CONSIDERATIONS AND CHALLENGES OF RESEARCH REACTOR MANAGEMENT

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Abstract. Technically, nuclear reactors are equipment were neutron chain reactions of fissile material are safely controlled. Particularly, Research Reactors (RR) use the produced neutrons to a variety of objectives in science, technology, innovation, education, and direct products to society as, for example, the radioisotopes for nuclear medicine. Management is a fundamental aspect to the mission success of a RR and essential to its sustainability and effectiveness. As higher the neutron flux and the RR utilization, more complex are the management actions required to the installation, and their out-installation interfaces as well. Nevertheless, basic management requirements are still necessary to low neutron flux RR, for example, a critical facility. There are many important areas to be considered in RR management as organizational structure, operation, utilization, safety, fuel management, waste management, accessibility and security, human resources development, and financial resources among others. This paper resumes the author invited oral presentation that covers relevant aspects of RR management. Examples are given, based on the author's experience, related to RRs fulfilling their planned missions and, particularly, related to the development and installation of a new RR project.
Key Words: research reactor management.

1. INTRODUCTION

I start this paper with fundamental concepts on RR. Nuclear energy, as the name expresses, is the energy existing in the nucleus of an atom. The quantities of particles in the nucleus, neutrons, and protons, determine the nuclear characteristic and properties of this nucleus. An unstable nucleus emits energy to achieve a stable condition. This is the principle of *radioactivity* where a *radioactive nucleus* loses energy through the emission of particles (β^+, β^-, α, p, n) and electromagnetic energy (γ). In nature most of the nucleus is stable and some have natural radioactivity, as uranium and thorium nucleus, due to the very low radioactive constant of decay (very large half-life). To produce a radioactive nucleus in an artificial way one needs to produce *nuclear reactions* within the nucleus. One can do this nuclear reaction through high energy charged particles using accelerators, or, through uncharged particles as neutrons, using a nuclear reactor. In opposite to high energy charged particles in accelerators, neutrons with very low energy can generate a nuclear reaction in different nucleus. The types of nuclear reactions with neutrons are absorption by the nucleus, neutron scattering and fission of the nucleus. By neutron absorption one can produce a radioactive nucleus, with neutron scattering one can lower the neutron energy and create beams of this thermalized particle, and with nucleus fission, one can produce high energy particles (including neutrons) and a variety of radioisotopes. One can create a nuclear reactor by using different materials and specific neutron energy spectra to enforce nuclear reactions. Technically, nuclear reactors are equipment were neutrons chain reactions of fissile material are safely controlled. If the emphasis of the reactor is to extract the energy of fission, as a thermal machine, we have the power reactors where the heat generated is transformed into electricity. The total energy generated is proportional to the electric power needed leading to the use of high volumetric reactors and complex engineering systems using high-temperature processes. The environmental concerns are also intense and graded to the size of the installation. If the emphasis of the reactor is to use the neutrons generated inside the reactor, we have the research reactors (RR). RRs use the produced neutrons for a variety of objectives in science, technology, innovation, education, products, and services. In opposite to power reactors, the RR volumes are small with low process temperature and less complex engineering technologies, leading to environmental concerns much less intense compared to power reactors. In RR the focus is to optimize the neutrons' availability to the main mission of the installation.

A principal consideration for RR management is that, normally, RR is the main installation of a research center in nuclear technology. With a RR the nuclear science (nuclear physics) is transformed in nuclear technology and innovation generating services and products applicable to the society. The areas covered by this nuclear technology term is really of broad-spectrum and can be also complex and sophisticated. Some examples of these areas are nuclear engineering, nuclear fuels engineering and materials, reactor physics, instrumentation and control, computer engineering, nuclear physics application, radiation protection, radiation dosimetry, radioactive waste management, spent fuel management, among others. The management of RR has to consider the interfaces with all these areas related to nuclear technology for the operation of the installation to comply with its designated mission.

The RR, as an installation, has to be safely and efficiently operated, so it depends on technical staff, infrastructure financial support and a very well-established management system. It has to comply with regulatory licenses and audits, it has to manage safely the spent fuels and radioactive waste generated by the regular operation and have to maintain the level of radiological doses as minimum as achievable both for the operating personnel, users and to the public in general.

One interesting point is that as the RR gets old, as a natural aging of its structures/systems /components (SSC), technology keeps improving and the techniques/equipment of the RR can also improve. The utilization, services, and products of the RR can be updated for a long time, and the RR can have a very good level of utilization and a very safe and effective operation. But as more efficient is the utilization and more products and services offered, the responsibility of the RR operation increases. For example, if the number of research equipment in the neutron beam laboratory allows more time for experimental works for the scientific and technical community, the existence of any problem that ceases temporally, or in an extended period of the reactor shutdown, can generate also a large impact to the users with relevant economical and technical issues to them. More drastic impact may occur if the reactor is the main radioisotope producer for nuclear medicine in the country or abroad, and many persons may not be treated using radiopharmaceuticals and even casualties may occur.

All the arguments written above characterize that RR managers have to understand its installation broadly, taking into account its mission and the negative impact of its deviation from the normal and efficient operation. RR management is, of course, a key point to be addressed.

2. GRADED APPROACH ASPECTS ON RR MANAGEMENT

One can associate the complexity of operation, utilization and associated risks of a RR to the intensity of its neutron flux. According to the flux intensity range of different RR (from 10^5 up to 10^{15} n/cm^2.s), a graded approach can be used for dealing with all aspects and requirements related to RR, taking always the consideration that *grading is applied to the implementation of the requirements and not to the requirements itself*. The principle of the graded approach applies also to RR management.

One can exemplify the application of this principle using simplified reactor physics equations, where the reactor is assumed as a homogeneous volume and the neutron spectra collapsed to only one group of energy. The reaction rate (R) of neutrons in the "homogeneous reactor" can be expressed as:

(i) $R_i=N_i\sigma_{xi}\phi V$ _ where N_i is the atom concentration of material i (atoms/cm^3); σ_{xi} is the microscopic type x cross-section for reaction with neutrons of material i (cm^2), ϕ is the neutron flux for one group of energy (neutrons/cm^2.s), and V the volume of the "homogeneous reactor".

The power (P) of this "homogeneous reactor" can be expressed as:

(ii) $P=E_fN_f\sigma_f\phi V$ _ where E_f is the energy liberated by the fission of material f (~200 MeV)

Inversely one can express the neutron flux of this homogeneous reactor as

(iii) $\phi=P/(E_fN_f\sigma_fV)$

From these equations, one can verify that, for the same power level, the neutron flux varies inversely with the volume. *FIG.1* shows a schematic relation of flux, power and power density for RR for a fixed core volume of 100 liters. From this, one can also compare the classification of the RR power level (low, medium or high) with the level of power densities of PWR type power reactors. So, one has to understand the range of the neutron flux and reactor power in applying a graded approach to the RR.

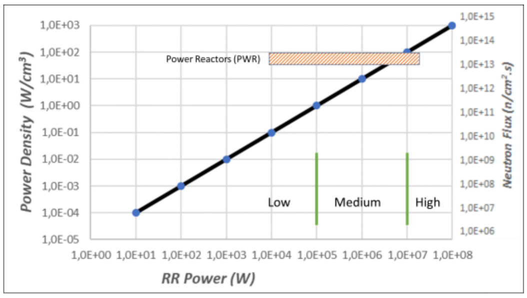

FIG. 1. Schematic relation of power, flux and power density for RR (100 liters core)

The neutron multiplication factor (k_{eff}) of the "homogeneous reactor" can be expressed as:

(iv) k_{eff}= (produced neutrons)/(lost neutrons)=(produced neutrons)/(absorbed neutrons + escaped neutrons)

$k_{ef}=\nu N_f\sigma_f\phi V\ /\ ((N_1\sigma_{a1} + N_2\sigma_{a2} + \ldots)\phi V + DB^2\phi V)$ or:

$k_{ef}=[\nu N_f\sigma_f\ /\ ((N_1\sigma_{a1} + N_2\sigma_{a2} + \ldots) + DB^2)]\ (\phi V/\ \phi V)$ - where ν is the mean quantity of neutrons produced in one fission, D is the diffusion coefficient for neutrons in the medium (cm), B^2 is the geometric buckling (cm^{-2}).

From these simplified equations, one can extract some principles to guide the application of the graded approach to RR.

i) The criticality of a reactor is independent of the neutron flux and relies only on the combination of materials and geometry arrangement;

ii) Critical reactors can have neutron flux as low as possible, compatible with the detection systems limits to keep the safety of the system;

iii) High neutron flux reactors have a combination of small volume and uranium enrichment in a way to maximize the flux up to the thermal system limits;

iv) All the reactions rates, for fission or absorption, depends directly on the neutron flux. If the neutron flux is low, as 1.10^5 n/cm^{2}s, the radioisotopes activities both from fission products or by transmutation will be also low; but if the neutron flux is high as 1.10^{14} n/cm^{2}s the radioisotopes activities will lead to a practical technical problem related to high-intensity radiation emission.

v) For high flux RR, the power densities are higher than power reactors and the graded approach is not useful.

It is also important to observe the main safety functions in a nuclear reactor which are necessary for achieving the overall safety objective of protecting people and the environment from harmful effects of ionizing radiation. These are control of fuel reactivity; fuel heat removal, and containment of radioactive material. Again, from the simplified equations, one can observe that reactivity control is independent of the reactor flux and applies to any reactor. But the importance and intensity of issues related to heat removal and containment of radioactive material are fully dependent on the reactor neutron flux.

In the world, there are RR in operation from the range of some watts to hundreds of megawatts. There is an interesting table in the IAEA publication [1] on reactor utilization that shows the relation of the reactor power and the techniques available for utilization. Some of these areas of utilization are education and training, neutron activation analysis, radioisotope production, neutron scattering, materials, and fuel testing. *FIG.2.* proposes to graphically indicate this relation of reactor power (or neutron flux) and utilization.

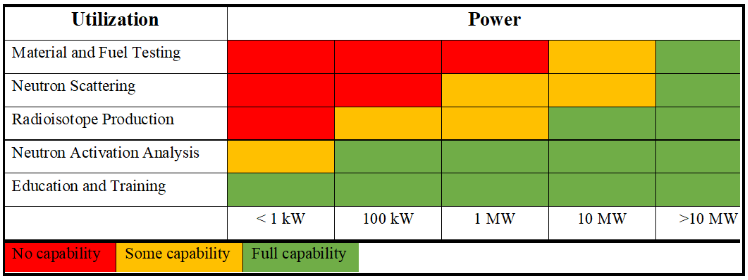

FIG.2. Schematic relation of power and utilization for RR

One can expand the same idea of *FIG.2.* to a graded approach for the areas important to RR management. One can identify areas where the management is of relevance, but also one can identify if the actuation on these areas is complex and intense. One can nominate areas of importance to management as operation, safety, security, integrated management system, human resources development, competence and knowledge management, succession planning, operational and experimental data, succession planning, finance resources, fuel cycle (new and spent fuel) management, decommissioning planning, etc. *FIG.3.* proposes to graphically indicate this relation of reactor power (or neutron flux) and areas important to RR management. One can identify some common areas that have to be developed by RR managers proportional to reactor power. Examples of this are:

i) Safety is an area very important to the management of RR, independent of its power. The phenomena intensities may be related to power, but the management of them is an obligation.

ii) Fuel management for very high-power RR is a key point to be addressed both related to operation and storage and final disposal. The quantities of fuel assemblies used yearly may be large and the spent fuel generated is of high burnup. In opposite the very low neutron flux RR has almost a unique core for the whole lifetime and with very low burnup, and its storage or final disposal is not a relevant problem.

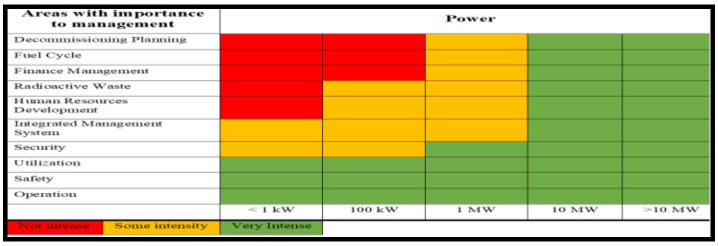

FIG.3. Schematic example of the relation of power and areas important to RR management

With schematic figures like these presented before, a RR manager can identify the graded approach to apply to RR management.

3. CONSIDERATIONS ON THE ROLE OF IAEA TO RR MANAGEMENT

The IAEA was created in 1957 by the United Nations based on the Atoms for Peace Program to allow Member States (MS) to develop nuclear technology for peaceful applications. The IAEA along the 62 years of existence has been structured to support and advise the MS to the nuclear technology application. Based mainly on technical documentation, workshops, training courses, symposia, technical cooperation, and technical missions, among others, the IAEA contributes strongly to the MS in the nuclear area.

Concerning RR, up to the nineties', few documents were published and they were mostly related to the areas of safety and utilization. Efforts were also done at that time to the conversion of high enrichment fuels to low enrichment fuels as cooperative work with the Reduced Enrichment for Research and Test Reactor (RERTR) Program from the US. After 2003 the IAEA started to work in a cross-cutting manner where divisions/sections of safety, physics (utilization) and energy start working cooperatively. The knowledge and organization existing at that time for power reactors were used as the basis for applying to RR.

Particularly, in my personal opinion, the launching of the "Code of Conduct on the Safety of RR" (CCSRR), in 2002-2004, was a turning point to support the MS not only for the safe operation of RR but also to apply it to the management of the RRs. While the CCSRR is not binding to the MS, they were encouraged to use it as the basis to conduct RR activities. The code establishes: (i) the role of the State; (ii) the role of the Regulatory Body; and (iii) the role of the Operating Organization. In applying the code, there must be a commitment of the MS to ensure the minimum conditions of financial support and preparedness for emergency response. The MS shall implement a Regulatory Body to maintain a safety verification level and adopt standards that require the RR Operating Organization to maintain a management system in place acting in all aspects related to the safe and effective operation of the RR. All these points of the CCSRR is one main guide for RR management.

Concerning documentation put available by the IAEA to MS, reference [2] shows a list of documents related to various areas where RR management is required. There are hundreds of publications ranging from standards, guides, safety series, nuclear energy series, technical reports, etc. Any RR manager may have these documents as a real basis for knowledge and actuation.

4. CONSIDERATIONS AND CHALLENGES ON RELEVANT AREAS FOR RR MANAGEMENT

A RR manager needs to understand the main mission of the research reactor under his management. In my point of view, the RR mission is bigger than its main utilization, being part of a system in transforming nuclear science in nuclear technology and through innovation to develop products and services to society, understanding that society means the public, the stakeholders and the scientific and technical community. In this sense is worthy to emphasize that the "aging" of the RR does not change nuclear science, but nuclear technology has a continuous development that can be utilized in the improvement of the reactor operation and utilization through innovation in products and services. A good example of this is the radioisotope utilization in nuclear medicine through radiopharmaceuticals. In the fifties, at the beginning of RR utilization, these materials were used mostly for radiotherapy using radiation detection systems available at that time. Today radioisotopes in nuclear medicine are used for imaging/diagnose and therapy, some of them as theragnostic, using sophisticated detection systems and digital imaging. Another example is the development of intelligent digital systems that can replace old analogic systems. The level of information is much higher with these new systems adding valuable tools for the management of the RR.

Many areas are important to the RR management as operation, safety, utilization, fuel management, integrated management system, human resources development, security, competence management, operational and experimental data management, configuration management, extended shutdown, decommissioning, emergency preparedness, etc. From these many areas I, particularly, chose some to comment without any priority.

i) ***Operation*** - In my opinion, to bring the technological developments in the various areas of knowledge to the real operation and utilization of the RR is one of the main management challenges. As mentioned before, the development of intelligent digital systems that can replace old analogic systems gives, in the future, the possibility of having, in parallel, a virtual system simulating the real system. This can be very expensive to old RR or low power RR, but this can be implemented in new RR projects and will bring advantages to operation management. An example is to use the digital plant SSC 3D layout as the basic information for operation, maintenance, and radiological protection management, among others.

ii) ***Safety*** - Safety is an obligation for the RR operation, that has to accomplish with the licensing rules of the MS Regulatory Body. When designing a RR one demonstrates its safety by analytical, numerical, statistical or experimental methods and a proven methodology is applicable. The Operating Organization has to maintain a system on this issue to analyze each modification and experiment on the reactor and system classified as related to safety, as well as to verify each core configuration and changes in the operational limits and conditions of the plant. The main challenge in this area is to maintain a high standard of safety with established methodology and procedures. Safety is an integrated management system because different areas can contribute to a failure that leads to an accident. In my opinion, a key point for safety is to establish and maintain a very active Safety Review Committee (SRC) with a high level of seniority. In the country level, the Regulatory Body operates as a general safety verification, but in the Operating Organization level, the SRC has a key role for safety. The SRC may analyze and verify the operational procedures, modification, utilization of the RR, giving a level of auditing and advisory behavior for the RR operation and management. For example, SRC established in the earlies nineties for the IEA-R1 RR in Sao Paulo changed it to a level of organization, improvement in SSC and safety in operation to a high standard. The SRC actuated as a permanent assessment group for the RR manager and a warranty to the head of the Operating Organization that the reactor was safely operated.

iii) ***Human Resources*** - One big challenge in RR is to keep, during the lifetime of the RR, a group of different skilled technicians not only to operate, but also to understand and to support utilization of the installation. The continuous education in the area of nuclear science and nuclear technology is a key factor. One way to motivate this continuous RR specialist's formation is to bring the formal post-graduation courses close to the RR, offering the installation to students to develop their final course works or Ph.D. thesis on subjects of the RR´s interest. This is also a way to bring innovation and create opportunities for improvements and the absorption of human resources in replacing competencies (knowledge management).

iv) ***Utilization*** - The mission of the RR is established since its design taking into account its flux level and experimental facilities. The effectiveness and the achievement of high levels of utilization depends on the "client" satisfaction to the products and services offered. To be in contact with the "clients" and users and to understand their needs is a must for utilization management of the RR. Strategic planning is an important tool on this and "users group meetings" is also a good practice for evaluating the performance achieved.

v) ***Management System*** - Management system implementation is a "must" for any RR operation. It is, in many MS an obligation imposed by Regulatory Body and is connected directly to the safe operation of the reactor. The Operating Organization has to maintain the management system alive and very active, and this is a challenge to the managers. In my opinion, one key point on this is to impose on the Operating Organization an ISO 9001 Certification Program. This was applied to IEA-R1 RR in Sao Paulo in the 2000´s. With this certification program, one is obliged to maintain and run the management system in a very pragmatic and technical way. The Certifying Institution audits are very important to demonstrate that the Management System is well established and executed. Having an ISO 9001 certified management system for the RR operation is just one of the possible ways for bringing a high-level performance to the RR operation.

vi) ***Fuel Management*** - The concern of fuel management is directly related to the power (or the neutron flux) of the RR. As lower the power, less are the concerns on fuel element acquisition and in spent fuel management as well. For medium and high power, the concerns with the fuel management may be one of the constraints to the RR operation. The RERTR Program imposed in the past that most of the RR in the world would use low enrichment uranium fuels. Developments were done in obtaining a qualified fuel for most of RR design and power, and today there are different options for the RR operation. Also, the international programs established to send back to the origin all high enriched uranium fuel gave margins to some RR for having more spent fuel (SF) storage space. This led to more flexibility for RR to extend its lifetime. The SF management involves the operational storage in the facility, the interim storage, the SF processing, the processed SF storage, and the processed SF disposal. The long-term challenge is to have all these steps covered for all RR in operation or planned. But of course, this is dependent on each MS strategy and nuclear program characteristic. For example, for some MS that have also power reactors in operation, the RR SF management may be overlapped with the SF management of the power reactor. Meanwhile, as the long-term solution does not reach, the SF interim storage is the main management concern. The challenge is to maintain a SF interim storage safely and effectively where the SF integrity should be maintained as long as possible until an acceptable final disposal is defined. Particularly, in my opinion, for long-term interim storage, dry storage technology is a better option than to maintain a wet storage system operational and effective.

vii) ***Emergency Preparedness*** - Emergency Preparedness is an obligation to any RR in operation, but can be an issue for some old RR that were constructed in regions with low populational density in its beginning, but had populational density increase around its site during lifetime. This is a very important point and a management issue as the emergency planning zone and emergency preparedness may include persons from the public. There is no way for overriding this process other than a governmental emergency response and intervention capabilities.

5. CONSIDERATIONS ON NEW RR

A new research reactor project, together with the infrastructure development of a new research center, gives an important challenge to the researchers and technicians in charge of them due to the complexity of matters and issues involved. My experience in the implementation of the Brazilian Multipurpose RR (RMB) shows that some of the points discussed before were taken into account in the decision of the project specification. Some of these examples of management are:

i) ***Mission*** – The RMB will be the main installation of a new nuclear technology center where the main mission is to develop and use nuclear technology, creating innovation for application to the society. It is a structuring and technological dragging project for the nuclear technology application.

ii) ***Emergency Planning*** – The criteria for the site area settlement imposes that the emergency planning zone should be kept inside the fence boundary of the site. Besides this, arrangements with the County Administration agreed that the County Urbanization Zoning law should impose a very low demographic occupation in a 3 Km radius surrounding the RMB site (agriculture occupation). These actions give warranty that emergency preparedness is restricted to the site and its workers during the lifetime of the installation.

iii) ***Fuel Management*** – To maintain sustainability for the fuel assembly supply for the reactor lifetime, a country coordinated program, managed by RMB, was developed to construct an enrichment cascade and to upgrade the existing RR fuel facility. This infrastructure is ready and can process all fuel assemblies yearly needed by RMB and the uranium targets for Mo-99 production. The design of RMB takes into account SF operational storage (wet) for the lifetime of the RR (50 years), and SF interim storage (dry) for other 50 years more in the same building of the reactor.

iv) ***Human Resources*** – RMB will create formal education courses in nuclear technology areas, acting as a national laboratory, to bring the young generation and new technologies to the operation and utilization of the RR along its lifetime.

v) ***Synergy with existing RR*** – New core at the IPEN/MB-01 Critical Facility in Sao Paulo was developed for using it as the reactor physics validation of the RMB core, and neutronic reactivities analysis of irradiation devices. The IEA-R1 RR and IPEN/MB-01 will be the bases for training operators and to elaborate RMB operational procedures.

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