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A Reverse Approach to Determine Research Reactor Configuration Based on National Demand Assessment

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Abstract - *This paper reviews recent experiences conducted worldwide tackling underutilization challenges faced by research reactors. A nuclear power program with ambitious goals, requires a well-established nuclear infrastructure and robust national framework. And to achieve that in a sustainable manner, countries aim to develop well-utilized research reactors. This paper explores case studies from different counties and sheds special light on the reverse approach to determine functional specifications, technical specifications (i.e. reactor core size, geometry, neutron flux, irradiation positions, fuel type, required irradiation duration) based on the captured national needs and aspirations through a set of analyses. Additionally, utilization requirements are presented using the mentioned approach considering three main applications which are radioisotopes production, neutron transmutation doping, and material testing.*

Keywords: Research Reactor, Radioisotopes, NTD, Fuel Testing, Utilization

I. Introduction

Designs of research reactors have always been unique from one another. Based on the intended utilization, their designs come with different configurations. The distinction of each research reactor is the result of having different national priorities for each country. Since 1953, the deployment of research reactors was rapidly increasing until there number peaked in 1975 reaching 373 operational research reactor. The current number of operational research reactors is 264 and two thirds of those have been operating for more than 30 years. [1] While aging is major contributor for research reactors shutdown, however, underutilizations is an equally formidable challenge that jeopardizes the sustainability of such facilities. Not knowing how to effectively use these costly machines drive governments to make budgetary cuts, consequently impacting reactor operations. [2] is mainly due to a lack of a through strategic planning for such a facility.

The IAEA provides its milestone approach for research reactor development as guide for countries to follow. If followed properly, the milestone approach results in an effectively justified, designed and implemented research reactor project. The initial “pre-project phase “ of the IAEA approach aim to have a justification of the research reactor that is based on the national demand and direction of a country. This phase also involves the conceptualization of the research reactor based on the established justification. To effectively achieve the intended outcomes of this pre-project phase, a suggested tool known as the reverse schematic approach can be employed. This tool serves as a visual link between the inputs – representing a country's national aspirations and needs as research reactor utilization – and the envisioned outputs in terms of research reactor design features and characteristics.

Research reactors nowadays are mainly planned to have two directions the first being products and services oriented facility, and the second being a platform for nuclear technology development. Planning for services and products-oriented facilities is relatively straightforward. Since they are planned to match existing and growing national needs. Opposed to the nuclear technology development facilities planning, which poses a more complex process. Since it requires full awareness of the global landscape of nuclear technology and international collaborative efforts. However, a research reactor can support the fulfilment of both directions through having the following capabilities:

1. Radioisotope Production
2. Material and Fuel testing
3. Neutron Transmutation Doping (NTD)

This review paper will highlight the use of reverse approach in planning for research reactors through linking the reactor utilization with the required core features and design characteristics. This will be illustrated through three new research reactor designs, which are PALLAS, KJRR, and JHR.

II. RadioIsotopes

Production of radioisotopes is one of the main services that could be provided by research reactors along with material irradiation and neutron transmutation doping (NTD). Two major sources of radioisotope production are accelerators and reactors. Radioisotopes produced in reactors account for a sizable portion of all uses of radioisotopes. [3] Those radioisotopes usually come as sealed and unsealed sources and are widely used in industry, medicine, agriculture, metrology, hydrology, and mining. Unsealed sources are mostly used in the medical field for therapeutic and diagnostic purposes while sealed sources are usually used in the industrial field and may be applied in chemical processing and non-destructive testing as some of the most common industrial applications. [4]

Unlike accelerators, the reactor provides considerable irradiation volume, simultaneous irradiation of several samples, production efficiency, and the ability to manufacture a wide range of radioisotopes.

According to the IAEA-TECDOC-1340, [3] research reactors used for radioisotopes production could be broadly classified into:

- Enriched uranium, light water moderated, pool-type reactors
- Natural uranium, heavy water moderated, cooled tank-type reactors

Radioisotopes are produced in the research reactor by exposing target materials to the neutron flux for an appropriate amount of time where the target materials undergo fission or neutron capture interaction with the neutrons. Pool-type research reactors have a visible, compact core that is reachable from the top of the pool. [3] Target materials are put into specially made irradiation holes, sealed in primary capsules, and then dropped in specific areas of the core for irradiation. Once put into the proper shielding containers, the irradiated targets are sent to the processing facilities. Unlike pool-type RR, the irradiation assemblies in tank-type reactors have many target capsules and are lowered using specialized jigs. The target capsules are loaded and unloaded after the irradiation by lowering the irradiation assembly into a hot cell equipped with master-slave manipulators. Producing a quality radioisotope with high specific activity depends on the target and irradiation conditions such as neutron flux and irradiation time. While delving into the realm of reactor-based radioisotopes, two highly valuable isotopes come to mind. The first and foremost is the prevailing radioisotope, Mo-99. This radioisotope accounts for approximately two thirds of the nuclear medicine diagnostic procedures. Mo-99 decays into Tc-99m and in turn Tc – 99m decays with a half-life of 6 hrs. The decay scheme connecting Mo-99 and Tc-99m, has granted it significant favour within the industry. [5]

The second noteworthy radioisotope is Lu-177, an emerging new isotope in the realm of reactor-based radioisotopes. Lu-177 presents numerous potential applications across the domains of healthcare and industrial sectors However, its primary spotlight is centered on Targeted Radionuclide Therapy (TRT). This therapy holds promise as a crucial application for

Lu-177, capitalizing on its distinctive properties for targeted medical procedures. [6]

III. Material and Fuel Testing

Research reactors were critical to the establishment of nuclear power reactors, as they formed the foundation of neutron-based technique for testing and qualifying fuels and structural materials. They will continue to be an essential tool to the development of advanced power reactor technology including Small modular reactors (SMRs). The technology development of nuclear fuel and nuclear grade components follow a very stringent quality control procedure, as it requires the characterization of parts and components behavior under various extreme conditions. A significant part of this safety demonstration of novel fuel and other components requires intense testing in extreme conditions that can only be achieved in research reactors. [7] Research reactors also provide various services to the current power reactors to support their long-term safe operation, where research reactors are usually used to effectively look into irradiation embrittlement of power reactors components. Services include material degradation studies for critical components such as Reactor Pressure Vessel (RPV) and core internals, corrosion tests of primary circuit internal structures, water chemistry experiments of primary circuit and many other services. [8] Research reactors can be designed to have higher neutron flux than that in conventional power reactors. This attribute is highly beneficial in material testing, where same dose received by certain material can be achieved in a shorter irradiation time. For example, irradiation time for selected material samples in material testing reactors take 1-2 years compared to the same dose received by the same material for 30-40 years in nuclear power reactors. [9]

Material testing in research reactors can be done with rigs and loops. Rigs act as a flux trap for samples to be irradiated in a control environment for separate effect testing. Loops are mostly used to mimic the conditions of power reactors for integral effects testing (coolant flow, temperature, pressure, and irradiation). In some instances, rigs and loops are used in compliment to each other. [10]

IV. NTD

Neutron Transmutation Doping (NTD) is a process where neutron irradiation in research reactors creates impurity in an intrinsic or extrinsic semiconductor wafer to increase its properties for various uses. There are many materials that are target for NTD such as Si, Ge, GaAs, GaP, InP, InSe, and HgCdTe. However, Si is the most prominent target for NTD. The demand for NTD was increasing in the 1980s but the emerge of other doping methods - such as gas diffusion - have reduced the demand for neutron doped semiconductors.

NTD can produce the best quality silicon for high power applications, as the uniform dopant concertation achieved by NTD is unmatched by other doping methods. That said, to achieve such uniformity, keen issues must be considered in the design of such instrument responsible for irradiating silicon ingots and its operation. The most important issue is radial and axial uniform irradiation of ingots. since ingots are large in size the flux variation across its volume must be incorporated in the design of the irradiation instrument. A suggested solution to this issue is to include a rotation device for irradiation.

Another important issue is the irradiation time of the ingots as it could also affect uniformity of doped material. The NTD process requires thermal neutrons, where the higher the thermal neutron flux, the less time required for ingots irradiation, which might sound favorable for research reactors as it reduces the time required to produce the commodity. However, it is difficult to produce uniform irradiation through short time irradiation and if the flux is too low it will take a longer period of irradiation and consequently reduce the practicality of NTD. The market demand for NTD technology is fluctuating depending on the advancements of other doping methods. However, as most research reactors performing NTD are ageing and possibly shutting down, the NTD is considered to be one of the commercial and revenue-generating applications of planned research reactors. A very careful and thought out feasibility must take place to decide whether it’s worthwhile to include this application in the utilization of a new reactor. The feasibility must consider all challenges and risks associated with this technology. [11]

V. Applying the Reverse Approach to Selected Research Reactors

There are three advanced research reactor projects of interest due to their magnitude, clear direction, and proper planning. These three research reactors resemble the future of research reactors landscape and a lot can be learned from their experience. They are:

1. PALLAS
2. Kijang Research Reactor (KJRR)
3. Jules Horowitz Research reactor (JHR)

Applying the reverse approach for these benchmarks will illustrate how this tool can be beneficial in visualizing the linking of the design inputs with design features.

V.A. PALLAS

The PALLAS Research Reactor is designed as a state-of-the-art facility with a tank-in-pool design, prioritizing safety and ease of maintenance. Its power level is flexible, ranging from 30 to 80 MW, allowing it to cater to a wide range of operational requirements. The reactor has been specifically designed as a versatile platform for scientific investigations. The ample space and capabilities provided by the reactor's reflector zone and core enable researchers to explore various phenomena and study the behavior of materials under controlled conditions. [12] One of the notable features of the PALLAS Research Reactor is its use of fully Low Enriched Uranium (LEU) fuel, with a particular focus on Uranium-silicide. Additionally, the reactor's design allows for the accommodation of U-Mo (Uranium-Molybdenum) fuel, providing flexibility for future adaptations or specific research needs. With its advanced capabilities and flexible operational parameters, the PALLAS Research Reactor serves as a vital asset in advancing scientific knowledge, addressing societal needs, and contributing to various industrial and medical sectors that rely on the production of radioisotopes. [13] The Dutch government has expressed a positive vision for PALLAS, recognizing that replacing the High Flux Reactor (HFR) with a state-of-the-art reactor will not only satisfy the need for nuclear research but also ensure the security of the radiopharmaceutical supply. The multipurpose nature of the reactor is highlighted, as it provides sufficient flexibility to fulfil these tasks while leveraging the existing knowledge infrastructure in the Netherlands in the fields of nuclear technology and radioisotopes. [12]

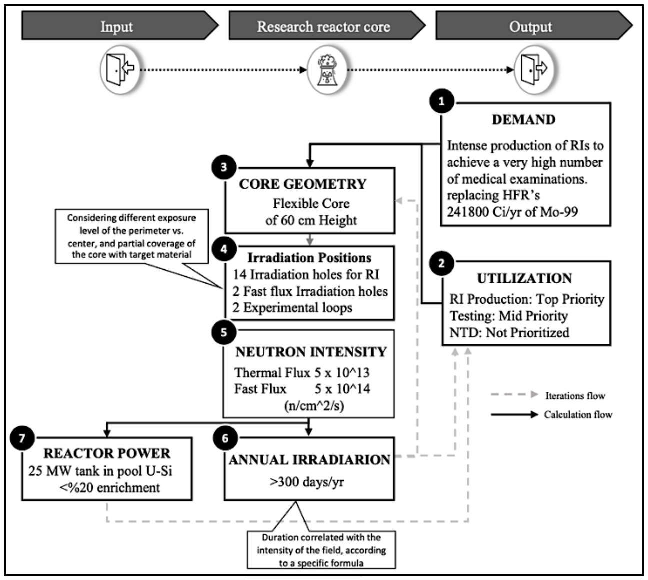

Figure 1. Reverse Approach Schematic for PALLAS

IV.B. Kijang Research Reactor (KJRR)

Located in Gijang-gun near Busan, South Korea. the KJRR research reactor aims to address the demand for radioisotopes, NTD service, and related research activities. To meet these demands, thorough considerations were given to the capacity requirements for major radioisotopes (RI) production and NTD services during the design process. The reactor is designed to produce Mo-99, I-131, and Ir-192. Additionally, the reactor is equipped to accommodate NTD production. These requirements serve as the guiding principles for the engineering design, ensuring the reactor's purpose is effectively fulfilled.

To meet the specified demands, the KJRR has undergone conceptual and basic design phases that incorporated specific design and performance requirements. The reactor is designed to operate for over 300 days per year with a power output of 15 MW, an open-tank-in-pool reactor type, and a maximum thermal neutron flux exceeding 3.0×10^{14} (n/cm^2s), achieving a burn-up of 60% to generate the required neutron flux necessary to meet the performance requirements. For Mo-99 production, a target holder with LEU fuel will be loaded and unloaded during reactor operation. The fuel consists of plate-type U-7Mo (19.75% enriched) in an aluminium matrix with aluminium cladding. The design also takes into account additional radioisotope production requirements for P-33, Lu -177, and Co-60.

In terms of NTD service, the KJRR features specially designed irradiation holes to accommodate silicon (Si) ingots, catering to the needs of the irradiation service market, ensuring that the reactor's capacity aligns with the demand from the market for irradiation services. [17]

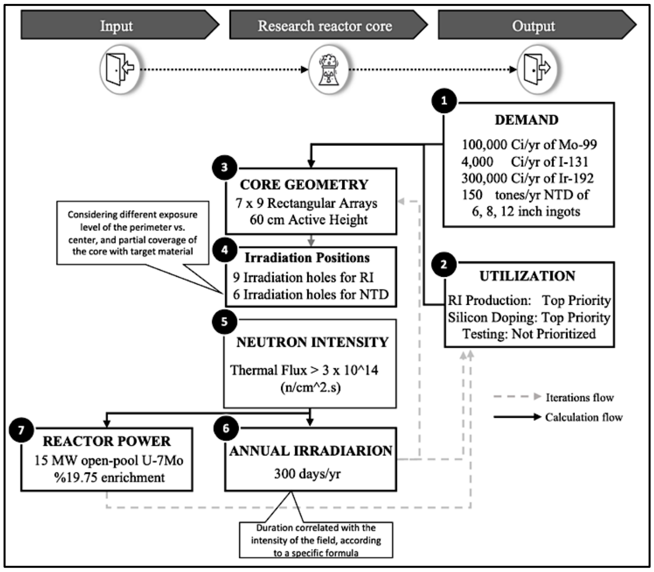

Figure 2. Reverse Approach Schematic for KJRR

IV.C. Jules Horowitz Research reactor (JHR)

Located in CEA's Cadarache center, Jules Horowitz Reactor (JHR) is an under construction 100 MW pool-type research reactor. A multipurpose reactor that has the ability to conduct around 20 experiments simultaneously along with mimicking the environmental conditions of various power reactor systems. Its capabilities also include generations for material screening, material characterization and fuel element qualification. The main objectives of JHR are R&D support for the nuclear industry through fuel and material testing, and production of medical radioisotopes to fulfill the existing demands.

The reactor building consists of pools and hot cells that are associated with the reactor core for the efficient management of the experiment cycle. JHR is designed to provide a high flux of fast neutrons, for researching the behavior of nuclear fuel. The JHR also provides a high flux of thermal neutrons which helps inducing a significant damage in materials tested which is approximately double the damage that is induced to structural materials of power reactors. [18]

In terms of radioisotope production, JHR will be able to produce Mo-99 through fission moly devices in the reflector. As for I-131 and Xe-133, they could be extracted from uranium targets through fission reactions. In addition, the thermal neutron flux would allow producing other radioisotopes that could be utilized in the medical and/or industrial field.

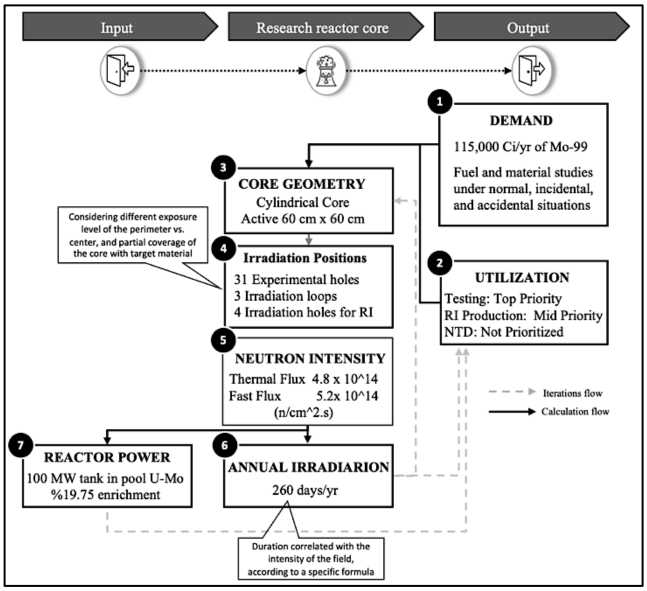

Figure 3. Reverse Approach Schematic for JHR

VI. Conclusion

Research reactors are facing many challenges and the answer to most of them is for research reactors to have a proper strategy and utilization through proper strategic planning. The reverse approach is helpful tool that will yield more value if used at the early stage of the research reactor project, as it connects the national demand, research reactor utilization, and design feature.

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References

1. INTERNATIONAL ATOMIC ENERGY AGENCY, *Research Reactors: Purpose and Future, Global Status (page 3*), IAEA, Vienna 2016
2. I. Alrammah, *Enhancing utilization and ensuring security: Insights to compromise contradicting conditions in new research reactors (section 2 the issue of underutilization in research reactors),* Nuclear Engineering and Technology, Volume 53, Issue 5, King Abdulaziz City for Science and Technology (KACST), Riyadh (2020)
3. INTERNATIONAL ATOMIC ENERGY AGENCY, *Manual for Reactor Produced Radioisotopes, IAEA-TECDOC-1340,Chapter 1(1.1,1.2*), IAEA, Vienna (2003)
4. A Gandini, J J Schmidt, S Ganesan*, Proceeding of the workshop on Nuclear Reactors-physics,* Design And Safety, World Scientific Pub Co Inc, Trieste (1994)
5. J. Moon, K. Myhre, H. Andrews, J. McFarlane,*Potential of electrolytic processes for recovery of molybdenum from molten salts for 99Mo production (introduction),*Progress in Nuclear Energy,Volume 152, (2022)
6. A. Dash, M. R. Pillai, F. F. Knapp Jr., *Production of (177)Lu for Targeted Radionuclide Therapy: Available Options.* Nucl Med Mol Imaging. 2015
7. INTERNATIONAL ATOMIC ENERGY AGENCY, *Characterization and Testing of Materials for Nuclear Reactors,* IAEA-TECDOC-1545,Introduction, IAEA, Vienna (2007)
8. F. HUET, *LVR-15 Fuel assembly qualification plan,3 Qualification plan,* European commission, (2020)
9. T. Mahmood, M. Griffiths, C. Lemaignan, R. Adamson, *Material Test Reactors and other Irradiation Facilities, Chapter 2,* Advanced Nuclear Technology International (A.N.T), Tollered (2018)
10. INTERNATIONAL ATOMIC ENERGY AGENCY, *Research Reactor Application for Materials under High Neutron Fluence, IAEA-TECDOC-1659, Chapter 1,*IAEA, VIENNA (2011)
11. INTERNATIONAL ATOMIC ENERGY AGENCY, *Neutron Transmutation Doping of Silicon at Research Reactors, IAEA-TECDOC-1681, Chapter 2,6* ,IAEA, VIENNA (2012)
12. *Trends and developments - Pallas Reactor. (2020, August 20). Pallas Reactor at* https://www.pallasreactor.com/en/medical-isotopes/trends and-developments/
13. R.P.C. SCHRAM, G. J. L.M. de HAAS, T.M.H.E. TIELENS, & S. KNOL (rep.). *THE HFR AND PALLAS ERA. DUTCH RESEARCH INFRASTRUCTURE*. NRG PALLAS, Lyon, 2022
14. C. JENSEN, D. WACHS, N. WOOLSTENHULME, S. HAYES, N. OLDHAM, K. RICHARDSON, & D. KAMERMAN. *Post-Halden Reactor Irradiation Testing for ATF: Final Recommendations. INL/EXT-18-46101 Revision 1,* Idaho National Laboratory. (2018)
15. J. Heller, & B. Hatala, D4. 1 GFR *refractory fuel qualification options*
16. International Atomic Energy Agency*, In Characterization and testing of materials for nuclear reactors: Proceedings of a technical meeting held in Vienna,* May 29 - June 2, 2006. Vienna: IAEA.
17. C. Park, J. Y. Kim, H. T. Chae, & Y. K. Kim. *Current Status of the KJRR project and its design features.* International Group on Research Reactors, November, 17, 2014.
18. The French Alternative Energies and Atomic Energy Commission (CEA), *Research Nuclear Reactors*, *95-96,* CEA, Paris (2012)