Jerzy Niagaj

Technical and Quality Requirements for Metallic Components of Nuclear Power Plants

Abstract: The article discusses the requirements of the ASME and AFCEN nuclear codes for metallic equipment, components and systems in the pressure and civil structures areas of nuclear power plants as well as the requirements of the ISO 19443 and NQA-1 standards for quality assurance systems in the nuclear industry.

Key words: nuclear power plant, metallic component, code, ASME, AFCEN, requirements, quality

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1. Introduction

A nuclear power plant is a special and very complex industrial facility. Unlike a conventional power plant, the operation of a nuclear power plant is accompanied by an additional hazard in the form of radiation generated by the nuclear fuel, used to initiate the nuclear reaction. As a result, the principles of design, fabrication, inspection, acceptance and operation of not only pressure and mechanical equipment as well as metallic components and structures, but also steel and steel-concrete structures of the reactor containment are subject to an entire range of special "nuclear" regulations.

Because of the lack of nuclear technology as well as an operating nuclear power plant built on the basis of any commercial nuclear technology used in the world, Poland currently does not have regulations regarding the design, fabrication and operation of nuclear devices, components and systems. However, there are related regulations applied in the country such as the Regulation of the Minister of Development of 20 May 2016 on the technical conditions of technical supervision for technical devices or devices subject to technical supervision in a nuclear power plant [1], which states in § 4.1 that "Unless the provisions of this Regulation provide otherwise, NPP devices belonging to the appropriate safety class are governed by technical requirements specified in reference documents applicable to such devices." In turn, § 4.2 states that "Unless the provisions of this Regulation provide otherwise, NPP devices for which no safety class has been determined are governed by the requirements contained in the technical standards appropriate for the devices in question as well as in other technical specifications related to design requirements". As a result, the construction of the first and subsequent nuclear power plants in Poland will be governed by the recognised technical "nuclear" regulations applied by the technology supplier during the design and licensing process, but also by national, EU and international regulations and standards where "nuclear" regulations will not be applicable.

Taking into consideration that preparations for the construction of a nuclear power plant with an AP1000 reactor from the American company Westinghouse have already begun in Pomerania and that potential suppliers of subsequent nuclear technologies may include companies from South Korea, Japan, Canada and France, the technical and quality requirements will be based on the "nuclear" regulations of these countries. In the USA, but also South Korea, Japan and Canada, the basis for the design, fabrication and operation of pressure and mechanical equipment as well as steel structures of nuclear systems are the relevant sections and standards of the ASME regulations (American Society of Mechanical Engineers) along with the standards related to them, including ASTM, AWS, ACI, ASNT. In terms of French technology, the aforementioned regulations are the relevant sections of the AFCEN regulations (*Association Française pour les règles de Conception, de construction et de surveillance en exploitation des matériels des Chaudières Electro Nucléaires, i.e. French Association for the rules governing the Design, Construction and Operating Supervision of the Equipment Items for Electro Nuclear Boilers*), referring primarily to European (i.e. EN-type) standards and international (i.e. EN ISO-type) standards.

2. Scope of application of "nuclear" regulations

The individual components, devices and systems of a nuclear power plant have different purposes, operate in various environmental and operational conditions and, to a varying extent, are responsible for nuclear safety. There are those which are in direct contact with the source of radiation or the cooling medium in the reactor circuit (primary circuit), but there are also a number of components and systems which have no or negligible effect on nuclear safety, e.g. many of the pressure and mechanical devices of the (conventional) turbine island. In relation to the foregoing, the structure of a nuclear power plant is divided into two main groups of structures, systems and components (*SSC*):
- connected with nuclear safety (i.e. *safety-related*),
- not connected with nuclear safety (i.e. *non-safety-related)* or
- relevant for nuclear safety (i.e. *Important to Nuclear Safety – ITNS*),
- not relevant for nuclear safety (i.e. *Non-Important to Nuclear Safety – Non-ITNS*).

Dr inż. Jerzy Niagaj – Leader of Nuclear Power Engineering Area, Łukasiewicz Research Network – Upper-Silesian Institute of Technology, Centre of Welding, Research Group for Welding Technologies
Corresponding author: jerzy.niagaj@git.lukasiewicz.gov.pl

The above-presented division of nuclear power plant components and systems into *safety-related* and *non-safety-related* is used primarily in American regulations, documents and classifications, including the regulations of the US NRC (Nuclear Regulatory Commission) [2]. In turn, according to the recommendations of the IAEA (International Atomic Energy Agency) [3] and those contained in international, European (including French) and national documents, components and systems are divided into ITNS and non-ITNS. In both cases, the intention is the same, i.e. to define the components and systems of a nuclear power plant which may affect nuclear safety. However, the term "Important to Nuclear Safety" covers a slightly wider group of components and systems of a nuclear power plant than the term "safety-related".

The IAEA TECDOC-1787 document [4] states that, despite the IAEA recommendations and guidelines, the SSC safety classification is established by the regulatory body of each country. In Poland, such a body is the National Atomic Energy Agency. The assignment of individual systems, structures and components (SSC) to the appropriate nuclear safety class (*Safety Class*) or quality group (*Quality Group*) as well as the indication of the component execution class (*Code Class*) in accordance with ASME Section III [5] or AFCEN RCC-M [6] is made solely by the supplier of nuclear technology (applicant), based on the instructions of the national regulatory body. The technology supplier submits the document for approval during the licensing process. Therefore, both the above-named ASME and RCC-M regulations only establish technical requirements for the design, fabrication and inspection of pressure equipment and systems for individual execution classes.

Presented below are primarily the requirements of technical and quality-related regulations for nuclear power plant equipment and systems classified as important to nuclear safety (*ITNS*), since other devices and systems are governed by the regulations and standards commonly known and widely used in many industries such as the machine-building industry, chemical industry, building engineering and transport.

3. Types of metal components and their location in a nuclear power plant

Each nuclear power plant, regardless of whether it has a PWR-type (Pressurized Water Reactor) or a BWR-type reactor (Boiling Water Reactor), consists of a nuclear island and a turbine island (Figures 1 and 2). The nuclear island is made up of the reactor building surrounded by auxiliary buildings. The primary task of the reactor building, also referred to as the reactor containment, is to protect the operating personnel and the environment from radiation. In turn, the reactor itself and other important pressure devices (e.g. steam generator, pressuriser (pressure stabiliser), pumps, main pipelines, cooling water tanks, etc.) must be protected from damage and the ingress of radioactive substances. Because of the above-presented requirements, both the containment and other safety-relevant buildings of a nuclear power plant are designed and calculated in such a way that they can withstand seismic shocks, terrorist attacks (e.g. aircraft crashes), tsunamis and the impact of many other factors (e.g. tornado, hurricane, snowstorm, etc.).

The proper design, construction and fabrication of pressure equipment and systems as well as steel or composite structures of nuclear power plants are based on the requirements of relevant regulations and standards. The high quality of workmanship determines the safe operation of the nuclear power plant, currently planned for a period of at least 60 years, with the possibility of extension up to 100 years. The aforesaid extendibility depends on the current technical condition of the basic components and process systems as well as structural elements of the power plant.

The primary pressure and mechanical components as well as metallic structures of nuclear power plants include the following components:

- primary circuit components: reactor, steam generators, pressuriser (pressure stabiliser), main pumps and main pipelines;
- secondary circuit components: turbine, condensers, heat exchangers, pumps, valves and pipelines;
- steel or steel and concrete safety containment of the reactor building;
- steel structure of the turbine building;
- pressure vessels in various types of process or auxiliary systems in the reactor and turbine buildings;
- external and internal storage tanks;
- steel housing for internal water tanks and spent fuel storage pools;
- pipelines and supports;
- valves and pumps;
- heating, ventilation and air conditioning (HVAC) components and ducts;
- structural and supporting steel structures, including those made using reinforcing bars and pins.

4. Steel structures

The type, dimensions and quantity of steel components, modules and structures as well as the grades of basic materials used for their fabrication, depend on the design and the supplier of the nuclear technology. The foregoing also involves the application of various regulations and standards in relation to the design, fabrication and inspection of these components and structures, depending on whether they belong to the group of components important to nuclear safety or not.

The steel structures in the building part of a nuclear power plant are not (as is often the case in conventional building engineering) only a steel or reinforced concrete building structure including foundations, walls, roof, floors, stairs and other elements. As already mentioned, presently, the reactor building always has a double safety containment. Depending on the design of the nuclear power plant, it may be a steel + panel structure (steel plates with a reinforcing layer of concrete between them) or a steel and reinforced concrete + reinforced concrete structure. The internal containment is very large (for instance, in terms of the AP1000 reactor, the containment is 39.6 m in diameter and 65.6 m high, whereas the thickness of the wall made of steel SA738 Grade B is restricted within the range of approximately 41 mm to approximately 48 mm). In view of the foregoing, on one hand, it might seem like a building structure, yet, because of its importance to nuclear safety, the regulations require the containment to be tight, qualifying the latter as a pressure device. Therefore,

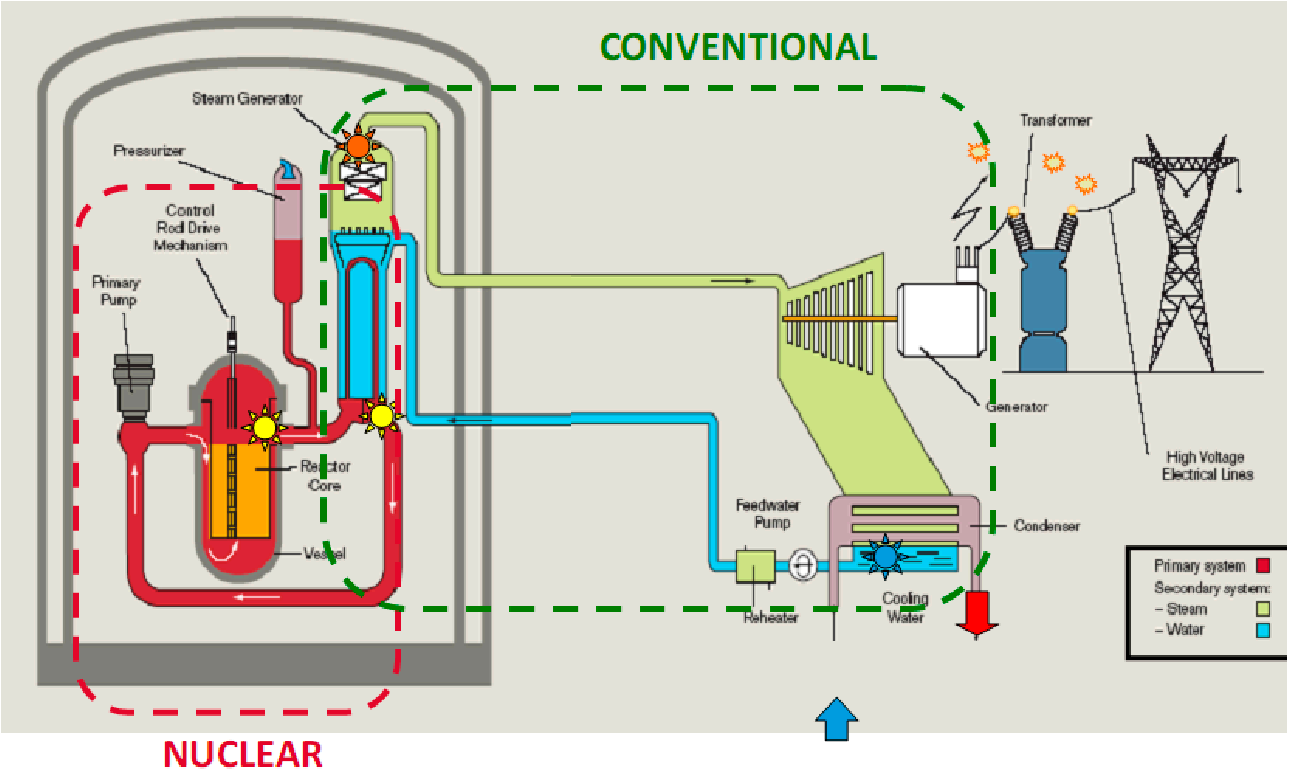

Fig. 1. Schematic diagram of a nuclear power plant with the pressurised water reactor (PWR) [7]

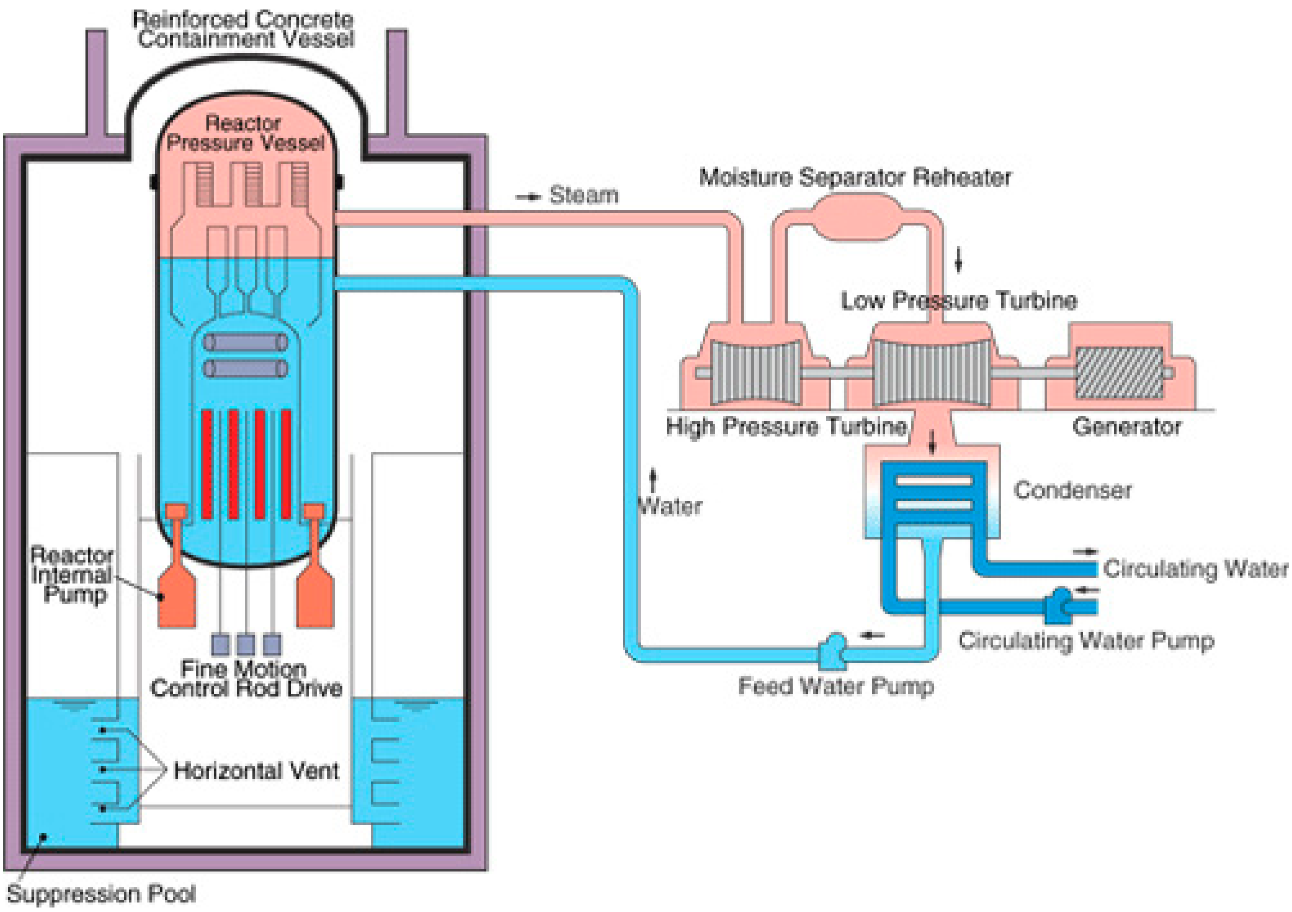

Fig. 2. Schematic diagram of a nuclear power plant with the boiling water reactor (BWR) [8]

in accordance with the "nuclear" regulations, a containment having a steel or steel and reinforced-concrete structure is treated as a pressure component.

The specific nature of steel structures of nuclear power plants is responsible for the fact that both building regulations and standards as well as regulations concerning pressure equipment and products are applicable during their construction. In the United States, these regulations are ASME B&PVC, Section III, Division 1 – Subsection NE [9] (steel housing) or ASME B&PVC, Section III, Division 2 [10] (reinforced concrete housing with leak-tight steel liner) as well as the American Concrete Institute ACI 349 [11] and American Institute of Steel Construction ANSI/AISC N690 standards [12]. In terms of the construction of a nuclear power plant based on French technology, all the requirements for building structures are described in the AFCEN RCC-CW regulations [13]. It should also be noted that countries such as Japan [14], South Korea [15] and Canada [16] have their regulations related to building structures of nuclear facilities, which, however, are very similar to or largely based on the American regulations.

4.1. Requirements of AFCEN RCC-CW regulations

The requirements concerning the design and construction of reinforced concrete and steel building structures are described in the AFCEN RCC-CW regulations [13], which, in March 2015, replaced the previously applied AFCEN ETC-C regulations. The RCC-CW regulations describe the requirements for the design, fabrication and testing of all reactor building elements. The structure of the RCC-CW regulations is as follows:

- Part G – General
- Part D – Design
- Part C – Construction
- Part M – Maintenance and Monitoring

The requirements for earthworks, construction works and the fabrication of individual concrete, reinforced concrete and metal elements of the nuclear reactor building are contained in the relevant chapters of Part C *Construction*:

- CGEOT – Earthworks and Soil Treatment
- CCONC – Concrete
- CFNSH – Surface Finish and Formwork
- CREIN – Reinforcement for Reinforced Concrete
- CPTSS – Post Tensioning System
- CPREF – Prefabricated Concrete Elements and Reinforcement Cages
- CCLIN – Leaktight Metal Parts on Containments
- CPLIN – Pools and Tanks
- CSTLW – Structural Steelwork
- CANCH – Metal Elements Embedded into the Concrete
- CBURP – Reinforced Concrete Pipelines
- CJOIN – Joint Sealing
- CTOLR – Survey Networks, Tolerances and Monitoring Systems

As can be seen in the above-presented list, the design requirements are described in Part D, whereas the fabrication requirements are presented in Part C. Part C Construction contains requirements for the following steel elements:

- reinforcement for reinforced concrete (CREIN);
- post-tensioning system (CPTSS);
- prefabricated concrete elements and reinforcement cages (CPREF);
- leak tight metal parts on containments (CCLIN);
- pools and tanks (CPLIN);
- structural steelwork (CSTLW);
- metal elements embedded into the concrete (CANCH);
- reinforced concrete pipelines (CBURP).

4.2. Requirements of ASME Section III regulations

In relation to nuclear power plant designs based on American codes, the reference standards or codes depend on the type of containment. In cases where the internal containment is designed as a steel liner (e.g. Westinghouse AP1000), the requirements concerning its design, fabrication, inspection, and acceptance are contained in the ASME Section III, Division 1 – Subsection NE [9]. In turn, the panel-type external safety liner of this reactor, the supporting structure of the internal steel liner of the containment and the steel structural modules are made on the basis of the requirements of the ANSI/AISC N690 standard [12], whereas the reinforced concrete structures are made on the basis of the requirements of the American ACI 349 standard [11].

If the containment is a reinforced concrete structure with a tight steel liner having a thickness of approximately 6 mm, the leading reference regulation is ASME Section III, Division 2 [10], but also ASME Section III, Division 1 – Subsection NE [9] and the ANSI/AISC N690 standard [12].

5. Pressure equipment and pipelines

5.1. General characteristic

Pressure vessels, valves, pumps and pipelines are indispensable elements not only of conventional power plants which operate using solid, liquid or gas fuel but also of those which use nuclear fuel. Regardless of the type of power plant, in each of them, a specific group of components performs basic technological tasks. At the same time, the operation of the power plant would not be possible without a number of more or less important auxiliary components, systems and installations, the reliable operation of which is no less important than that of the basic components. Pressure devices, depending on their purpose, operate in various environmental conditions and are filled with various working substances. They also must meet various requirements, e.g. in relation to operating temperature and pressure (overpressure or partial vacuum).

Depending on the nuclear technology supplier and reactor power, the number of pressure vessels (including heat exchangers) in one nuclear power unit with the PWR reactor can vary from over 100 to 260. The most important of them are (nuclear) reactor, steam generator and pressuriser (pressure stabiliser). Apart from the technical parameters of the above-named devices, the difference between reactors from different technology suppliers consists in the different number of steam generators. In terms of the AP1000 and APR-1400 reactors, there are two steam generators, whereas in terms of the EPR reactor – four. Irrespective of the types of regulations, the reactor, steam generator and pressuriser are categorised as pressure equipment of Class 1.

The pipelines or pipe components are made of various materials, e.g. unalloyed and stainless steels, as well as nickel, titanium or zirconium alloys. The diameters of the pipelines and pipe components range from a few millimetres to as many as 2.4 m. The range of functions performed by the pipelines is equally wide. Pipe systems

constitute inseparable parts of, among other things, the following systems:
- reactor cooling;
- discharge of residual heat;
- chemical and water quantity control;
- cooling of non-safety-related nuclear island devices;
- cooling and purification of the water of the spent fuel pool;
- heat exchange in steam generators;
- sprinkling the inside of the containment;
- process (technical) water (or seawater);
- water demineralisation;
- fresh steam;
- condenser and other devices of the turbine island devices;
- return of cooled water;
- air;
- nitrogen supply;
- turbine oil systems;
- cooling and fuel supply for emergency diesel engines;
- versatile fume extraction devices;
- fire protection;

and many others.

The total length of the pipelines may vary significantly depending on the type of reactor, its power and the supplier of nuclear technology. Press information and technical publications indicate that, in terms of one unit, the total length of pipelines is restricted within the range of 70 km to 150 km.

Other devices containing pipes are steam generators. Depending on the design, the total length of the pipes in the steam generator is restricted within the range of 75 km to 220 km. Materials used in the fabrication of the pipes include various types of nickel alloys. Presently, commonly used pipes are made of alloy 690 (UNS N06690). Pipes made of other nickel alloys were previously used in steam generators, yet many years of experience have demonstrated the advantage of alloy 690 TT over other alloy grades. The diameter of the pipes used in the generators is restricted within the range of 14 mm to 25 mm, whereas the wall thickness is restricted within the range of 0.5 mm to 1.3 mm. Pipes also constitute some of the basic structural elements of heat exchangers. In the above-named devices, the pipes are primarily made of stainless steel, yet in cases of severe operating conditions, e.g. connected with the use of seawater in turbine island condensers, pipes are made of titanium alloys.

For instance, the steam generator delivered from the Chalon plant (France) to the Olkiluoto 3 nuclear power plant (Finland) contains 6,000 tubes with a total length of 140 km [17]. These tubes are made of nickel alloy Alloy 690 TT and have a diameter of 19.05 mm and a wall thickness of 1.09 mm.

5.2. National regulations, ASME Section III and AFCEN RCC-M

As mentioned at the very beginning of the article, Poland does not have regulations regarding the design, fabrication and operation of nuclear devices, components and systems, yet two regulations concerning the above issues have been published in the Journal of Laws. The Regulation of the Minister of Development of 20 May 2016 [1] has already been mentioned (in the introduction to the article). Another regulation is the Regulation of the Council of Ministers of 17 December 2013 on the types of technical devices subject to technical supervision in a nuclear power plant [18]. The regulation enumerates devices and systems classified as pressure equipment and, as such, subject to technical supervision, yet it does not indicate their affiliation to specific safety classes. In terms of pressure equipment, these are:
- devices making up the reactor cooling circuit and its auxiliary systems:
  - reactor vessel, pressure channels and other elements of the reactor structure;
  - steam generators with auxiliary systems;
  - heat exchangers;
  - pressuriser with auxiliary systems;
- pressure equipment making up the feed water systems;
- technical devices or devices making up the compressed air and other technical gases system in auxiliary technological systems;
- pressure devices making up the working medium circulation systems and turbine sets;
- devices making up active and passive safety systems and other systems of significant importance for ensuring nuclear safety and radiological protection, in particular, the emergency reactor cooling system and systems for discharging residual heat, including indirect cooling systems and power generators;
- devices making up cooling systems, including the cooling water system, in particular devices for cooling circuits essential for ensuring nuclear safety and radiological protection and fluids used in technological systems;
- pressure devices in fire extinguishing systems;
- devices for filling and emptying tanks;
- pressure devices other than those listed above, containing fluids under overpressure, in particular:
  - fixed tanks for which the product of the overpressure expressed in bars and the capacity expressed in dm^3 is more than 50 and overpressure exceeds 0.5 bar, intended for the storage of liquids or gases or for performing technological processes in them;
  - liquid and steam boilers having a capacity of more than 2 dm^3, containing fluids under overpressure higher than 0.5 bar;
  - portable tanks used in upper airways (respiratory) protection devices;
  - portable tanks changing places between filling and emptying, having a capacity of more than 0.35 dm^3 and an overpressure of more than 0.5 bar, intended for the storage or transport of liquids or gases;
- devices making up heating, ventilation and air conditioning systems.

The above-named devices are subject to technical supervision along with fastening elements and supporting structures, pressure and safety equipment, safety systems, control and measurement equipment and control systems.

The provisions of the above-named regulations indicate that pressure equipment, components and systems classified as important to nuclear safety (ITNS) are governed by ASME B&PVC Section III [5] or AFCEN RCC-M [6] regulations, regarding the fabrication of pressure components, pipelines, valves and pumps rated among Classes 1, 2 and 3. It should also be noted that the ASME B&PVC Section III [5] regulations refer to the material section of ASME B&PVC Section II [19], non-destructive testing specified in ASME B&PVC Section V [20] and welding procedure qualification specified in ASME B&PVC Section IX [21] as well as to many American standards such as ASME, ASTM, ASNT and AWS. In turn, the structure of AFCEN RCC-M [6] regulations already contains a material section (Section 2), a section concerned with testing methods (Section 3), a welding section (Section 4) and a section on manufacturing (Section 5), which in most cases refer to the European EN standards or international standards such as EN ISO (well known to the Polish industry).

6. Quality assurance requirements in the nuclear industry

The primary recommendations regarding the requirements concerning the quality assurance system in nuclear power engineering have been developed by the International Atomic Energy Agency (IAEA) and are contained in document no. GSR Part 2 [22]. Based on the aforementioned IAEA guidelines, countries leading in the production, use and delivery of nuclear technologies, i.e. the USA, France, Russia, South Korea, China and Japan, have developed their regulations and standards used in the construction and operation of nuclear systems. These standards are also applied in countries to which nuclear technology is supplied. The most commonly used regulations in these countries are French and American ones.

In France, the body responsible for the development of regulations regarding the design, construction (fabrication) as well as the operation and testing of components used in nuclear power plants is the aforementioned AFCEN association. The AFCEN RCC-M and RCC-CW regulations include requirements related to design, fabrication, supervision and testing, but also indicate requirements concerning the quality assurance system. Until recently, the aforesaid requirements were based on the IAEA No. GSR Part 2 recommendations [22] and the ISO 9001 standard [23], but since 2018 they have been increasingly based on the new ISO 19443 standard [24]. The ISO 19443 standard is based on the requirements of the well-known ISO 9001:2015 standard [23], which have been supplemented with requirements related to nuclear safety culture, risk assessment, a stepwise approach and top management responsibility.

The regulations related to quality assurance during the construction and operation of a nuclear power plant as well as during the generation of nuclear energy in the USA are found primarily in the US Code of Federal Regulations (CFR), in Book 10 of these regulations entitled "Energy" and, in particular, in Annex B to Part No. 50 of this book entitled: "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants" [25]. These regulations have been developed by the Nuclear Regulatory Commission (NRC) and therefore apply only to the United States. The criteria, which are listed in Annex B, include organisation, quality assurance program, design control, supervision over purchasing documentation, instructions, procedures and drawings, document supervision, inspections of purchased materials, equipment and services, identification and inspection of materials, parts and components, monitoring of special processes, inspections, check tests, inspections of test and measurement equipment, handling, storage and shipping of products, inspection and test status, the handling of nonconforming products, corrective actions, quality records and audits. Based on the above-named criteria of 10 CRF Appendix B to Part 50, the ASME developed the ASME NQA-1 standard entitled "Requirements for quality assurance programs for nuclear facilities" [26] (also applicable outside the USA), establishing requirements directly related to the development and implementation of a quality assurance programme used during the selection of the location, design, construction, operation and decommissioning of a nuclear power plant. These requirements must be strictly satisfied in their entirety as they are primarily concerned with all activities affecting the quality and safety of the operation of all components and devices in a nuclear power plant.

In the 1970s, the ASME developed a document designated as ASME Section III, Division 1 and 2, General Requirements NCA-3700, which was later designated as NCA-3800. This part of the ASME Section III requirements [5] is entitled "Metallic Material Organization's Quality System Program". The NCA-3800 document defines, among other things, such notions as metallic material, source material and Metallic Material Organization. The document also specifies requirements regarding the responsibility and quality assurance system which must be satisfied by organisations involved in the fabrication, processing and sale of metallic materials for the widely defined nuclear power engineering industry. The quality assurance program in accordance with NCA-3800 should cover such areas of the organisation's activities as personnel, documentation, supervision of purchasing, supervision of methods and procedures for identifying and marking materials, monitoring of special processes (welding, bending, etc.) used during material processing, supervision of measurement equipment and requirements concerning material certificates. Presently, the ASME certifies Material Organizations and issues Quality Systems Certificates confirming that the Material Organization's processes and services related to the manufacturing, processing and sale of metallic materials comply with the requirements of ASME B&PVC Section III, NCA-3800.

Regardless of the standard applied, the key issue in both NQA-1 and ISO 19443 is to ensure the highest level of reliability and safety at every stage. The condition for implementing a quality assurance system in accordance with NQA-1 or ISO 19443 is the prior implementation of a quality management system according to ISO 9001 or similar. Experience related to the operation of the system increases the awareness of the fact that the quality assurance system in nuclear power engineering emphasizes the continuous improvement of procedures and regulations by drawing conclusions from regularly performed analyses and audits (system improvement). This process must support individual employees and entire teams so that they can perform their tasks effectively. The system should give particular emphasis to gaining experience and deepening knowledge as well as to the continuous development and improvement of nuclear safety culture.

7. Summary

The above-presented information concerning technical and quality requirements during the design, fabrication and quality control in the nuclear power engineering industry shows that the lack of national regulations in the aforesaid area necessitates the application of recognised global regulations concerned with devices, components and systems important from the nuclear safety point of view (ITNS). Because of the advancement of preparatory works, the first nuclear power plant in Poland will be built in Pomerania by a consortium of American companies Westinghouse/Bechtel, which means that the reference regulations for ITNS components will be American ones, in particular the ASME Section III technical regulations and the NQA-1 standard, concerning the quality assurance system. Similar requirements will also apply to units of large or small modular (SMR) nuclear power plants which may be subsequently built in Poland by companies from South Korea, Canada or Japan.

In turn, if another nuclear power plant in Poland was to be built by a company from France, the AFCEN RCC-M and AFCEN RCC-CW technical regulations would apply to the production of metallic ITNS components, whereas the EN ISO 19443 standard would apply to the quality management system.

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