 5 neutron beam tubes that provide reactor radiation for experiments external to the biological shield. There are two tangential beams and 3 horizontal beams.

3.6 Neutron Radiography

The neutron radiography system on a radial neutron tube is adequate but fairly unsophisticated. The current system uses film and neutron-gamma converter (Indium foil) which, although reliable and has good resolution, must be processed in a darkroom after each exposure. Future plans are to install a digital or real-time neutron radiography camera, but adequate training on the design and use of the facility must be provided. Experience with digital processing of captured images is essential if the ETRR-2 is to eventually install and operate a neutron tomography system on another beam port system (a current plan).

Recommendation: A member of the ETRR-2 staff responsible for the neutron radiography system should obtain training in state-of-the-art technology specifically for digital neutron tomography

3.7 Boron Neutron Capture Therapy Facility

A shielded room has been installed at the end of the graphite thermal column at ETRR-2. The room was designed from the beginning to be used for Boron Neutron Capture Therapy (BNCT) cancer treatment. In BNCT, the patient is given a boron-loaded drug, which will preferentially concentrate in (usually) a tumor in the patient. The patient is then exposed to a neutron beam, and the thermal (slow) neutrons are absorbed in the boron. Upon absorption of a thermal neutron, the Boron-10 isotope will disintegrate into an alpha particle and a lithium ion. The high kinetic energy of the particles and the highly positive charge produces high biological damage in the near vicinity (a few cell diameters) of the original boron atom.

Research and use of thermal neutrons in BNCT has been generally replaced by epithermal (energies between fast and thermal) neutron irradiation. Epithermal BNCT was devised to use the patient's tissue as the neutron slowing down medium. It has been determined that a large percentage of a thermal neutron beam is captured too soon for effective deep tumor treatment (a few centimeters). The epithermal neutrons are slowed to thermal energies as they passed through the patient and (if correctly performed) would reach thermal energies at the approximate location of the tumor. Some thermal neutron BNCT research is still performed, but the weakness of the method makes it unlikely to become a standard therapeutic treatment.

One method to increase the available neutron energies utilizing a thermal column is to install a Fission Converter. A Fission Converter is a large single plate or several plates of uranium clad in stainless steel or aluminum and placed at the end of the thermal column in the region of high thermal neutron flux. The thermal neutrons are absorbed in the uranium and fission, multiplying the available neutron flux and increasing the average energy of the neutron field. The average energy of neutrons produced from fission is 2 MeV so there is a possibility of filtering the thermal neutrons while allowing the higher energy neutrons to pass through to the patient.

Even if the ETRR-2 neutron beam could be filtered or the graphite thermal column replaced (to produce a higher average energy neutron beam), the large distance of the ETRR-2 facility from any medical center or hospital makes it unlikely that research will occur in this area in the near future.

The facility could be better utilized for large area irradiations. One such use would be neutron auto-radiography of paintings or other large flat objects. In auto-radiography the object is irradiated and then placed directly onto radiography film. The decay radiations from the object produce exposures in the film. Concentration of materials or changes in composition may be deduced from the developed film.

Recommendation: ETRR-2 should conduct a large-scale literature search of current progress and research in the use of neutron capture therapy. A survey of potential research hospitals in the Cairo area should be completed to evaluate if there is significant interest in the development of a neutron capture therapy research and treatment program in Egypt. EAEA should then determine if the development and use of resources in the completion of the BNCT facility will bring a significant return on the investment.

3.8 Other Potential Neutron Beam Uses

The remaining beam ports have not been developed, but current strategic plans suggest they might be used for a neutron tomography system and a cold-neutron source. The cold source would be installed on a tangential beam port, but the location does not provide a long flight path. This negates the reasoning for a cold neutron beam (bending of neutron beam to low background area) and thus makes it unnecessary to install a cold source until significant building remodeling is accomplished.

Recommendation: ETRR-2 staff should evaluate current international research programs that utilize neutron beams and attempt to develop facilities that represent the next generation of neutron beam experiments. Neutron scattering (small angle and powder) for materials analysis requires a neutron beam of high intensity that could be available from the 22 MW ETRR-2 reactor. The development of a Prompt Gamma Activation Analysis system with or without a cold-neutron source will expand the analytical capabilities of the facility.

3.9 Pneumatic Systems and Instrumental Neutron Activation Analysis (INAA)

The ETRR-2 facility has two fast pneumatic systems that can be used for short-lived INAA. The pneumatic terminus can be installed near the reactor or in the reflector for epithermal or thermal neutron activation. Samples produced are counted on one of two 100% efficient HpGe gamma spectroscopy systems. This program is relatively active with respect to other INAA laboratories around the world.

3.10 Materials Testing Hot Cell

A shielded hot cell is positioned near the auxiliary storage pool such that irradiated samples can be moved directly from the pool into the hot cell. This facility has not been used for the examination of any irradiated specimens. The hot cell contains the following equipment

1. Universal Testing Machine capable of tensile strength, binding and fracture mechanics testing.
2. Impact Machine for Charpy tests
3. Micro-hardness Testing Machine
4. Optical Microscope

The cell has manipulators for movement of samples and a polishing wheel available for small samples. The computers and software for data acquisition are outdated and might require upgrades to produce acceptable data. There is no current project at EAEA that would utilize this facility for research. To fully support an irradiated materials testing program the samples would need to receive a high radiation exposure, which would correlate to lengthy hours of operations. This hot cell is unlikely to be utilized until a government-sponsored or university materials research program is initiated and the ETRR-2 facility is able to operate for long irradiations.

Recommendation: Advanced nuclear reactor designs will require the testing of new materials in order to evaluate performance over long irradiation times. This represents a potential long-term service opportunity for the ETRR-2. A 22 MW nuclear reactor might be on the lower limit of the necessary neutron density but might compensate with longer irradiation times for equivalent fluences. The ETRR-2 staff is relatively well trained in materials testing, but there is a continuing need for the research staff and technicians to keep abreast of current techniques and to develop technical skills. It is recommended that several members of ETRR-2 conduct training visits to facilities of the U.S. Idaho National Laboratory or Oak Ridge National Laboratory where there are active post-irradiation examination programs. The ETRR-2 can consider using the hot cell for other research or commercial purposes while a materials testing program develops.

4.0 Uranium Fuel Supply and Use

The ETRR-2 is fueled with low-enriched uranium (LEU) U_3O_8 in an aluminum matrix and clad with aluminum. The fuel plates can be manufactured at the Inshas site in a dedicated fuel-fabrication facility. The fuel fabrication facility has the capabilities to convert UF_6 directly to the oxide for reactor fuel. Raw materials for additional fuel elements are provided from overseas brokers or sources (e.g., Russian, Germany, or the U.S.). A shipment of approximately 40 kg of U_3O_8 is expected to be delivered from Argentina (U.S. enriched) in the next few months. UF_6 would not be shipped due to difficulties in transporting the materials. Currently, all uranium at the ETRR-2 site has been converted into fuel plates. Approximately 2 fuel plates per month can be manufactured at the current production rate. EAEA estimates it would need to add new fuel after 15 days of round-the-clock operation of ETRR-2.

Spent fuel is transferred from the reactor and reactor pool through a transfer canal to the adjacent auxiliary pool for long-term storage. There is sufficient storage available for several years of operation without a spent fuel shipment. It is expected that disposal of the spent fuel would be accomplished through the U.S. DOE if that was the original source of the enriched uranium.

A comment often heard from the reactor operations staff regarding increased reactor utilization is that operating the reactor uses valuable fuel -- which has a limited supply. This concern, although valid, limits facility use. The single issue of fuel usage, and the affect on the daily control of the reactor operations schedule, should be resolved by EAEA management as a high priority.

The Oak Ridge National Laboratory (ORNL) was contacted concerning the potential procurement of uranium metal by Egypt. ORNL does not expect a problem providing uranium but would need a contract and export license to ship uranium directly to Egypt. The current shipping package for overseas shipment is no longer certified but a new package for shipment may be ready by next year. The ORNL staff highly recommends that EAEA consider ordering uranium in metal form, as that is the normal form produced for shipment at the ORNL Y-12 plant. The uranium metal could be converted to oxide form at ORNL, but it would likely turn out to be very expensive for the relatively small amounts produced for EAEA. Alternatively, the uranium metal would better be converted to U_3O_8 in Egypt for fuel plate fabrication.

5.0 Staff Training

The ETRR-2 and EAEA staff are very well trained and highly competent. An important enhancement will be the ability to confidently redesign or extend the reactor facility significantly beyond the original design capabilities. Safety analysis of experiment or facility modifications requires the ability to perform detailed modeling and analysis of the impact to the entire reactor system. Design envelopes for smaller (1-5 MW) facilities are usually more forgiving than the temperatures and radiation levels of a 22 MW facility, making a small miscalculation potentially significant in terms of radiological safety. The following areas of training or technical support would thus improve the operations and management of the ETRR-2 experimental and operations programs:

1. Experimental Design and Safety Analysis
   a. Additional training to support the safety evaluation of the mechanical, thermal-hydraulic, and neutronic aspects of new, in-core experimental designs
   b. Training to support the characterization and modification of existing experimental facilities
   c. Support in the design of new experimental facilities from concept to completion
   d. Advanced training using RELAP5/Mod3.2 code as adapted for research reactor to evaluate coolant accidents or changes in reactor core flow rates from new experiment designs

2. Reactor Operations
   a. Auditing and self-evaluation training
   b. Reactor core burnup and fuel loading considerations using SCALE 5.
   c. Safety Culture: What is a Safety or Service Culture? How to develop and maintain the culture.
   d. How to develop and write operation and maintenance procedures
   e. Public relations and building support from the community
   f. Operational health physics, maintenance, and reactor operations training at research reactors with advanced materials analysis or isotope handling programs

3. Materials Testing
   a. Non-destructive testing using a research reactor
   b. Current techniques in materials testing following irradiation

6.0 Conclusio

The ETRR-2 facility has tremendous potential and excellent support from the EAEA. The facility is going through a growth period that is typical for the period following commissioning. It will be important for staff and management to reemphasize why the facility was built and to remain committed to the long-term strategic goals outlined in several internal planning documents. As the ETRR-2 staff works as a team to meet the goals of the strategic plan, all will understand the individual contributions of each to the program's success. The ultimate preeminence of the ETRR-2 facility depends upon the long-term commitment of EAEA management and the Egyptian government in providing the resources (funding for fuel and experiment development) to reach these goals.