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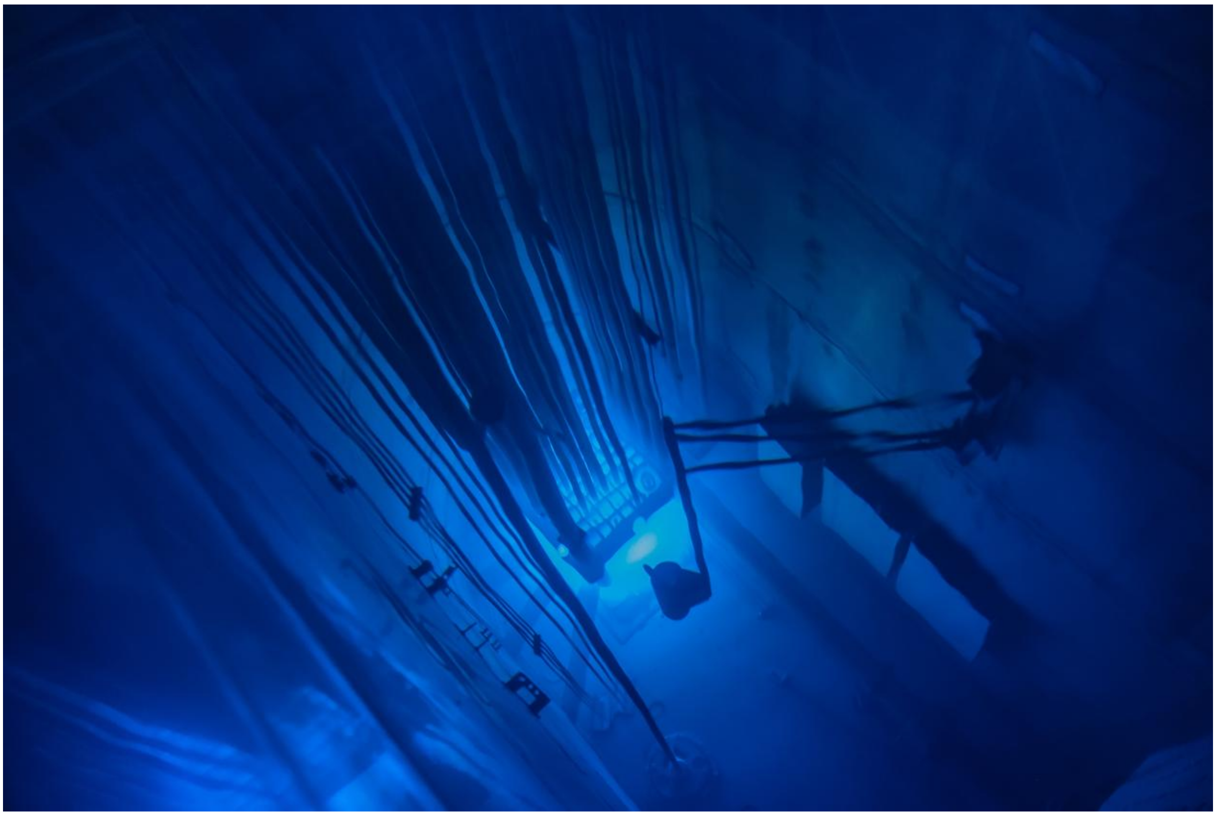
Trends in the use of research nuclear reactors featuring the OPAL, KJRR, and PALLAS type reactors



There is a growing amount of information in the public domain concerning the construction of large-scale nuclear reactors and small modular reactors in Poland. However, in addition to nuclear reactors used for electricity generation, research reactors also play an important role. The MARIA research nuclear reactor has been operating for many years at the National Center for Nuclear Research in Otwock, mainly used to produce radioisotopes for medical purposes.

Introduction

This analysis presents three research reactors under construction or in operation in different parts of the world: OPAL in Australia [1], KJRR in South Korea [2], and PALLAS in the Netherlands [3]. These reactors were selected to analyze the rationale for their construction in highly developed countries, which may provide Polish decision-makers with grounds for initiating conceptual work on the possible replacement of the MARIA reactor [4] or the construction of a new reactor and accompanying infrastructure as an alternative to the MARIA reactor. The expected remaining lifetime of the MARIA reactor is approximately 20 years [5], and the overall process leading to the commissioning of a new research reactor is estimated in this analysis to take approximately 15-19 years. This relationship directly indicates the imminent need to begin conceptual work related to the construction of a new research reactor in Poland. The analysis also aims to identify the main trends in the construction of scientific and commercial infrastructure related to the operation of research reactors. The criteria for selecting reactors for analysis were based on their location – highly developed, economically stable countries; the type of reactor – multifunctional pool-type reactors; the time of the decision to build – the decision to build was made no later than 30 years ago; and transparency in access to reliable information about the reactor.

Research reactors

Research reactors can serve many functions depending on their design and use during operation. They are mainly used to produce radioisotopes for medical (e.g., scintigraphy) and industrial (e.g., radiography) purposes, neutron doping of silicon to produce high-quality semiconductor material, materials research, and educational and training purposes. It is worth noting that many research reactors can be used simultaneously for all the above activities, thanks to their universal design. Research reactors have unique design features that allow materials to be irradiated with a precisely tuned neutron spectrum and flux, enabling advanced scientific and commercial work. In addition, due to their multifunctionality and operational flexibility, research reactors play an important role in nuclear energy, as they allow for the testing of new materials (e.g., nuclear fuel, structural materials) and systems and devices intended for use in nuclear power reactors. Testing is carried out under conditions like the actual operating conditions of nuclear power reactors and cannot be performed in other devices, which is one of the indisputable advantages of research reactors.

It is also worth noting the commonly used nomenclature. The term "research reactor" does not necessarily refer to its function strictly related to scientific research, but to its use for purposes other than commercial electricity generation or propulsion of vessels. This type of nomenclature is used by the IAEA (International Atomic Energy Agency), which in a broader context may introduce inaccuracies in the definition of research reactors [6]. A distinction should also be made between reactors used for scientific research and demonstration reactors, i.e., prototypes of commercial reactors. The main purpose of building and operating research reactors is to use the reactor for dedicated scientific, production, and training activities. Demonstration reactors, on the other hand, are used to test new reactor technology under conditions similar to actual operating conditions, but on a smaller scale, which provides final confirmation of the safety of the developed technology.

Data points

Currently, there are 228 research reactors operating in 54 countries worldwide, with another 12 reactors under construction in 11 countries and 11 reactors planned in 9 countries. Of the research reactors in operation, most are in Russia (54), the USA (48), and China (17). There are currently 32 nuclear research reactors operating in European countries, with the largest number in Germany (5) and Italy (5). There are 166 research reactors older than 40 years, which accounts for 72% of all research reactors in operation [7]. Research reactors are typically designed for a 50-year operating life, so most of them will soon need to be replaced or extensively modernized to extend their service life.

The statistics presented consider every type of research reactor as defined by the IAEA, regardless of its mode of use or design. Thus, the statistics also include so-called subcritical assemblies, in which a self-sustaining chain reaction is not achieved, or low-power reactors often used for educational and training activities, whose use for other purposes is limited. Interestingly, only 22 research nuclear reactors of all types have been commissioned worldwide in the last 25 years, including only 5 reactors with a power output of more than 1 MWth of the pool or pool-and-tank type. Two of these reactors were commissioned in China – CARR (China Advanced Research Reactor) and CMRR (China Mianyang Research Reactor), one in India – Apsara-U (Apsara-Upgraded), one in Jordan – JRTR (Jordan Research and Training Reactor), and one in Australia – OPAL (Open Pool Australian Lightwater reactor).

The Polish MARIA nuclear reactor with a capacity of 30 MWth was launched on December 18, 1974. Over the years, it has been fully modernized to meet the safety standards required by current regulations. It is mainly used to produce radioisotopes for medical purposes, covering approximately 10-15% of the global demand for the molybdenum isotope 99Mo. The configuration of the reactor core and the availability of vertical and horizontal activation channels for irradiating material samples offer potential prospects for the use of the reactor by the scientific community for advanced research supporting the implementation of nuclear energy in Poland.

OPAL Reactor

One example of a multifunctional research pool-type nuclear reactor is the OPAL reactor, located in Lucas Heights on the outskirts of Sydney, as part of the research infrastructure of the Australian Nuclear Science and Technology Organisation (ANSTO). It is worth noting that this is the only nuclear reactor in Australia, which has officially banned the construction of nuclear reactors and selected nuclear fuel cycle infrastructure at both the federal and state levels [8]. Even though the country has no other research or power reactors, it plays an important role in the global nuclear industry due to its large uranium reserves and advanced scientific research in the field of nuclear energy.

Plans to build a research reactor were initiated in 1991, which was related to the need to replace the previous HIFAR (High Flux Australian Reactor) reactor due to its planned decommissioning after 49 years of operation (January 26, 1958 – January 30, 2007). The final decision to build was made in 1997, and the turnkey construction contract was signed in June 2000 with the Argentine company INVAP, which has extensive experience in research reactor projects. The construction work was contracted to the Australian companies John Holland Construction and Engineering and Evans Deakin Industries Limited.

Construction of the reactor began on April 1, 2002, and it was commissioned (first criticality) on August 12, 2006, giving a total construction time, including commissioning procedures, of approximately 52 months. Thus, the entire process from the decision to build a new reactor to its commissioning took approximately 15-16 years. The cost of constructing the reactor is estimated at approximately AUD 475 million [9], which at the current exchange rate is approximately USD 320 million.

The reactor has a power output of 20 MWth and operates in cycles of 30-35 days, followed by a technological break of approximately 2 days for fuel replacement – three fuel assemblies are replaced. The reactor core consists of 16 fuel assemblies containing low-enriched uranium (19.75% isotope 235U) in the form of U3Si2 -Al plate fuel. It is arranged in a 4x4 fuel cassette matrix, arranged in four square clusters, 4 cassettes each. The reactor uses fuel cassettes containing 484 grams of 235U and a burnable cadmium absorber. The mass of the fissile isotope uranium 235U in the core is approximately 6 kg, depending on its configuration and stage of the fuel cycle. The height of a single fuel cassette is approximately 105 cm, the height of the fuel is approximately 60 cm, and the dimensions of the cassette are approximately 8x8 cm. Between the cassettes there is space for operating five control rods that together form a cross shape (four symmetrical, outer, rectangular plates and a central cross-shaped rod), made of hafnium and zirconium alloys. The reactor is cooled and moderated by light water, but its neutron reflector consists of a zirconium tank filled with heavy water. The core size is approximately 35x35 cm, the diameter of the reflector tank is 260 cm, and its height is 122 cm [10]. The reactor core is situated in a pool under a layer of light water approximately 13 m thick. The expected operating life of the reactor is 60 years.

The main purpose of this reactor is to produce radioisotopes necessary for medical diagnostics, cancer treatment, and industrial applications. The reactor provides approximately 80% of the radioisotopes used for medical purposes in Australia and covers approximately 9% of the global demand for the isotope molybdenum 99Mo. It also provides neutron beams for materials research using neutron activation analysis. One of the most interesting applications of the reactor is neutron doping of silicon crystals to produce high-quality semiconductor material used in advanced electronics (Neutron Transmutation Doping). Maximum production can reach around 60 tons of doped silicon per year. The reactor has the necessary infrastructure to carry out the activities in the form of approximately 80 vertical channels and 5 horizontal channels, ensuring the possibility of irradiating material samples in any thermal or fast neutron flux [11]. It is worth noting that the reactor is the primary device providing neutrons for a range of scientific and commercial activities carried out in related research infrastructure, e.g., at the molybdenum manufacturing facility for medical purposes (99Mo Manufacturing Facility) or at the neutron scattering center (Australian Centre for Neutron Scattering), where advanced materials research is conducted. Also noteworthy is the high level of transparency of the ANSTO organization regarding the nature of its research, the available research infrastructure, and how it is used by the scientific community.

KJRR Reactor

On April 28, 2023, construction began on the Korean KJRR (Ki-Jang Research Reactor) research reactor with a capacity of 15 MWth [12]. The reactor is being built in the Busan area near the Kori nuclear power plant in Kijang-gun. The reactor is based on the HANARO (High-Flux Advanced Neutron Application Reactor) research reactor, which has been in operation since February 1995, and the Jordanian JRTR reactor, which was launched in April 2016. The latter reactor is a successful example of the export of Korean nuclear technology to Jordan, a country that is building its expertise in the use of research nuclear reactors and the future implementation of nuclear energy. The motivation for building a new research reactor in Korea was the need to increase the production of radioisotopes for industrial and medical purposes, as well as to increase the capacity for neutron doping of silicon. The launch of the KJRR reactor is intended to ensure full self-sufficiency in the production of radioisotopes, mainly molybdenum 99Mo, for the domestic market, as well as to expand its export capabilities, ultimately covering 20% of global demand. The reactor itself is intended to confirm the high competence of the Korean nuclear industry and serve as a technology demonstrator for potential export customers.

The decision to build a new reactor was made on April 1, 2012. The project coordinator and technology supplier is KAERI (Korea Atomic Energy Research Institute), and its contractors are a consortium of several Korean companies led by Daewoo Engineering & Construction. Construction is expected to be completed in early 2027, with first criticality by the end of the same year. Thus, the construction of the reactor and commissioning tests are expected to take approximately 56 months, and the total time from the investment decision to the start-up of the reactor is estimated to be approximately 15-16 years. The planned operating life of the reactor is 50 years, and its construction costs are estimated at approximately US$575 million [13].

The reactor is a pool-type reactor and operates on low-enriched uranium fuel containing 19.75% of the 235U isotope. It is cooled and moderated with light water, and surrounded by a neutron reflector consisting of graphite and beryllium, and partly aluminum. The diversity of materials surrounding the core is determined by the requirements for the appropriate shaping of the neutron flux and spectrum in the available activation channels. The annual operating time of the reactor is expected to be 300 days in cycles of approximately 37.5-50 days. The reactor fuel consists of fuel cassettes containing plates made of U-7Mo/Al-5Si. The reactor core has a rectangular shape forming a 7x9 matrix of elements, consisting of 63 internal positions measuring approximately 7.5x7.5 cm. It contains 22 fuel assemblies, including 16 standard assemblies and 6 assemblies connected to control rods made of hafnium [14]. Operating the control rods simultaneously changes the axial position of the fuel assemblies, which provides an additional safety system by extending the fuel assemblies beyond the reactor core. The height of the fuel in the cassette is approximately 60 cm, the total height of a standard cassette is approximately 100 cm, and that of a mobile cassette is 76 cm. The mass of the fissile isotope uranium-235U in the fuel cassette is approximately 618 g, which means that there is approximately 13.6 kg of 235U in the core. Most of the space in the reactor core is occupied by 29 neutron reflector elements surrounding the fuel cassettes, made mainly of beryllium.

The reactor is equipped with many activation channels enabling the production of radioisotopes, silicon neutron doping, and other research related to activation analysis and neutron scattering. The main systems inside the core include the HTS (Hydraulic Transfer System), six positions to produce 99Mo in uranium targets, and five positions containing channels for neutron irradiation. Outside the core, there are two Pneumatic Transfer Systems (PTS), six positions for silicon neutron doping (maximum capacity 150 tons/year), and accompanying infrastructure necessary for scientific and commercial work. In addition, the reactor complex will include the construction of the infrastructure necessary to produce the molybdenum isotope 99Mo – FMPF (Fission Molly Production Facility), the production of radioisotopes – RIPF (Radio Isotope Production Facility), and a unit responsible for nuclear waste management – RWTF (Rad-Waste Treatment Facility). It is worth mentioning that three major technological innovations were developed during the design of the reactor [15]: a system of control rods located below the reactor core, a new type of fuel cassette with U-7Mo/Al-5Si fuel, and a new type of activation channels with cut edges.

The KJRR reactor has a unique core designed for scientific and commercial activities, particularly in the context of using multiple materials to shape the neutron flux and spectrum. The core is technically complex, but it can be reconfigured largely for dedicated activities, which demonstrates the universal nature of the reactor as an advanced research infrastructure.

PALLAS Reactor

Another example of a nuclear research reactor currently under construction is the PALLAS reactor being built in Petten, the Netherlands, as part of the EHC (Energy & Health Campus). It is intended to replace the High Flux Reactor (HFR), which has been in operation since November 9, 1961. The main motivation for building the new research reactor was the need to ensure a continuous supply of radioisotopes used in medicine for the local and foreign markets, mainly the molybdenum isotope 99Mo. The planned decommissioning of the HFR reactor may disrupt the production process in the future and make the Netherlands dependent on foreign suppliers. Currently, the HFR reactor accounts for approximately 25-30% of the world's production of molybdenum-99m.

Plans to replace the HFR reactor began in 2002, but it was not until 2012 that the final decision to build was made, backed by official support from the Dutch government for the investment. Preparatory work on the construction site began in 2021, and the official start date of construction is September 29, 2025, when construction work on the nuclear part of the reactor began [16]. The reactor is expected to reach first criticality on April 1, 2031. In the same year, the HFR reactor is to be decommissioned, which will ensure the smooth production of radioisotopes for medical purposes. The total cost of the project is estimated at around €2.4 billion, which at the current exchange rate is approximately $2.85 billion [17]. The total construction time, including start-up tests, is planned to be approximately

66 months, and the total investment process, from the binding decision to build to the start-up of the reactor, will take approximately 19 years. The reactor is expected to have a service life of 50 years.

The reactor technology was provided by ICHOS, owned by the Argentine company INVAP, and its construction was carried out by the Spanish company FCC Construcción. The reactor has many features in common with the Australian OPAL reactor, e.g., a similar arrangement of the reactor pool and service pool, the use of a heavy water tank as a neutron reflector, the same type of fuel assemblies, and a similar design of plate control rods. The PALLAS reactor is a 25 MWth pool-type reactor.

The reactor core consists of a 5x4 matrix, giving a total of 20 positions for its elements. It can contain up to 20 plate-type fuel assemblies. The reactor core consists of a 5x4 matrix, giving a total of 20 positions for its elements. It can contain up to 20 plate-type fuel assemblies, and a maximum of two of these can be replaced with elements with activation channels designed for neutron irradiation. The core also contains six hafnium control rods, shaped like plates arranged parallel between the rows of fuel assemblies, three next to each other. The reactor fuel is low-enriched uranium in the form of U3Si2-Al, like the OPAL reactor. The fuel cassettes also have the same design, i.e., dimensions of approximately 8x8 cm, a total height of approximately 105 cm, and a fuel height of approximately 60 cm. The maximum mass of the fissile isotope uranium 235U in the core is approximately 9.7 kg [18]. The estimated annual operating time of the reactor is 300 days, in cycles of approximately 43 days.

One of the main purposes of the reactor is to test technologies intended for implementation in SMR (Small Modular Reactor) reactors and Generation IV reactors, mainly tests of structural materials, alternative coolants, and innovative nuclear fuels. Most of the infrastructure dedicated to scientific and commercial work is in the reflector tank, around the core, i.e. 14 positions for irradiating uranium targets to produce molybdenum 99Mo and 15 activation channels for irradiating materials in different neutron fluxes, depending on the needs of the research activity. In addition, the reflector tank contains a beryllium matrix that allows several separate experiments to be placed, thus enabling advanced research, e.g., on liquid salt-based coolants. The accompanying infrastructure also includes the NHC

(Nuclear Health Center) nuclear medicine center and new laboratories equipped with hot cells for post-activation testing of material samples. It is worth noting that the reactor under construction is in the vicinity of advanced infrastructure already used to service the HFR reactor, e.g., a molybdenum production plant, laboratories equipped with hot cells, laboratories dedicated to actinide research, and units responsible for decontamination and nuclear waste management. Thus, the PALLAS reactor will naturally become a key addition to the complex.

The PALLAS reactor can largely be considered a hybrid design with features of both NOAK (Next Of A Kind) and FOAK (First Of A Kind) reactors. Its design is partly based on the OPAL reactor design and was carried out by the same Argentine company, INVAP, but it has distinctive design features adapted to the specific conditions of its use. This is a very important fact, as the experience gained during the construction of the OPAL reactor can be used in the construction of the PALLAS reactor. In addition, the introduction of changes to the reactor design demonstrates the real possibility of taking into account the customers' requirements, rather than forcing them to invest in a serial product that is not necessarily optimized for the intended use.

Conclusions and recommendations

The actual construction time for a research reactor estimated in this analysis is approximately 4-6 years, and the total investment time is 15-19 years. However, it is worth noting that the reliable indicator is the construction time, not the total investment time, as it may be determined by factors other than the desire to start up the reactor as soon as possible. The costs of constructing research reactors vary significantly, ranging from approximately $320 million to $2.85 billion. The cost data are officially reported in communications from the institutions responsible for the investment, but they are not reliable, as they are not supported by data breaking down the costs into individual parts of the investment (e.g., they do not specify whether they include the construction of the entire infrastructure or only the reactor, etc.) and do not show the financial parameters used to calculate them, making it impossible to compare them reliably.

This analysis presents new trends in the construction of research reactors, which may be used during conceptual work on the construction of a new research reactor in Poland. Three pool-type reactors were analyzed as being the most similar in terms of their operating profile to the potential successor to the MARIA reactor. The analysis directly shows that:

a) The main activity planned for all three reactors described is the production of radioisotopes for medical purposes, mainly molybdenum-99m, to meet domestic market demand and for export. The new research reactor in Poland should also focus on this area due to the need to secure the domestic demand for radioisotopes used in the production of radiopharmaceuticals, which are essential in the Polish healthcare system. From a purely commercial point of view, production should also focus on export markets in order to financially balance the operation of the necessary infrastructure.

Unlike the current situation, the new infrastructure should cover the entire production cycle of radiopharmaceuticals, not just selected parts of it, which requires the construction of advanced supporting infrastructure.

b) The second activity planned for implementation in the reactors under consideration is silicon neutron doping, but it is only expected to be carried out on a large scale in the OPAL and KJRR reactors. The new reactor should also be equipped with the infrastructure necessary for silicon neutron doping. Domestic semiconductor production using this method will allow Poland to establish its own capabilities for producing high-quality semiconductors used, for example, in the military or energy industries. Such production can also be commercially exported as a high-margin product. To make this possible, the infrastructure necessary for further processing of the manufactured semiconductor material should be located in Poland, creating a local ecosystem.

c) Each of the reactors described has at least one unique target use dedicated to a given design, i.e. the OPAL reactor – the use of neutron beams for advanced scientific research related to activation analysis; the KJRR reactor – the demonstration of innovative solutions developed in Korea for the purpose of exporting reactor technology to foreign customers; PALLAS reactor – dedicated research infrastructure for testing materials and systems intended for use in SMR reactors and Generation IV reactors. The new Polish research reactor should also have at least one unique application option not available in other reactors to monopolize the market by providing exceptional services, e.g., related to the possibility of testing nuclear fuel in simulated severe accident conditions.

d) In each case, research reactors constitute the main infrastructure around which an ecosystem of subsidiaries is created, utilizing the reactor's capabilities, i.e., the construction of a new research reactor should always be associated with the construction of additional infrastructure that maximizes its potential in the scientific, technological, and production areas. In the case of the concept of replacing the MARIA reactor, the main objective should not only be the construction of a new research reactor, but the construction of a completely new research complex (e.g., a nuclear valley), whose main research facility is the reactor.

e) Research reactors constitute scientific and commercial infrastructure to which there should be clear and transparent access for the local and international scientific community, as well as commercial entities, e.g., in the form of a grant competition for the use of the reactor and its infrastructure. In addition, the entity responsible for operating the reactor should have world-class infrastructure at its disposal to compete freely with other research centers of a similar profile and attract top-class specialists. In the case of the reactors under consideration, these conditions appear to be met, especially in the case of the OPAL reactor, which is already in operation. The new reactor potentially planned in Poland should absolutely meet these conditions. Currently, the access mode for the scientific community or commercial entities to the MARIA reactor and related infrastructure is not very transparent in terms of access paths and procedures.

f) In addition, the new reactor and related research infrastructure should be used to train future personnel for the development of nuclear energy, which is of key importance in Poland. Admittedly, in the case of research reactors, training related to interference with reactor operation is impossible, but training on reactor operation, design, and use, as well as experiments in the accompanying infrastructure, are entirely feasible (e.g., related to activation analysis, radiation protection, radiation detection, etc.).

Conclusion

The analysis clearly indicates an urgent need to begin conceptual work on a new research reactor, which will replace the MARIA research reactor currently operating at the National Center for Nuclear Research. The construction of a new innovative nuclear reactor will allow for the maintenance of existing competencies and the development of new ones in the field of nuclear energy, which is of key importance in the era of the construction of the first nuclear power plant in Poland. In addition, a reliable indicator of a country's scientific and development potential is the possession of technologically advanced infrastructure, such as a modern, multifunctional research reactor. The new reactor will not only enable scientific research at the highest international level, but also a range of commercial activities, which will directly create a bridge between science and industry. An important aspect of the construction of the new reactor is the simultaneous construction of accompanying infrastructure to maximize its use. The potential creation of a “nuclear valley” in Poland, with the new research reactor at its heart, will place the country among the leaders in innovative scientific research and development work, the effects of which have a direct, positive impact on the development of many technologically advanced sectors of the national economy.

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