**Multipurpose research reactor for countries with ambitions**

**on the example of Polish MARIA**

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Abstract – *Research reactors are nuclear reactors used for radiopharmaceuticals production, basic and fundamental research, development of nuclear power technologies, education and training. They have usually low-temperature and low-pressure design with light water as the cooling medium. Since they serve as a neutron-producing machine for various medical, scientific and industrial applications, they have high neutron fluxes, usually at least an order of magnitude higher than the power nuclear reactors. Their cores can be filled with experimental devices that mimic the conditions in both fusion and advanced fission reactors. In the paper, the examples of the aforementioned applications are presented. MARIA's flexible design is described as an example of medium-sized reactor for countries with ambitions in fields of nuclear medicine and advanced power reactors technologies.*

**Keywords:** research reactor, material testing, medical radioisotopes, components testing

I. Introduction – what is a research reactor?

A research reactor is a type of nuclear reactor whose primary role is to produce intense fluxes of neutrons that can be used in various applications, i.e. medical radioisotopes production and research (both fundamental and applied). The aforementioned functions will be described in the following chapters on the example of the MARIA. Saudi Arabia is during the process of its first small research reactor LPRR **[1]**, following paper can contribute to its utilization planning or to the decision of constructing the full-scale research reactor.

Research reactors shall have lower operating temperatures and a simpler design than nuclear power reactors **[2]**. There is no binding definition, however, on its webpage IAEA, states that ‘Research reactors are nuclear reactors used for research, development, education and training. They produce neutrons for use in industry, medicine, agriculture and forensics, among others’ **[3]**. Similar passage can be found in **[4]**: ‘Research reactors comprise a wide range of different reactor types that are not used for power generation. The primary use of research reactors is to provide a neutron source for research and various applications, including education and training. They are small in comparison with power reactors whose primary function is to produce electricity. (…) Research reactors are also simpler than power reactors and operate at lower temperatures. (…) Research reactors also have a very high power density in the core’. It is worth mentioning that the above quotes narrow research reactors designs for water-cooled and moderated types.

Out of the 222 operational research reactors worldwide, only 33 have a high flux of neutrons, combined with a thermal power > 10 MWth, whereas 113 objects have thermal power < 0,1 MWth). Most are at the power level of 1-20 MWth, with the most prominent representative having a thermal power of 250 MWth **[5]**. Reactors within the power range > 10 MWth are relatively multipurpose, although there are specialisations of individual objects, e.g. beam sciences, material testing, and medical production. Their global geographic distribution is presented in figure 1. The smallest research reactors’ designs (critical or subcritical) with thermal power < 1 kWth usually serve education and training purposes only.



*Fig. 1. Countries that operate research reactor(s) with thermal power > 10 MWth* ***[5]****.*

As it can be seen in Fig. 2, thermal neutron flux corresponds with the thermal power in an exponential way, finitary relation being given by Eq. (1)

$φ\_{th}=1.14∙10^{14}∙P^{1.03}$ (1)

Where:

φth – thermal neutron flux [n/cm2/s]

P – thermal power [kW]

and coefficient of determination R2=0.944

*Fig. 2. Correlation of research reactors thermal power and thermal neutrons flux, data from* ***[2]****. For comparison, modern power reactors have thermal neutron flux below 1014 n/cm2/s at thermal power level of several gigawatts* ***[6]****.*

A simpler design usually means a lack of the components connected to the steam generation and a lack of the thick reactor pressure vessel (RPV). However, the core’s geometry could be complicated and have a conical or twisted hyperbolical shape that increases the neutron flux. Open-pool and tank designs are among the most common. Lower operating temperatures and/or lack of steam generation distinguishes the research reactors from experimental reactors, often prototypes of the future, full-scale power nuclear reactors. Their notable examples are Argentinian CAREM-25 **[7]** (experimental 32 MWe power unit with PWR reactor), Chinese HTR-10 **[8]** and HTR-PM **[9]** (HTGR prototypes) or three Russian reactors from the BN series **[10]** (SFR). The main differences between the research and experimental reactor and their specific applications are presented in figure 3.



*Fig. 3. Main differences between the research and experimental reactor.*

Historically research reactors were considered necessary prerequisite to nuclear power development **[11–12]**. However, nowadays, although they remain valid for this purpose, they shall instead be treated as a separate, highly-specialized research facility class, expanding the national capabilities in the fields of science and raising the standard of living of citizens, both for the widespread progress of the country and region **[13]**.

II. Applications of Research Reactor and its justification

Selection of the research reactor type and its construction in the newcomer country is a major undertaking. It should be preceded by a detailed analysis that will justify the programme, followed by the steps that lead to the feasibility study. Those activities can be named as the initial phase of the programme, which simplified pipeline is presented in figure 4. The step initiating Phase 1 should be the selection of the applications to be fulfilled with the reactor operation. In the following paper, only Phase 1 is described. From a safety point of view, Phase 1 might additionally contain initial site studies (pre-screening) and an initial environmental impact assessment **[14]**.

*Fig. 4. Simplified research reactor construction project pipeline and infrastructure development programme. Based upon* ***[15]****.*

Research reactor justification shall start with identifying needs in terms of its utilisation and the profile of potential national and international stakeholders (e.g. medicine, industry, science, energy). Potential stakeholders shall be consulted in the pre-project phase that will lead to the portfolio of the reactor's most needed applications, e.g.:

* hospitals – medical radioisotopes, BNCT
* oil industry – geochronology
* universities – introductory nuclear physics, NAA
* research centres – uses of neutron beams and in-core irradiations, biomedical research
* government – national policy
* energy sector – training, in-core irradiations and testing
* other potential stakeholders (e.g. silicon doping)

The result of the consultation should lead to the portfolio of applications indicated in Table I. This part of the planning can be treated as the SWOT analysis since no reactor is fully universal, and each has its limitations. Additionally, the resources (mainly staffing and its training, and money) needed for each application shall be assessed. For the newcomer countries, two approaches exist:

1. Construct a small, low-flux facility with limited thermal power at kilowatts, and concentrate only on teaching nuclear reactor theory, nuclear physics and limited engineering experiments. Its example is Saudi LPRR with thermal power up to 100 kWth **[16]**.
2. Construct a larger, high-flux facility at several megawatts or more thermal levels. It will have broader applications; however, their prioritisation is needed due to the limited in-core positions, beam number and reactor operation time.

Traditionally (excluding the pioneering years of nuclear power), countries with nuclear ambitions have chosen the latter. The notable examples are Jordan which constructed 5 MWth JRTR in 2016, and Egypt, with its 22 MWth ETRR-2 constructed in 1997.

Additionally, the two approaches mentioned above might be implemented together since < 1 kWth critical assemblies have several orders of magnitude lower construction costs than the research reactors with the higher power. Notable examples of such approaches are pairs HOR–DELPHI (Netherlands) and (now decommissioned) EWA-MARYLA (Poland), both housing two reactors in one shared building.

*Table I Selected applications of research reactors within their specific thermal power. Based upon* ***[17]****, modified by the author.*

|  |  |
| --- | --- |
|  | Power Level |
| < 1 kW | c.a.100 kW | c.a.1 MW | > 10 MW |
| Education and Training | + | + | + | + / – |
| NAA | + / – | + | + | + |
| PGNAA | – | – | + / – | + |
| Isotope production | – | – | + / – | + |
| Geo chronology | – | – | + / – | + |
| Silicon doping | – | – | – | + |
| Gamma Irradiation | – | + / – | + | + |
| Neutron Imaging | – | + / – | + | + |
| Neutron Scattering | – | + / – | + | + |
| I&Ctesting | + / – | + | + | + |
| Materials testing | – | – | + | + |
| Fuelstesting | – | – | + / – | + |

Theoretically, it is possible to deal with all the applications mentioned in table 1. However, it is hardly possible in a practical environment due to staff restrictions, limited funding, and a reactor operation regime. Literature review [**13,18**] indicated that globally, the most needed and/or promising applications of the research reactor are:

1. Production of medical and industrial radioisotopes;
2. Irradiation services: Silicone doping for the semiconductor industry, tests of electronic devices. Research and development for advanced fission and fusion energy, e.g. material testing;
3. Analytical techniques, including neutron activation analysis for identifying trace elements, and geochronology;
4. Neutron beam techniques such as neutron imaging, small angle neutron scattering and neutron diffraction;
5. Education and training.

Reactor justification should also include the preliminary cost to design, build and commission, safety and regulatory requirements, and resources required to operate and maintain the reactor. All of this leads to the preliminary functional specification of the reactor’s requirements that shall include, but is not limited to **[14]**: thermal power, irradiation capabilities, auxiliary support equipment and facilities and required measurement capabilities.

III. Ancillary infrastructure and staffing

Operation of the high-flux research reactor requires specialized staff with both university and secondary technical education. The continuous operation requires at least four shifts with adequate manning. Its organizational scheme is presented in Table II. Note that this constitutes the absolute minimum that shall be supported by the adequately sized analytical team from thermal hydraulics, neutronics, design engineering, record keeping, and quality assurance. As a rule of thumb, the absolute minimum is three people per position plus management.

*Table II Minimum staffing in the research reactor (excluding experimental specialists). Based upon* ***[19]****, modified by the author. Ancillary personnel such as cleaners and security guards is not included.*

|  |  |
| --- | --- |
| **Position** | **Minimum staffing** |
| Manager | 1 |
| Reactor supervisor | 1 |
| Assistant supervisor | 1 |
| Shift group supervisor | 4 |
| Operators | 8 |
| Maintenance supervisor | 1 |
| Craftsmen | 5 |
| Instrument supervisor | 1 |
| I&C and electric craftsmen | 3 |
| Experiment liaison | 1 |
| Health physicist | 5 |
| Analytical laboratory team (radiochemistry, NAA, dosimetry) | 5 |
| Support analytical team | 20 |
| **Total** | **56** |

**IV.A. Production of medical and industrial radioisotopes**

The use of medical isotopes for medical purposes is an essential part of modern diagnostics and therapy, including but not limited to cancer treatment. Additionally, some radioisotopes are used in industrial and research applications. Although most imaging radionuclides (excluding 99Mo/99mTc) are produced with particle accelerators, the therapeutic ones are produced almost exclusively with neutrons in research reactors. Medical science advances, countries develop, populations grow, and life expectancy rises. Demand for medical isotopes can increase over the next decades, especially in emerging economies [**20**]. For some, the increase is expected to be at least threefold **[21]**. At the same time, the ageing fleet of the production research reactors is expected to be unable to cover that demand [**22-23**]. Additionally, due to the decaying nature of radioisotopes, their supply chains are complicated. Therefore, it is advisable to have a local production source i.e. research reactor.

For the production of the majority of the isotopes, a high flux reactor (>1014 n/cm/2/s) is needed. Additionally, requirements consist of (but are not limited to): hot cells, gamma spectroscopy laboratory, encapsulation system, hydraulic rabbit. In order to fully use the production potential of the reactor, it is necessary to build an accompanying specialized radioisotope facility with several specialized production lines in hot cells. The total number of required employees will vary from dozen to about one hundred, depending on the production profile.

**IV.B.** Irradiation services

A research reactor is a valuable source of neutron and gamma radiation that can both be used to change the properties of the irradiated materials. The former can be used for silicon doping purposes, the latter for sterilization of various materials (e.g. food, antiques).

The silicon crystals’ resistivity is decreased, and their capacity to conduct electricity is increased as a result of a reaction between thermal neutrons and silicon atoms that convert part of those atoms to phosphorus. As a result, extrinsic semiconductors with superior uniformity and enhanced electroconductivity are created. For that purpose, the relatively low flux of neutrons is needed (~1013 n/cm/2/s), with a high ratio of thermal to fast neutrons **[24]**; however significant power of the reactor is usually needed **[25]**. Usually this is technically implemented by localizing the irradiation rig on the peripheries of the core, behind the highly-moderating barrier (e.g. heavy water, beryllium). Additionally, peripheral position gives the possibility of installing a large irradiation position as the commercial standard of the irradiated ingot is 6–8 inches **[26]**. Usually, those applications do not require additional staffing, but hot cells, storage place for decay, and flux monitoring equipment are needed.

A separate branch of irradiation services is testing the materials for advanced fission and fusion (e.g. SiC, window material, blankets), and electronic components, mostly as a means of introducing accelerated aging by the specific neutron flux. For those purposes often, thermostatic rigs are needed to control the irradiation temperature, atmosphere and pressure in the tested conditions [**27–28**].

**IV.C.** Analytical techniques

Neutron activation analysis is often performed using a nuclear reactor. It is an analytical technique for the determination of trace elements in a variety of complex sample matrices. It has a broad applications, from biological research and quality control of chemical compositions to forensic **[29–30]**. It depends on detecting gamma rays released from a sample that has undergone neutron irradiation. An element's concentration correlates with the rate at which it emits gamma rays from a sample. The irradiations may be performed with neutron beams or in the hydraulic rabbit(s) with sample loader(s). No additional equipment is usually needed, but the gamma-ray spectrometer.

The variation of the NAA is Prompt Gamma Neutron Activation Analysis, performed solely with neutron beams. It uses the prompt gamma rays emitted during the neutron capture. It can determine elements that cannot be measured by the conventional NAA, i.e. Cd, H, B, C, Gd, N, P, Pb, Si, and Sm **[31]**. The use of a cold neutron source is preferable for this technique, and its installation and operation is the significant technical and financial difficulty **[28]**.

**IV.D.** Neutron beam techniques

Derivation of neutron beams from the core makes using these particles for research outside the reactor core possible. In addition, the energy spectrum in such beams can be tailored (e.g. to cold, epithermal) to specific research needs. The applications consist of neutron scattering and radiography.

The former uses the high penetration of matter primarily due to the lack of an electrical charge. Neutron radiography produces an image (static or in motion) of the interior of the scanned object. Compared to gamma rays and Röntgen radiation, neutrons are absorbed in materials fundamentally differently. In contrast to x-rays, neutrons are attenuated by certain light materials but pass through many heavier ones. Neutron radiography can be used for specific unusual purposes since the penetration depth can reach several centimeters. This technique can be used, e.g. in quality control and archaeological research. Additionally, neutrons from beams can be used for activation purposes in autographic imaging methods. For both techniques, the acceptable neutron flux is higher than 106 n/cm2/s. However, the higher the flux, the shorter the exposition time, and the higher the resolution **[33]**, the appropriate beam collimator is required.

Neutron scattering is another branch of beam techniques that can be used in nuclear facility.
It allows, among others, to study the size of magnetic domains in amorphous, nanocrystalline and polycrystalline materials and the influence of external factors such as temperature, mechanical stress and magnetic field on the size of these domains **[34]**.
In addition, neutrons are mainly used to study the collective motions of atoms and magnetic moments by inelastic neutron scattering. They are also used to study electronic energy levels in ions that make up a solid by inelastic neutron scattering. Both are used in many studies, including in the field of materials science and electronics **[35]**.

As many possible applications of neutron beam exist, together with many types of specialized equipment (e.g. various diffractometers, reflectometers and interferometers), it is difficult to predict the needed staffing and equipment. Generally, one beam is usually occupied by one instrument. For their installation, a separate hall is needed and preferably a separate laboratory building.

**IV.E.** Education and training

Nuclear reactor with all of the facilities mentioned above is able to support nuclear education and training in the country at the level of higher education. Students can take advantage of unique hands-on training. Typical laboratory experiments are flux measurement, NAA, calibration of instruments, radioactivity detection, and shielding effectiveness measurement.

Additionally, research reactor is a unique infrastructure that can be presented to the broad public in order to raise awareness of the benefits that the nuclear technology brings to the society, that includes not only the public tours and visits, but also the possibility of teaching people at the high school level of education.

It is difficult to use a full-scale research reactor (i.e. > 1 MWth) for hands-on training of the reactor’s operation due to its tight operation regime: safety and regulatory issues exist for such an approach. However, some possibilities exist, e.g. prediction of start-up conditions and comparison of calculations with the actual procedure performed by the skilled operator.

For the purposes of actual operation training, smaller facility is better (i.e. < 1 kWth, or even subcritical), however experiments (e.g. safety, transients and fundamental research on the nuclear fuel cycle) will be performed rather by the students than operators during training, as nuclear power plant simulators are nowadays better suited for the latter.

Most of the capabilities mentioned above can contribute to the support of existing and planned power nuclear reactors. Research reactor can contribute either directly as the place for fuel qualification, material testing (e.g. witness samples irradiation) and education, or indirectly as the aggregator of competences necessary for the nuclear power project development and future staff training centre. Some of them will be covered by the LPRR **[1,16]**, however broader utilization requires higher power of the reactor.

**V. Recommendations based upon experience with MARIA reactor operation**

MARIA reactor has operated in Poland since 1974; it has thermal power of 30 MWth corresponding with thermal neutron flux 2∙1014 n/cm2/s, and it is a channel-in-pool type cooled by water. It is a derivative of the Soviet MR design that served as a material testing reactor with multiple loops for fuel testing **[37]**. This particular design choice was the only possibility at the time due to Poland’s political dependence on the Soviet Union.

The original design was modified in Poland to make it more multipurpose: vertical irradiation channels for isotope production and horizontal neutron beams were added. However, the original design still causes numerous limitations, mainly the number of irradiation positions and unusual fuel type in the shape of concentric tubes in fuel channels. The main advantage of the design is modularity – beryllium blocks that serve as a moderator and graphite reflector can be shuffled depending on the needs, together with irradiation position within them.

The main issue during the reactor’s operation has always been the lack of a strategic plan indicating the expected development directions and the resulting financial and operational problems **[38]**.

Lessons learned from nearly fifty years of MARIA operation are of operational and technical design nature. The former is the necessity of a flexible strategy plan of utilisation that determines the reactor’s priorities. For newly-built reactors, their creation must be combined with selecting the reactor design and its possible applications. The latter is that simplicity is the technical goal of the well-utilised nuclear reactor. Pool-type constructions are preferred, preferably with the MTR-type nuclear fuel elements (plates). Additionally, the reactor has to be the central object in the research centre and have adequate ancillary infrastructure needed for its applications.

VI. Conclusions

Research reactors are facilities that support the development of national nuclear power programmes and have applications that go beyond. The multipurpose research reactor with specific thermal power and high neutron flux will offer a flexible facility to meet future needs for basic and applied research, material irradiation, and radioisotope production in medicine and industry. Their decreasing number in the world and the anticipated increases concerning the needs of their use (e.g. advanced fission and fusion technologies, radiomedicine, batteries e.g. for electric vehicles) will make this type of device invaluable for the country with nuclear and scientific ambitions. The key to its construction and efficient use is a well-tailored design and connecting the facility to the appropriate research network.

Nomenclature and abbreviations

CAREM-25 – Central Argentina de Elementos Modulares (es. Argentinian Modular [nuclear] Plant)

DELPHI – subcritical assembly operated by Delft University of Technology

BNCT –Boron Neutron Capture Therapy

ETRR-2 – Experimental Training Research Reactor Number two

EWA – Eksperymentalny Wodny Atomowy, 8 MWth decomissioned (pol. Experimental Water Atomic)

HOR – Hoger Onderwijs Reactor, 2 MWth
(nl. Higher Education Reactor)

HTR-10 – Chinese experimental HTGR, 10 MWth

HTR-PM – Chinese experimental HTGR, 2x250 MWth

HTGR – High Temperature Gas-cooled Reactor

IAEA – International Atomic Energy Agency

I&C – Instrumentation and Control

JRTR – Jordan Research and Training Reactor

LPRR – Low Power Research Reactor

MARIA – Poland’s Research Reactor, 25 MWth

MARYLA – Mały Reaktor Laboratoryjny, 0.1 MWth decomissioned (pol. Small Laboratory Reactor)

NAA – Neutron Activation Analysis

PWR – Pressurized Water Reactor

PGNAA – Prompt gamma neutron activation analysis

RR – Research Reactor

SFR – Sodium-cooled Fast Reactor

SWOT – Strengths, Weaknesses, Opportunities, and Threats

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