Technology Readiness Level indicators, and the nuclear technologies currently being offered

Wskaźniki poziomu gotowości technologicznej (TRL), a oferowane obecnie technologie jądrowe

Andrzej G. Chmielewski
Institute of Nuclear Chemistry and Technology
(Instytut Chemii i Techniki Jądrowej)

Abstract: The paper presents the process of assessing the degree of development of a technology or product based on the Technology Readiness Level (TRL) scale in the understanding of both institutions operating in the country where this scale was created, as well as in the European Union and Poland. A practical example of the implementation of complex radiation technology in the energy sector is also presented, which proves that it is analogous to the procedures used to scale up in the implementation of engineering projects. In the final part of the paper, the results of the assessment of the progress in the development of new nuclear technologies, such as SMR reactors, were presented with the use of TRL.

Keywords: Technology Readiness Level, radiation technologies, SMRs.

Streszczenie: *W pracy prezentowany jest proces oceny stopnia rozwoju technologii lub produktu oparty na skali poziomu gotowości technologicznej (TRL) w rozumieniu zarówno instytucji działających w kraju, w którym ta skala powstała, jak również w Unii Europejskiej i Polsce. Przedstawiono też przykład praktyczny działania polegający na wdrażaniu w energetyce skomplikowanej technologii radiacyjnej, co jest dowodem na to, że jest on analogiczny do stosowanych procedur powiększania skali w realizacji projektów inżynierskich. W końcowej części referatu przedstawiono rezultaty oceny z wykorzystaniem TRL postępów prac w zakresie rozwoju nowych technologii jądrowych, jakimi są reaktory SMR.*

Słowa kluczowe: *Poziom gotowości technologicznej, technologie radiacyjne, SMR.*

1. Introduction

The process based on the *Technology Readiness Level* (TRL) scale is used to quantitatively and qualitatively assess the maturity of a given technology. The TRL process was developed and is therefore used by the US *Department of Defense* (DoD) for the development and implementation of new technologies and systems for defence applications. In the 1980s, NASA successfully used the TRL process to develop and implement new systems for space applications. TRLs, i.e. the technology readiness levels, are used to define the degree of advancement of technology and enable a comparison of the state of advancement of work on technologies. The introduction of new technologies from the laboratory to the market requires a transition through the continuum of research, development, demonstration and implementation of RDDD (*Research, Development, Demonstration & Deployment*). This is successfully used by the Office of Technology Transitions of the Department of Energy (DoE), which is tasked with overseeing commercialization activities across the department and beyond. In order to implement new solutions on a commercial scale, both technical and ecosystem-related obstacles must be overcome. The management of modern technology portfolios can be improved by complementing the widely used technological readiness level framework. However, technical feasibility is only half the battle when it comes to implementing a product on a commercial scale. Other adoption issues – such as product matching, demand, supply chain, regulatory risk, and workforce availability – play a role in the likelihood of successful implementation of technology.

The need to create such a scale results from the fact that currently decisions regarding the financing of projects and the commercialization of technology are decided by industrialists, economists, lawyers, and in the case of defence or large projects that are complex technical activities and of great social importance, such as the construction of nuclear power plants, also politicians. The sequencing of activities similar to TRL results from the knowledge passed on to students, future engineers during lectures at technical universities. This direction was created for people who want to be a bridge between scientists, creators of new solutions and engineers from other fields, combining, when implementing the project, their skills and an interdisciplinary view of industrial processes.

The diagram of activities taught to students includes all stages listed on the TRL scale: Laboratory research and development of selected technology elements; Technology optimization; Miniature model installation; Semi-technical installation – scale-up; Industrial installation – production [1].

2. Definitions of Technology Readiness Levels (TRLs) in the World, the EU and Poland

The TRL scale has been designed to streamline decision-making processes and technology development from idea to implementation. Firstly, the main advantage of the TRL scale is that it establishes a universal framework for assessing the level of maturity of technology. Therefore, it promotes a common understanding among various stakeholders in the field of technological maturity assessment, serving them as a common language in project evaluation and making appropriate decisions.

The use of TRLs currently serves as an eligibility criterion for certain EU programmes, providing a clear indication of the level of technological maturity required to qualify a project for funding. EU funding programmes have different objectives that require different levels of TRL, and an in-depth understanding of TRL can help to provide the necessary funding for a project. Applicants may use this information to ensure that their project meets the necessary requirements and evaluators shall use it to assess the project.

The TRL also allows project managers to identify and predict potential risks in the initial stages of the project, through the initial stages of testing the proposed solutions and processes. Lower TRLs are typically associated with higher risk. Various processes and milestones integrated into the TRL scale allow managers to address potential risks, reducing the possibility of encountering significant problems in the later stages of the project. In this way, the TRL indicators help to ensure that the technology is properly tested and verified before it is deployed on a large scale.

The TRL serves not only as a tool for managing and mitigating risk, but also as a valuable planning tool in decision-making in general. It defines a roadmap, allowing project managers to set realistic goals and identify key milestones to be achieved before the technology is ready for commercialization. Although projects with lower TRLs typically experience more missed deadlines than projects with higher TRLs, the TRL scale still proves useful in setting achievable targets.

Definition and description of individual indicators of technological readiness (TRL) developed and adopted by the said Office for Technological Transitions of the DOE are presented in Table 1.

This document gives the development to achieve TRL 8, commercialization takes place in TRL 9. Usually in the USA, the EU and Poland, a scale from TRL 1 to TRL 9 is used.

In the “Horizon Europe“ programme, the technological readiness levels are used as an indicator for a better classification of presented projects [3]. Technological readiness levels enable applicants and evaluators to adapt project applications to the expectations of the European Commission by providing a common unit of measure of their progress and value. For example, in the guidelines of various financing programmes, a higher level of technological readiness means that projects in the area of submitting applications are sought. On the other hand, the low level of technological readiness may indicate that the invitation focuses on research and development projects. With regard to its financing instruments, the European Commission has adapted the definition of TRL. TRLs describe different stages of technology, product or service development on a scale of 1 to 9. Technology readiness levels are a way of describing the maturity of technology and a tool for comparing the state of advancement of work on various technologies. According to this scale, the maturity of the technology is described from the conceptualization phase of a specific solution (TRL 1) to the stage of maturity (TRL 9), when this concept (as a result of scientific research and development works) takes the form of a technological solution that can be applied in practice – e.g. in the form of launching market production. This scale makes it easier for external investors to track the progress of product development and is a helpful tool and indicator of KPI (*Key Performance Indicator*) development. From the point of view of the investor, the higher the TRL, the greater the chance of success and the lower the investment risk.

The Polish National Centre for Research and Development (NCBR) co-finances projects according to the TRL

Table 1. Technology Readiness Levels (TRL) (acc. to US Department of Energy – DOE Technology Readiness Levels-(TRLs).
Tabela 1. *Poziomy gotowości technologicznej (wg US Department of Energy – DOE Technology Readiness Levels-(TRLs).*

EERE R 540.112 – 02 [2]: Technology Readiness Levels (TRL): It is necessary to determine the level of readiness of the technology related to the project, as well as the planned progress during the project implementation. A detailed explanation of the rationale for the estimated technology readiness level should be provided. Specific criteria for entering the next higher technology readiness level should be defined. The following definitions apply:
TRL-1. Basic principles observed and reported: Scientific problem or phenomenon identified. Essential characteristics and behaviors of systems and architectures are identified using mathematical formulations or algorithms. The observation of basic scientific principles or phenomena has been validated through peer-reviewed research. Technology is ready to transition from scientific research to applied research. **TRL-2. Technology concept and/or application formulated: Applied research activity.** Theory and scientific principles are focused on specific application areas to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application. **TRL-3. Analytical and experimental critical function and/or characteristic proof of concept:** Proof of concept validation has been achieved at this level. Experimental research and development is initiated with analytical and laboratory studies. System/integrated process requirements for the overall system application are well known. Demonstration of technical feasibility using immature prototype implementations are exercised with representative interface inputs to include electrical, mechanical, or controlling elements to validate predictions. **TRL-4. Component and/or process validation in laboratory environment- Alpha prototype (component):** Standalone prototyping implementation and testing in laboratory environment demonstrates the concept. Integration and testing of component technology elements are sufficient to validate feasibility. **TRL-5. Component and/or process validation in relevant environment- Beta prototype (component):** Thorough prototype testing of the component/process in relevant environment to the end user is performed. Basic technology elements are integrated with reasonably realistic supporting elements based on available technologies. Prototyping implementations conform to the target environment and interfaces. **TRL-6. System/process model or prototype demonstration in a relevant environment- Beta prototype (system):** Prototyping implementations are partially integrated with existing systems. Engineering feasibility fully demonstrated in actual or high fidelity system applications in an environment relevant to the end user. **TRL-7. System/process prototype demonstration in an operational environment- Integrated pilot (system):** System prototyping demonstration in operational environment. System is at or near full scale (pilot or engineering scale) of the operational system, with most functions available for demonstration and test. The system, component, or process is integrated with collateral and ancillary systems in a near production quality prototype. **TRL-8. Actual system/process completed and qualified through test and demonstration- Pre-commercial demonstration:** End of system development. Full-scale system is fully integrated into operational environment with fully operational hardware and software systems. All functionality is tested in simulated and operational scenarios with demonstrated achievement of end-user specifications. Technology is ready to move from development to commercialization.

logic – the aim of most programmes is to refine the technology so that it can be applied in real conditions (i.e. so that it reaches the technological readiness level 9). Of course, one should also remember about its own IT Due Diligence, because companies offering a product or technology do not always rate TRL well, and even increase the scale of product maturity. NCBR uses a nine-level system of classification of technological readiness to evaluate research and development and innovation projects, determining their degree of advancement and readiness for practical application. This classification of levels helps in identifying areas where technologies require further development and support, as well as facilitates decision-making on financing and investing in projects of various technological advancement [4].

It should be mentioned that the Regulation on defence projects mentions the need to use the proposed projects according to the TRL scale [5], undoubtedly this scale should be used in projects related to radiation and nuclear technologies.

3. An example of the use of TRL in scale-up in the case of the implementation of radiation technology in the power industry

A good example of the procedure in accordance with the recommendations of the TRL scale was the process of implementing nuclear and radiation technologies in the power industry, it concerned the use of the radiation method of treatment of waste gases from coal-fired boilers [6]. The design offices Energoprojekt Warsaw and Katowice, Proatom BP, and contractors Energobudowa, ELWO Pszczyna and others were involved in the implementation of the project by the employees of the Institute of Nuclear Chemistry and Technology.

The projects were carried out by the investment departments of EPS Kawęczyn and the Dolna Odra Power Station. Industrial installations, pilot and full-scale, required the issuance of permits by the PAA, the Ministry of the Environment, the Ministry of Health and the voivodship authorities. It was the largest radiation installation ever built in the world; the power of the installed accelerators was 1.2 MW.

TRL 1–2 (i) was observed and the primary principles of the process were announced, (ii) the basics of the technology were defined); this stage was based on the observed phenomena of creating low-temperature plasma in a gas irradiated with an electron beam, and the basis of the technology resulted from the knowledge about the possibility of oxidation non-reactive and poorly water-soluble NO and SO_2 forming harmful sulphites, to anhydrides of nitric (NO_2) and sulphuric (SO_3) acids. Further confirmation of the effectiveness and creation of technical assumptions for the implementation of the process required laboratory tests [7].

TRL 3–4 (i) verification of the concept confirming analytically and experimentally critical functions or characteristics of the technology, (ii) verification of components of the technology in laboratory conditions; this stage requires the construction of a laboratory installation in the ICHTJ and conducting appropriate experiments. Such installations were also created in Japan and Germany, and later in other countries of the world: South Korea, China, Malaysia, Turkey. The ICHTJ installation used an ILU-6 electron accelerator with a beam power of 20 kW and regulated electron energy up to 2 MeV. The flue gases were produced in an oil burner, and the concentration of gaseous pollutants was regulated by additional dosing of gases (– nitrogen oxide and sulphur dioxide), the volumetric flow of gases reached 400 Nm^3/h. The diagram and photo of the laboratory installation are presented in Figure 1 [8]. The effect of the dose on the efficiency of the process of removing acidic gas pollutants was determined. During

Table 2. Technology Readiness Levels (according to the National Centre for Research and Developments).
Tabela 2. *Poziomy gotowości technologicznej (wg Narodowego Centrum Badań i Rozwoju).*

The TRL scale can be divided into three groups: TRL I: Conceptual works, analysis of the idea, product, feasibility of its creation TRL II-VI: Industrial research on the product TRL VII-IX: Product development
Level I – basic principles of technology. Observation and description of the basic principles related to the functioning of a given technology: Technological readiness examples at this level may include studies on the basic properties of technology. This level indicates the actual beginning of the development of technology understood as formulated theoretical knowledge that can be verified measurably.
Level II – definition of the technology concept. This means the commencement of activities related to the future application of technology: The identified theoretical foundations of the new technology allow for the formulation of the assumptions of its practical application. Planned future applications are based on predictions. There may not yet be any evidence or detailed analysis confirming the adopted assumptions of the practical application of the technology. Activities are limited to analytical studies. These studies may include publications or other materials that present the possibility of applying the technology, while providing analyses confirming the concept of technology. However, it is important that the new technology is described consistently and in detail.
Level III – verification of the concept confirming analytically and experimentally the critical functions or characteristics of the technology: Active activities are initiated, including analytical studies and laboratory tests to physically confirm the analytical predictions regarding different elements of the technology. Technological readiness examples at this level include components that are not yet integrated in their entirety or are not representative of the entire technology.
Level IV – verification of technology components in laboratory conditions: The basic technology components are integrated to confirm that they will work together. General (low fidelity compared to the target system) mapping of the technology in laboratory conditions is obtained. Technological readiness examples at this level include ad hoc integrated equipment in the laboratory.
Level V – verification of technology components in an environment close to the real one: The fidelity of technology mapping increases significantly. Basic components of the technology are integrated with supporting elements, imitating real elements. The technology can be tested under simulated operating conditions. The verification of the new technology should be carried out in the context of its specific use in a future system or equipment and use elements reflecting the specific, intended use in the tests.
Level VI – demonstration of technology in conditions close to real: A significant progress in the field of technological readiness is achieved. The representative technology, which is much more advanced than the one at level V, is subjected to research and testing. Research at this level includes research on a model or technology demonstrator in laboratory conditions mapping real conditions with high fidelity or under simulated operating conditions. The use of commercially available components with reduced immunity is still possible if it is not contrary to the type of environmental conditions in which the model or technology demonstrator will be tested.
Level VII – demonstration of the technology prototype in operational conditions: The prototype is almost at the operating system level or at the achieved level. This level of technological readiness represents a significant progress in relation to level VI and requires demonstration of the developed technology prototype in operational conditions, e.g. on an aircraft, in a vehicle, in an IT operating environment or in space. Achievement of this level should be justified by the activities carried out in the field of system engineering and management of the development process.
Level VIII – completing and checking the developed technology as a result of tests and demonstrations: It was confirmed that the technology can be used in its final form and under the conditions expected for it. Technological readiness examples at this level include research, validation and assessment of technology in the conditions intended for its use, e.g. as part of the weapon system, in order to confirm the design assumptions. Practically (in almost all cases) this level represents the end of actual technology development.
Level IX – checking the developed technology in the operational environment: The technology is used in its final form and under the expected operating conditions, e.g. in the operational conditions of the mission or in the actual operational environment.

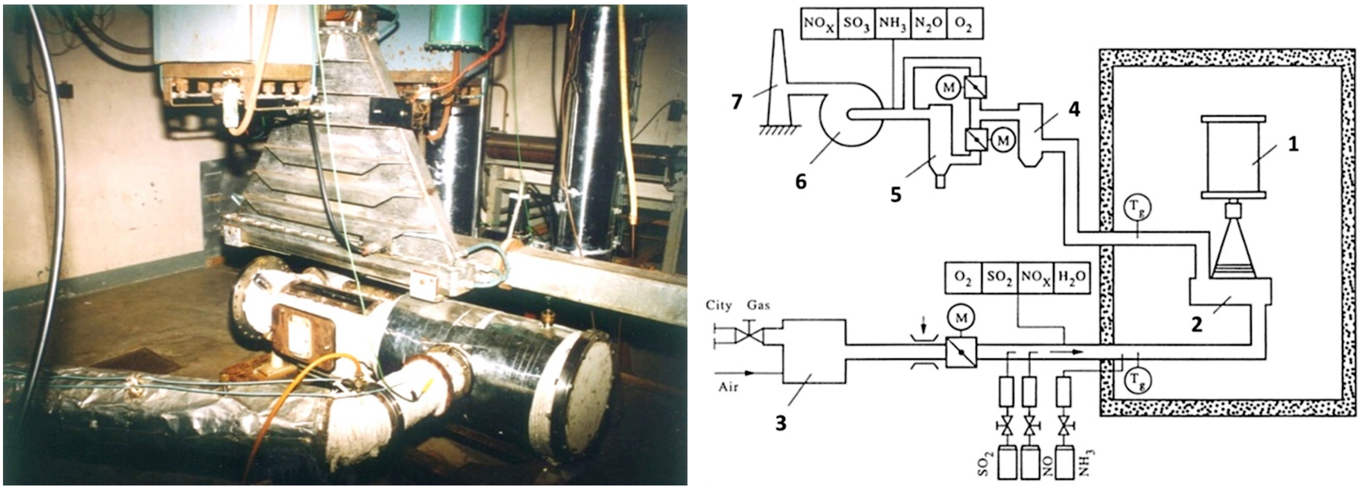

Fig. 1. Photo and scheme of laboratory installation for flue gas treatment. 1 – accelerator ILU – 6; 2 – process vessel; 3 – gas mixer; 4 – retention vessel; 5 – bag filter; 6 – ID fan; 7 – stack (author's own work).

Rys. 1. *Fotografia i schemat instalacji laboratoryjnej do radiacyjnego oczyszczania gazów spalinowych. 1 – akcelerator ILU – 6; 2 – komora reakcyjna; 3 – mieszacz gazów; 4 – komora retencyjna; 5 – filtr tkaninowy; 6 – wentylator; 7 – komin (opracowanie własne autora).*

our own experiments and those conducted on other installations, it was found that the mixture of the resulting acids (related to the presence of water vapour in the gas) creates a mist, the removal of which from the gas is not possible with the use of known devices (demisters). Therefore, the idea of adding gas ammonia and producing solid particles in the form of a mixture of sulphate and ammonium nitrate was created. An additional advantage of this solution was the production of valuable fertilizer.

TRL 5–6–7 (i) verification of technology components in an environment similar to the real one, (ii) demonstration of the technology in conditions similar to real ones, (iii) demonstration of the technology prototype in operational conditions; this stage required the construction of a pilot plant in a coal-fired power plant. This installation was built in ESP Kawęczyn, the flow of flue gases was 20,000 Nm^3/h, two ELV – 6 accelerators were used with a power of 50 kW each and a beam energy of 600 keV. A photo of the power plant and the water block building, at which the building containing accelerators and other elements of flue gas cleaning was built, is presented in Figure 2 [9]. During the tests required to be carried out under TRL 7, three types of devices for removing suspended solids of the product were tested: bag fabric filter, wet bed filter and electrostatic precipitator (ESP). It was found that the best solution is the ESP, however, although

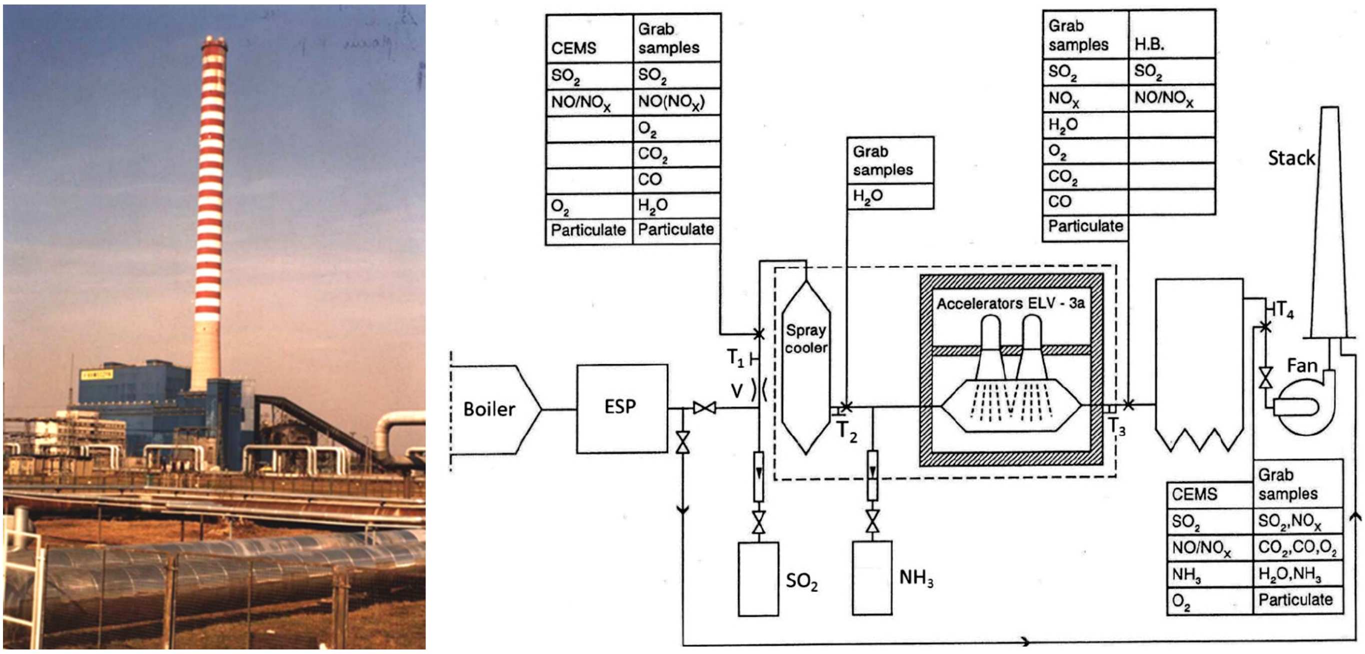

Fig. 2. Photo of EPS Kawęczyn complex and layout of pilot plant for electron beam flue gas treatment (author's own work).

Rys. 2. *Zdjęcie kompleksu elektrowni EC Kawęczyn i schemat ideowy instalacji oczyszczania spalin wiązką elektronów w skali pilotowej (opracowanie własne autora).*

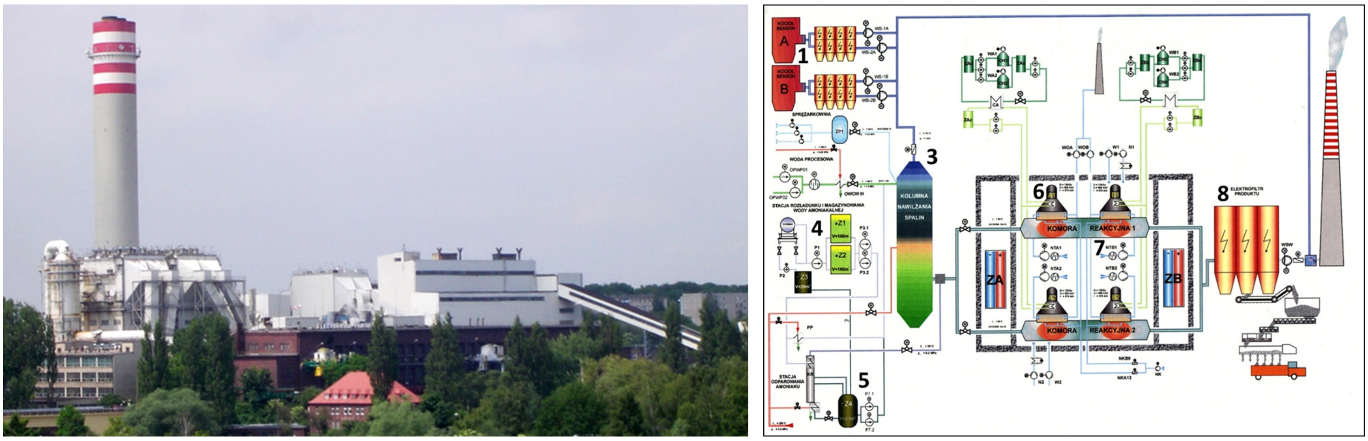

Fig. 3. Photo of EPS Pomorzany, gas humidification tower in front and EPS belonging to EB flue gas treatment plant in a photo centre. A scheme of installation for radiation flue gas purification at right (author's own work).

Rys. 3. Fotografia EC Pomorzany – na planie frontowym kolumna nawilżania, na środku zdjęcia EF należące do instalacji oczyszczania spalin. Obok schemat instalacji radiacyjnego oczyszczania spalin (opracowanie własne autora).

it is a commercial product, it has required many improvements to obtain the correct operating conditions for this device.

After reaching TRL7, confirming all technological and engineering assumptions, the next stages of the project were implemented. It was necessary to prepare a document describing the impact of the facility on the environment, design taking into account the safety report in terms of radiological protection, the use of hazardous chemicals and explosion (ammonia). The arrangements and consents concerned the Ministry of the Environment, the Chief Inspectorate for Environmental Protection, the National Atomic Energy Agency, the Ministry of Health and the relevant provincial authorities. After approving the technical designs, conducting tenders and the selection of the accelerator manufacturer, the next stages leading to the implementation of the technology in the power industry in full technical scale began.

TRL 8–9 (i) completing and checking the developed technology as a result of tests and demonstrations, (ii) controlling the developed technology in the operating environment, this stage required construction on a full industrial scale with a gas flow at least 10 times greater than that obtained in the pilot plant. Such an installation was built in EPS Pomorzany belonging to the Dolna Odra Power Plant Complex [10]. The flue gas from the WP-100 coal-fired boiler was cleaned, the flue gas flow was 270,000 Nm^3/h, four accelerators (600 keV) were used with a power of 300 kW each, powered by two power supplies with a power of 600 kW each. The photo of the power plant with the flue gas humidification column belonging to the flue gas cleaning system visible on the photo front and the installation diagram are presented in Figure 3.

The technology developed in the above activities removes both acid contaminants at the same time, which is not possible in the case of other conventional technologies. During the implementation of the project, a number of new solutions were developed that were patented and have a broader value, regarding their use in other pollution control technologies. It should be emphasized that the ionizing radiation emitted by one 15 kW accelerator delivers a dose equal to the dose provided by a Co-60 source with an activity of 1 MCi. Thus, in this case, it was a source of radiation equivalent to 80 MCi Co-60. In practice, the activity of most sources used in radiation processing does not exceed 1 MCi, in rare cases it reaches 4 MCi.

The implementation of individual stages of this project indicated the importance of applying the recommendations resulting from the implementation of activities according to the TRL scale. The type of accelerators used in the pilot plant (EPS Kawęczyn) was different from those provided by the supplier selected for the implementation of the industrial plant (EPS Pomorzany). It turned out that 600 kW power supplies (transformer with oil insulation) had not been tested before. There was a break in the insulation in one of the two devices supplied. It has been sent back for repair. This error was strange, because the construction of oil transformers is a classic of the technique used in this field. It is the only device that has not been prepared using the TRL scale requirements and it is a warning not to use short cuts in any new technology, even if it is not about the technical principles of solution used, but only about changing the scale of the solution.

An additional observation, important in the implementation of new technologies, was the statement that such activities attract suppliers offering products that do not yet exist on a technical scale. The principle of operation offered by the third of the possible accelerator suppliers was fascinating, but unfortunately it has not been built to this day. The letter from the sales office about considering the possibility of using this device in our project was only used to present it at the meeting of the company's shareholders.

4. Technology Readiness Levels (TRLs) for SMRs

Small modular reactors have an output power below 300 MW [11]. The term "modular" in the context of small modular reactors refers to their scalability and the possibility of producing the main elements of the nuclear reactor in the factory environment and then transferring them to the site. Moreover, it is a design concept in which reactors are built as a series of small, self-contained units. They can be combined to create a larger power plant. The modular design of SMR reactors allows for greater flexibility in the construction and operation of the reactor. The modular approach allows for standardized designs that can be replicated across multiple units, reducing the costs and time required for licensing, construction and operation. In addition, the modular design of SMRs allows for scalability, within which additional modules can be added to increase plant efficiency. This flexibility and scalability make SMRs well suited to meet the energy needs of small communities or for use in remote or isolated areas.

One of the very important barriers to the development of SMRs is the licensing of new reactor designs. For example, by regulating the design, site, construction and operation of new commercial nuclear power plants, the US NRC (United States Nuclear Regulatory Commission) currently applies a combination of regulatory, licensing and oversight requirements. Historically, the licensing process was developed for large commercial reactors. The process of licensing new reactor designs is lengthy and expensive.

A very good and up-to-date assessment of the situation was presented by the Pacific Northwest Laboratory in the report "*Emerging Technologies Review: Small Modular Reactors*" [12] made for the Air Force Civil Engineer Centre under a Work-For-Others Agreement with the U.S. Department of Energy. The importance of this documentarises, among others, from the fact that from the very beginning of its creation, the idea of building SMRs concerned the possibility of their use in hard-to-reach regions of our globe (e.g. the Arctic regions of Canada) and for good security of the source of power supply for military bases.

Designers and suppliers offer SMRs that have reached different levels of design maturity. Light water (LWR) SMRs are the most mature in terms of technology and production. The projects originate from the existing large LWR structures. SMRs other than LWR are still considered to be under development, far from the stages of implementation and commercialization, as they are based on reactor designs for which there are few actual implementations and even fewer of them are explored as long as large LWR nuclear power plants are in operation.

According to the report, there are many limiting factors related to the implementation of SMR technology. And a limited number of specialists and a limited supply of production components and nuclear fuel dedicated to SMRs affect the degree of advancement of technology. None of them has been implemented commercially in the United States. The NRC attaches great importance to the evaluation of the proposed SMR construction site: "The human environment, public health and safety, engineering and design, economics, institutional requirements, environmental impact and other factors should be taken into account in the selection of the site. The potential impact of the construction and operation of nuclear power plants on the human environment and on social, cultural and economic characteristics (including environmental fairness) is usually similar to the potential impact of any large industrial facility, but nuclear power plants are unique in the extent to which the potential impact of the environment on their safety needs to be taken into account. Safety requirements are the main determinants of suitability of the site for nuclear power plants, but the environmental impact is also valid and must be assessed."

In the last seventy years, many types of nuclear reactor technologies have been tested and are characterized by a high technological readiness level. Light-water reactors, liquid-metal reactors, high-temperature gas-cooled reac-

Table 3. Most common nuclear reactors [12].
Tabela 3. *Główne typy reaktorów jądrowych [12].*

Reactor type	Coolant	Moderator	Neutron spectrum
Pressurized water reactors (PWR)	Light water (H_2O)	Light water (H_2O)	Thermal
Boiling water reactors (BWR)	Light water (H_2O)	Light water (H_2O)	Thermal
Reactors – molten metals	Liquid sodium, lead or bismuth lead	Graphite	Thermal
		None	Fast
Gas Cooled High Temperature Reactors (HGTR)	Helium (hydrogen, carbon dioxide)	Graphite	Thermal
		None	Fast
Reactors – molten salts	Mixture of salts – chlorides or fluorides	None	Fast

tors (HTGRs) and molten salt reactors (MSRs) were built, licensed and operated in the United States and around the world. Table 3 provides an overview of the different main reactor types. The values of operating pressures and temperatures in the descriptions are approximate and representative for different types, and specific values can vary depending on the design, within each type. For example, when it comes to operating pressure, PWR reactors usually operate at about 150 atmospheres (150 times the normal atmospheric pressure), while reactors using liquid metals operate slightly above the atmospheric pressure. These are the precursors of the main families of currently offered SMRs, so it is worth recalling them.

The situation regarding the licensing of SMRs that are clones of the above solutions is presented below.

a) Pressurized water reactors (PWR)

Almost two-thirds of commercially operated reactors are of this type. All reactors of the United States Navy are PWR. The US Army's nuclear power programme was operated by PWRs operated from 1954 to 1974.

The NuScale PWR design (since the steam generator and reactor share the same reactor tank, this particular design feature is commonly referred to as Integrated PWR (iPWR)) is the only American SMR design that has a design certificate issued by the NRC and the standard design certification.

b) Boiling water reactors (BWR)

BWRs operate at high pressure, typically about 68 atmospheres and at a temperature of about 285°C. They use a single-loop steam supply system in which steam leaves the reactor and flows to the generator turbine.

According to the report, there are currently (the end of 2024) no design proposals for BWR SMR reactors in the NRC.

c) Sodium fast reactors (SFRs) – molten metals

Since SFRs are designed to use fast neutrons to fission uranium/plutonium, they do not use a moderator. SFRs operate at a pressure similar to the atmospheric pressure, the overpressure is about 0.1 atmosphere. Other subtypes of reactors using liquid metals, can use lead or lead-bismuth as a coolant.

Japan's Joyo SFR test reactors (1977–1997 and 2004–2007), two Russian commercial reactors SFR BN-600 (1980-present) and BN-800 (2014-present), and China's experimental fast reactor (2011-present) are currently operating. The BN-600 and BN-800 are the only two operating commercial SFRs in the world.

No project applications for SFR SMR have been submitted to the NRC.

d) High-temperature gas-cooled reactors (HGTR)

HTGRs are nuclear reactors using gases, such as helium, as a coolant. Since most HTGRs are designed to use thermal neutrons to fission uranium, most use graphite as a moderator. The moderator is not used in HTGRs using fast neutrons. HTGRs operate at lower pressures than the design pressures of PWRs and BWRs, they amount to about 60 atmospheres. There are two main HTGR designs based on the moderator configuration: (1) a prismatic block in which the reactor core is configured in graphite prismatic blocks and (2) a bulk-bed HTGR, in which the moderator and the fuel are formed into spherical structures.

In 1958, the Philadelphia Electric Company ordered the Peach Bottom 1 reactor, an experimental, helium-cooled, graphite-moderated 40 MWe HTGR nuclear prototype. The construction of Peach Bottom 1 began in 1962. It was commissioned in 1967 and operated until 1974; it was closed after successfully demonstrating the viability of HTGR.

General Atomics also designed the Fort St. Vrain reactor as a proven, helium-cooled, graphite-moderated, 330 MWe commercial HTGR. The construction began in 1968, and preliminary tests began in 1972. The power plant began supplying electricity to the grid in 1979. Although the project successfully proved the operational character of HTGR and other technologies, maintenance and extensive modifications of the installation were required to maintain it. Due to unfavourable economic and technical issues, the power plant was decommissioned in 1989.

Other experimental HTGRs have been designed and operated worldwide. The British Atomic Energy Authority operated the Dragon reactor. The Dragon reactor tested fuel and materials for the European high-temperature reactor programme of the Organization for Economic Cooperation and Development/Nuclear Energy Agency NEA/OECD in 1965–1976. The reactor design used an early form of tri-structured isotropic fuel (TRISO) of various shapes. The reactor is no longer in service and is currently decommissioned.

Germany designed the Arbeitsgemeinshaft Versuchsreactor (AVR) and the high-temperature THTR 3000 reactor. The AVR was a test reactor with a power of 15 MWe, which operated in the years 1967–1988. The THTR-300 reactor was a 300 MWe power plant that operated from 1985–1989. It is no longer in use. Japan's Atomic Energy Agency operates a high-temperature engineering test reactor. The gas-cooled, graphite-moderated reactor was designed to supply 30 MWe.

Its operation was suspended in 2011 and resumed in 2021.

China's first high-temperature, gas-cooled, bulk-bed HTR-10 test reactor operates at Tsinghua University. It has been designed to test the concept and has a power of 10 megawatts of thermal power (MWt). In addition, in 2021, two high-temperature, gas-cooled HTR-PM reactors with a capacity of 100 MWe began operation in China.

The NRC has not licensed HTGRs and none of them currently operates in the United States.

e) Reactors – molten salts

MSRs are reactors that use liquid mixtures of chlorides or fluoride salts as a coolant. MSRs can use liquid fuel in which uranium-235 is admixed in a salt mixture and circulates in the reactor, or solid fuel is used. MSRs can also be thermal reactors using graphite as a moderator or fast reactors in which a moderator is not needed.

In addition, MSRs operate at lower pressures than the design pressures of PWRs and BWRs; it amounts to about 2 atmospheres.

In the United States, the AEC conducted two experiments using MSRs: one for the United States Army Air Force (which became the United States Air Force in 1947) and the other internally to determine whether MSRs can be commercially operated safely and are reliable and can be maintained in motion without undue difficulty.

The Molten Salt Reactor Experiment (MSRE) was a test reactor operated by Oak Ridge National Laboratory (ORNL) to demonstrate that molten salt reactors mainly used to generate electricity can be operated safely and reliably. The 7.4 MWt breeding reactor, cooled with molten salt and moderated with graphite, was built in 1964 and operated until 1969. It used a mixture of uranium, thorium and plutonium fluoride isotopes.

Currently, two projects of MSRs have been submitted to the NRC. In September 2021, Kairos Power, LLC submitted an application to the NRC for permission to build the HERMES test reactor. In August 2022, Abilene Christian University submitted an application to the NRC for permission to build a molten salt research reactor. The NRC is reviewing both applications and has not yet (the end of 2024) made a decision on either of them.

Based on the definitions of the TRL adopted by the Department of Defense (DoD) and published by the Government Accountability Office (GAO) [13], the TRL SMR can be 5 or 6. TRL level 5 means that the basic technological components are integrated with quite realistic supporting elements, so that they can be tested in a simulated environment. TRL level 6 means that the systems or subsystems have been demonstrated in the appropriate environment.

The NRC has set overall milestones for the completion of the proposal's reviews for the different regulatory actions. The full list of licensing and regulatory activities and the corresponding general milestones has been published on the public NRC website [14]. The review period begins when the NRC has completed the acceptance review and accepted the application for review, and ends when the personnel have completed the safety assessment report. Reviews of early construction licenses last 24 months; reviews of combined licenses last from 30 to 42 months.

In 1989, the NRC established an alternative licensing process that combines construction and operating license, with certain conditions, into a single license. This license is called a Combined Construction License and Operational License (Combined License) or Combined License Application (COL)[1]. The provision in 10 Code of Federal Regulations (CFR) Part 52 also allows the owner/operator to apply for an Early Site Permit (ESP)[2], in which the NRC will determine whether the site is suitable for a nuclear power plant. If the owner/operator wants to apply for ESP, the application will address site safety, environmental protection and emergency response plans without the

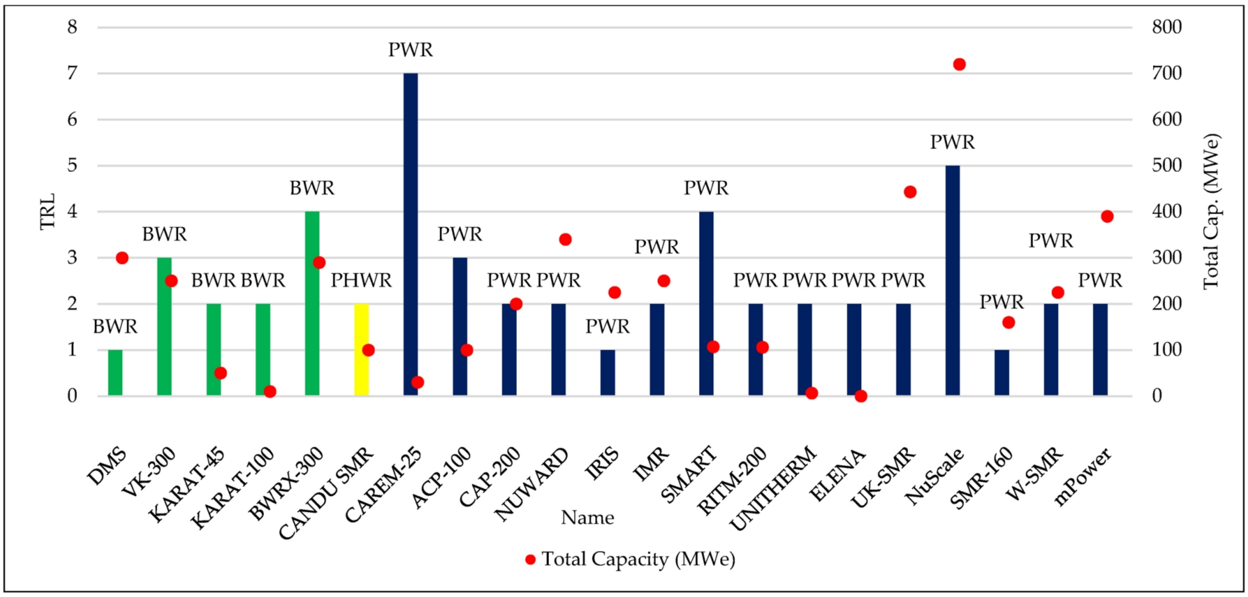

Fig. 4. Evaluation of the TRL for selected SMRs [15].

Rys. 4. *Ocena poziomu TRL dla wybranych SMR [15].*

1 https://www.nrc.gov/reactors/new-reactors/large-lwr/col.html
2 https://www.nrc.gov/reactors/new-reactors/large-lwr/esp.html

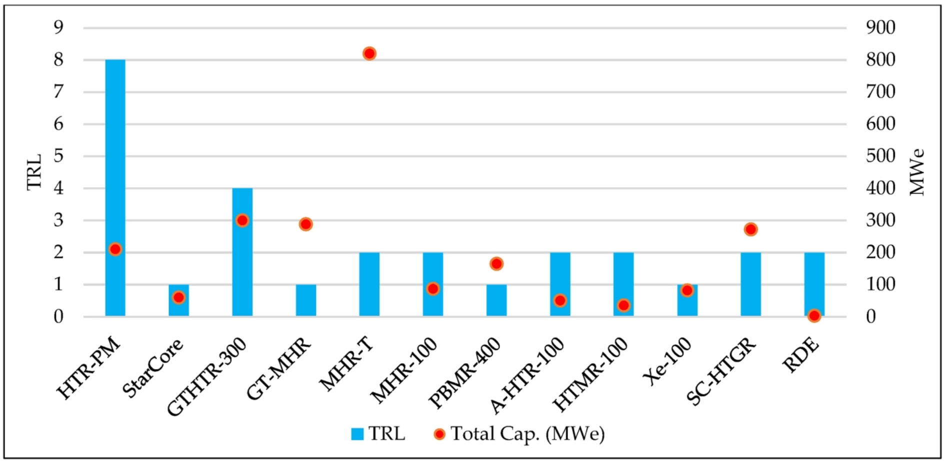

Fig. 5. Evaluation of the TRL for HTGR SMR [15].
Rys. 5. *Ocena poziomu TRL dla HTGR SMR [15].*

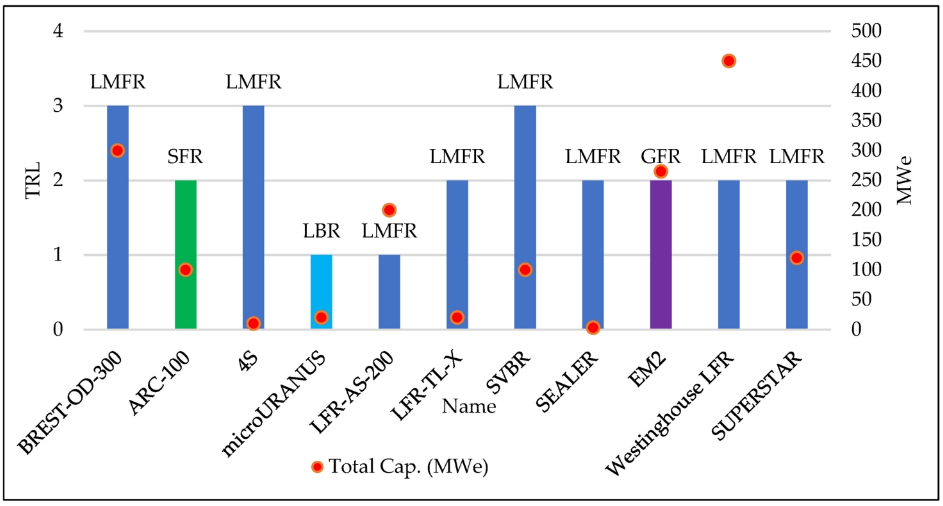

Fig. 6. TRL for fast neutrons reactors [15].
Rys. 6. *Poziom TRL dla reaktorów wykorzystujących neutrony prędkie [15].*

need to review the specific design of the nuclear power plant. As part of the application, the owner/operator may also apply for Limited Work Authorization (LWA). The ESP is not required before the owner/operator submits a COL request, but it can be beneficial as it will resolve any specific issues related to the security of the facility before submitting a COL request. At the moment, the NRC has issued 6 ESP opinions, and one in the evaluation has been withdrawn by the applicant. Of the six ESP opinions, the last was issued in December 2019, and its adoption was a tedious action lasting 3.5 years; in the case of the latter, it was 6 years (2016); for the fourth – 3 years (2009), for the third, as well as the second and the first reported at this age – 3.5 years (all issued in 2007). The decision-making process consists of three phases: nuclear safety analysis, environmental assessment, mandatory hearings before the commission.

In the case of COL, the application submitted in 2020 regarding the microreactor, which was to be built on the premises of the Idaho National Laboratory (Oklo Power LLC), was rejected in 2022 due to the fact that Oklo did not provide the NRC with the necessary information about the reactor, which did not allow the NRC personnel to establish a schedule of activities and conduct a full review of the custom Aurora Combined Reactor License Application.

Most interesting is the case of the application filed by the Southern Nuclear Operating Company (SNC) on March 28, 2008 for combined licenses for two advanced AP1000 passive water reactors for units 3 and 4 of the Vogtle Electric Generating Plant (VEGP). On 22 October 2009, SNC granted its request for COL by submitting an application for a limited authorization to carry out activities in order to obtain consent to perform selected construction works. COL and LWA were issued for the Vogtle Electric Generating Plant (VEGP) – units 3 and 4, on February 10, 2012. Vogtle Unit 3 began commercial operation in July 2023, and Unit 4 in March 2024.

An interesting complement to the previously discussed NW Pacific NL report is the publication [15] ranking the proposed SMR solutions according to their status on the TRL scale and power (Fig. 4, 5, 6). Since there are too

Table 4. Selected SMRs at TRL 5 [15].
Tabela 4. *Wybrane SMR-y o TRL 5 [15].*

Name	Type	Power (MWe)	Manufacturer	Country	TRL
NuScale	PWR	12×60	GE-Hitachi Nuclear Energy	United States and Japan	5
VBER-300	PWR (FNPP)	325	JSC "Afrikantov OKBM"	Russian Federation	6
CAREM-25	PWR	30	IRIS Consorsium	Argentina	7
KLT-40S	PWR (FNPP)	2×35	JSC "Afrikantov OKBM"	Russian Federation	8
HTR-PM HTGR		210	INET, Tsinghua University	China	8

many of them to describe them in this article, we refer the reader to the IAEA publication cataloguing these solutions [16].

The 210 MWe HGTR-PM, which works in Shidao Bay, has the highest TRL of 8. This demo gas-cooled bulk-bed reactor module has been connected to the grid.

Russia's BREST-OD-300 reactor is in the development phase of TRL 3. It is a lead-cooled reactor on fast neutrons, which is currently being built in Seversk in the Russian Federation and is to be commissioned in 2026. This is an attempt to demonstrate a prototype of the architecture of the incoming high-power reactor, which will allow the use of a closed nuclear fuel cycle. In the reactors on molten salts of the SMR type, a salt obtained on the basis of fluoride or chloride is used. The fuel can be solid or liquid when the fuel is dissolved in the carrier salt. Natural salt safety, for the creation of a low-pressure, single-phase cooling system that does not require the full encapsulation of this high-temperature system, ensuring high process efficiency, and closed fuel cycle are just a few of the benefits of this type of SMRs. In Canada, the United Kingdom and the United States, several projects of such SMRs are in the initial phase of licensing analyses. Most SMRs of this technology are still in the conceptual design phase (TRL 2). Only one reactor, Fuji, designed by the International Thorium Molten Salt Forum (ITMSF), has a TRL 3 indicator.

Summing up this review, it can be concluded that there are several SMRs that are in the development phase of TRL 5 (Tab. 4).

Of course, in this case, the best available knowledge concerns the first SMR on this list.

It is also worth mentioning the NEA report (Volume I), which this Agency calls a dashboard for small modular reactors. The first one contains an analysis of 21 SMR projects and a description of progress on their implementation and commercialization [17]. The summary of the NEA SMR dashboard goes beyond the level of technological readiness and assesses progress on six additional basic conditions: readiness for licensing, location, financing, supply chain, commitment and fuel. In combination with the assessments of technical readiness, it reveals which SMR technologies and projects are rapidly moving from concept to commercialization in various markets around the world. The second volume [18] is another milestone in the ongoing efforts of the Nuclear Energy Agency (NEA) of the OECD for a comprehensive assessment of the progress made towards the commercialization and implementation of SMR technology. The second volume does not constitute an update of the set of reactors assessed in the first volume, the information contained in it extends the same methodology to another 21 SMR projects from around the world, according to the state of knowledge obtained on April 21, 2023. The assessments do not in any way reflect the opinions of the OECD or NEA, but are based on assessments prepared jointly with the designers of individual solutions. These publications do not provide TRL values for individual solutions, but enrich such an assessment with additional, above-mentioned information. Therefore, together with the previously cited TRL values, they constitute a valuable comparative material helpful in the activities of analysts and institutions interested in the future implementation of SMRs in various areas of the economy.

5. Summary

The facts indicated in the study show that the activities related to the construction of nuclear power plants must be well prepared, and the main aspect of these activities is of a technical and economic nature (in the engineering nomenclature, technical and economic assumptions must be developed). This document also covers ecological and social assessments to a large extent. When it comes to the development of SMRs, the level of their development determined on the TRL scale is crucial for the implementation. The example presented in Chapter 3 is of a didactic nature, illustrating the stages of implementing difficult radiation technology according to successive points of the TRL scale, using the principles of engineering projects, analogous to those used in the construction of nuclear power plants.

Proof of the importance and necessity of performing a technical assessment of SMRs are the actions taken by the Canadian Nuclear Safety Commission (CNSC), which implements the “Small Modular Reactor Readiness project overview“. It started in 2023 and will last for five years. The project fund is 50.7 million Canadian dollars. Many different parameters and procedures will be taken into account in the assessment [19]. The CNSC wants to prepare for effective and efficient regulation of SMRs without any damage to the developed safety rules, will also sponsor the conduct of independent research by external entities, obtaining internal expertise and the preparation of documented regulatory rules, in the areas listed in the document under the above link, so as to support the licensing activities carried out by this institution. Similar activities should also be carried out in Poland, and the activities of external TSO institutions financed, for example, from the National Centre for Research and Development programmes established for this purpose.

The report of the Presidential Commission on the Three Mile Island accident, Publishing House of the US Government, stated [20]: “Nuclear energy requires broad, organized support from scientists and engineers.“ It was emphasized that special attention should be paid to the development, review and supervision of the procedures used in the power plant so that they are based on both engineering thinking and operational experience". In addition, after the Chernobyl accident, the investigation carried out by IAEA advisers found that the operating procedures were not satisfactorily based on technical analyses. It was found that the exchange of important safety information between operators and the technical support organization (TSO) was insufficient and did not lead to their full use.

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About the author

Prof. dr hab. inż. Andrzej G. Chmielewski is the director of the Institute of Nuclear Chemistry and Technology, which is the IAEA Collaborating Centre, and the deputy chairman of the Council for Nuclear Safety and Radiological Protection with the President of the PAA. For many years he worked at the Warsaw University of Technology, the University of Tennessee, the USA and the International Atomic Energy Agency, Vienna, Austria. In the years 1990–2011, he was the deputy chairman and chairman of the Council for Atomic Sciences with the President of the PAA. He served as President of PTN and SEREN, and for a number of years was a member of SAGNA, an advisory body to DDG NA IAEA.

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