INL/MIS-23-73634-Revision-0

Assessment of Nuclear Sensors and Instrumentation Maturity in Advanced Nuclear Reactors

July 2023

Changing the World's Energy Future

Thabit Abuqudaira, Pavel Tsvetkov, Piyush Sabharwall

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/MIS-23-73634-Revision-0

Assessment of Nuclear Sensors and Instrumentation Maturity in Advanced Nuclear Reactors

Thabit Abuqudaira, Pavel Tsvetkov, Piyush Sabharwall

July 2023

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Assessment of Nuclear Sensors and Instrumentation Maturity in Advanced Nuclear Reactors

Thabit Abuqudaira, Pavel Tsvetkov
Texas A&M University

Piyush Sabharwall
Idaho National Laboratory

Abstract

In the last decade, 97% of the worldwide commercial nuclear reactors connected to the grid were Light Water Reactors (LWRs). LWRs are expected to stay the dominant type of nuclear reactors for the next few decades. Reliable and redundant safety systems are required in nuclear reactors to ensure safe operation and shutdown in abnormal conditions. These safety systems are actuated by the signals obtained from several sensors and instrumentation in and out of the reactor core. Research and Development (R&D) in advanced sensors and instrumentation has gained extra attention, particularly following the accident at the Three Mile Island Unit-2 (TMI-2). In LWRs, these sensors and instrumentation have shown a high level of maturity with long operating experience. Ensuring the compatibility of these sensors and instrumentation with advanced nuclear reactors (Generation IV) is necessary, particularly with the expected expansion of the nuclear industry in the next few decades. Nuclear Sensor and instrumentation technologies used in the current generation of LWRs were investigated. The compatibility of these technologies with advanced reactors was assessed by comparing the advanced reactors' environments with those of the currently operating reactors. In addition to that, the needed R&D for such technologies was highlighted. In comparison with the LWRs environment, it was shown that advanced reactor environments are expected to experience elevated temperatures, a fast neutron spectrum, and a harsh corrosion environment. It was demonstrated that R&D is required mainly for fixed in-core nuclear sensors and instrumentation, while it is not a priority for ex-core nuclear sensors and instrumentation.

1. Introduction

According to the Power Reactors Information System (PRIS) developed by the International Atomic Energy Agency (IAEA) [1], Light Water Reactors (LWRs) share 84% of the nuclear reactors in operation worldwide. 85% of these reactors are Pressurized Water Reactors (PWRs), whereas the remaining 15% are Boiling Water Reactors (BWRs). The remaining reactors in operation worldwide are Pressurized Heavy Water Reactors (PHWRs), Light Water Graphite-moderated Reactors (LWGRs), Gas-Cooled Reactors, Fast Breeder Reactors (FBRs), and High-Temperature Gas-cooled Reactors (HTGRs). A pie chart showing the currently operating reactors classified by their type is shown in Figure 1.

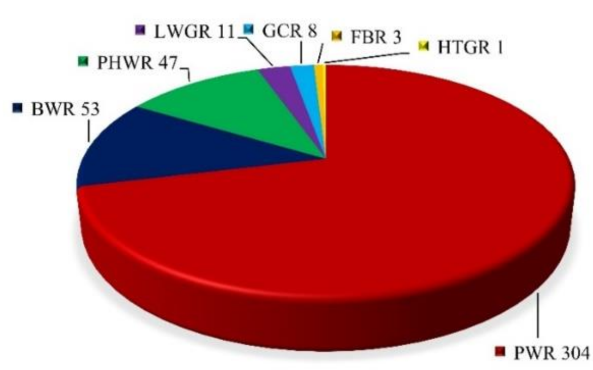

Figure 1. The number of currently operating reactors by type.

Sixty-eight commercial nuclear reactors have been connected to the grid worldwide in the last decade. Sixty-four of these reactors were LWRs (PWRs). In the previous five years, construction was started in 30 nuclear reactors, 29 of them were also LWRs (PWRs). A pie chart showing the nuclear reactors under construction in the last five years classified by their type is shown in Figure 2.

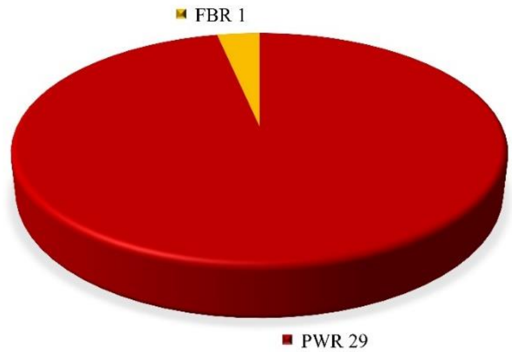

Figure 2. The number of reactors under construction by type.

In 2016, the first Generation III+ reactor was connected to the grid. Generation III+ reactors have been dominating the newly constructed reactors. It is anticipated that they will be leading for the next few decades. Generation IV reactors are expected to be deployed commercially within at least two decades [2]. With this trend of domination of LWRs, specifically PWRs, improvement, and development have to be continued for such types of reactors. On the other hand, the technological advancement in the next generation of reactors requires parallel progress in the R&D efforts for all needed components for their operation.

A nuclear reactor requires various redundant sensors and instrumentation systems to operate safely and reliably. These sensors and instrumentation vary in function and the degree of precision necessary to fulfill their purpose. The information gained from these sensors and instrumentation is used as input for the reactor's control and to indicate transients and deviations [3]. Thus, in addition to their role as control systems, sensors and instrumentation play a role as safety systems.

Since the first experiment with a nuclear reactor (Chicago Pile-1), sensors and instrumentation were required to monitor and ensure the safe operation of the reactor. Afterward, the number of sensors and instrumentation needed for all nuclear reactors constructed tended to increase. This increment was mainly to improve the safety of the newly operated reactors. Research and Development (R&D) in sensors and instrumentation have gained extra attention following the accident at the Three Mile Island Unit-2 (TMI-2). Investigations were performed by several National Laboratories, private companies, and consultants for the Department of Energy (DOE) to assess the instrumentation and electric components' ability to accomplish their design function [4]. The accident provided an opportunity to evaluate sensors and instrumentation performance in severe conditions [5].

In LWRs, sensors and instrumentation passed a long way of R&D until they reached a high level of maturity. However, the advanced reactor designs pose new challenges to these sensors and instrumentation, mainly due to the differences in the operating environments of the reactors. Some sensors and instrumentation, particularly in-core sensors and instrumentation, will operate in conditions significantly different from those in the current generation of nuclear reactors. High-temperature and corrosive environments can impose significant challenges to the design of sensors and instrumentation. In addition to that, these operating conditions could also impact sensors and instrumentations' reliability and accuracy. As a result of these factors, R&D programs are emerging, intending to commercially obtain sensors and instrumentation specifically designed for these types of reactors.

Advanced reactor designs are experiencing rapid technological advances. For this reason, R&D in sensors and instrumentation technologies must be initiated. The United States Nuclear Regulatory Commission (U.S.NRC) addressed Congress that research is needed to develop and assess the performance of new types of sensors and instrumentation for advanced reactors [6]. The Department of Energy, Office of Nuclear Energy (DOE-NE) has established several projects to accelerate R&D in sensors and instrumentation technologies in the United States. One of these programs is the Light Water Reactor Sustainability (LWRS) program. The program focuses on improving the economics and reliability and sustaining the safety of the U.S.'s fleet of Nuclear Power Plants (NPPs) [7]. Modernization of instrumentation technology is one of the technical areas of R&D of the program.

Another program is the Nuclear Energy Enabling Technologies (NEET) program. Advanced Sensors and Instrumentation (ASI) is one of its elements [8]. ASI focuses on research to develop new types of sensors and instrumentation systems that will likely be used in existing and advanced reactors. The program began in 2011. R&D activities have been effectively supported through directed research and competitive awards, enabling significant advancements in the field.

Nuclear sensors and instrumentation are one of the main types of reactor sensors and instrumentation required to operate the reactor safely and efficiently. Various detectors measure neutron flux and reactor power in the currently operating reactors. It is expected that a new generation of such types of detectors is required to be able to work in advanced reactors environments. Thus, R&D has to be continued to modify and improve the currently available set of sensors and instrumentation and to develop the next generation of such technologies.

The first step toward developing new types of nuclear sensors and instrumentation is to assess the maturity of the currently available sensors and instrumentation. Identifying the compatibility of the currently used sensors and instrumentation with the advanced reactors environment and analyzing the technological gaps and the needed improvements in the available technology will help to guide the R&D toward the most crucial areas. Such an assessment can help to meet the requirements of a new NPP license. For these reasons, an approach was developed to assess the R&D needs in nuclear sensors and instrumentation technologies tailored to future designs of nuclear reactors.

2. Nuclear Reactor Environments

Many reactor designs have been proposed since the first critical reactor, Chicago Pile 1. However, not all of them could achieve the stage of commercial operation. Few designs have reached the experimental stage, while many stayed as concepts. Differences in nuclear reactor designs led to significant differences in the operating environments. Thus, adopting a new reactor design into commercial operation faces many challenges, mainly due to the lack of operating experience with the new reactor environment. Understanding the differences in the operating conditions between the commercially available nuclear reactors and the proposed advanced reactor types will help to analyze the problems that sensors and instrumentation would face in advanced reactor environments.

2.1. Current and Advanced Reactor Designs

In this study, the proposed Generation IV reactors provided by the Generation IV International Forum were adapted for comparison with the currently available LWRs [9]. These are the Supercritical Water Reactor (SCWR), the Very High-Temperature gas-cooled Reactor (VHTR), the Sodium-cooled Fast Reactor (SFR), the Lead-cooled Fast Reactor (LFR), the Gas-cooled Fast Reactor (GFR), and the Molten Salt reactor (MSR). This study did not include a comparison of the operating conditions of the currently operational PHWR and LWGR designs.

2.1.1. Pressurized Water Reactor

LWRs are thermal neutron spectrum reactors. They have gained their name since light "ordinary" water is used as a coolant and moderator [10]. Huge experience has been achieved in operating LWRs, including Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs). In the United States, all currently operating 93 reactors are LWRs. Sixty-two of them are PWRs, and 31 are BWRs [11]. This operating experience has given enough maturity to nearly all components required for a reactor operation.

Since the first PWR "Shippingport" constructed by Westinghouse [12], PWRs have dominated the worldwide nuclear reactors market. For this reason, PWRs have been considered a reference "Benchmark" in developing new reactor designs. In general, newly proposed advanced reactor designs are compared with PWRs to assess their advantages and benefits. In addition, most of the proposed LWR designs for the future technology of Small Modular Reactors (SMRs) are PWRs [13]. Several vendors of PWRs are available worldwide. AP1000 reactor design is selected to be a reference for the operating environment for PWRs [14]. All other PWRs designs have quite similar operational parameters.

2.1.2. Boiling Water Reactor

Unlike PWRs, light water in BWRs is permitted to boil within the reactor core. The steam from this boiling process is sent directly to the turbine without passing through a heat exchanger. Thus, BWRs operate at a lower pressure than PWRs (around 7 MPa). The maximum coolant temperature in the reactor core is around 288 ℃. In addition to that, the reactor has lower power density in comparison with PWRs.

Future designs for BWRs are significantly fewer than PWRs. In the United States, two BWR designs have been approved by the U.S.NRC [15]. These are the Advanced Boiling Water Reactor (ABWR) and the Economic Simplified Boiling Water Reactor (ESBWR). Furthermore, BWRs are considered for small modular reactor designs (SMR), such as the BWRX-300 design by GE Hitachi in the United States [16]. The development of these advanced BWRs resulted from many years of design improvements, drawing from the valuable experience gained through early reactor designs. For operating parameters comparison, the ABWR design was selected.

2.1.3. Supercritical Water Reactor

Supercritical Water-Cooled Reactor (SCWR) is a high-temperature, high-pressure, light water-cooled reactor that operates above the thermodynamic critical point of water (374°C, 22.1 MPa) [17]. Even though it uses light water as a coolant, SCWR is considered an evolution of both PWRs and BWRs. It is one of the proposed advanced reactor designs by the Generation IV International Forum (GIF). Unlike LWRs, SCWRs have designs to operate with a fast-neutron spectrum [18]. The United States is interested in SCWRs with a thermal neutron spectrum.

Currently, there is no SCWR under construction. The reactor is still in the phase of pre-conceptual design. Several reactor designs have been proposed worldwide. However, this type of reactor is expected to have meager chances for commercial development compared to other advanced reactor types. However, the share of research papers published on this type of reactor during 20042018 among different reactor types was around 9% [19]. The reactor parameters of the proposed U.S. thermal-spectrum SCWR are used as a reference for this study for comparison purposes [20].

2.1.4. Very High-Temperature gas-cooled Reactor

Various experimental and commercial gas-cooled reactor designs have been developed around the world. These designs are Dragon (United Kingdom), Peach Bottom (United States), Arbeitsgemeinschaft Versuchsreaktor - AVR (Germany), Fort St. Vrain (United States), Thorium High-Temperature Reactor - THTR (Germany), High-Temperature Engineering Test Reactor - HTTR (Japan), High-Temperature Reactor - HTR-10 (China), and the Advanced Gas-cooled Reactor - AGR (United Kingdom). This operating experience has given enough maturity to nearly all components required for reactor operation. However, advanced gas-cooled reactors would exhibit more challenging operating environments.

VHTR is an evolutionary proposed design of the previously mentioned reactors. It would have operating temperatures of around 1000 °C. It uses helium as a coolant, with the fuel being tiny, coated fuel particles embedded in a graphite matrix [21]. Compared with LWRs, the reactor power density is significantly lower, while the coolant temperature is much higher. This type of reactor got attention since the produced heat can be used for other industrial purposes. In addition to that, the operating pressure considered for the VHTRs is comparable to BWRs.

2.1.5. Sodium-cooled Fast Reactor

In SFR, the molten sodium metal is used as the reactor coolant enabling the reactor to have a fast neutron spectrum. Many safety and economic features were the reason for selecting this reactor design as one of the proposed generation IV nuclear reactors. Several SFR has been built around the world. Currently, two reactors in operation in Russia are SFR. TerraPower plans to construct the Traveling Wave Reactor (TWR), a sodium-cooled reactor in the United States.

The technology for sodium-cooled fast reactors (SFRs) has mainly been established through previous fast reactor programs. SFR is one of the most promising reactor technologies to close the nuclear fuel cycle. The design of the SFR will be used as a breeding/burning uranium-plutonium fuel cycle [22]. The proposed Generation IV SFR was used as a reference to be compared with other reactor operating conditions [23]. It can be observed that the main feature of such a reactor is the reactor's high-power density in comparison with the conventional LWRs. In addition, sodium's high boiling point allows the reactor to operate at atmospheric pressure.

2.1.6. Lead-cooled Fast Reactor

A fast-neutron spectrum with lead or lead/bismuth as the coolant characterizes the LFR. Lead as a coolant has several advantages compared to other reactor coolants. The coolant's high boiling point provides a large margin for safety in preventing coolant boiling and maintaining core integrity during accidents. Thus, many simplifications in the reactor design improved the overall economic performance. Compared with LWRs, the reactor operates at atmospheric pressure, and the molten lead coolant is at higher temperatures.

Several countries, including China, Russia, the United States, Sweden, Korea, and Japan, actively develop various LFR concepts. The LFR system may be the first Reactor of Generation IV to be deployed. The first lead-cooled reactor construction started in 2021.

2.1.7. Gas-cooled Fast Reactor

The GFR features a fast-neutron spectrum with helium as the coolant [24]. Thus, in addition to the increased operating temperature in such reactors as the (VHTR), it has a fast neutron spectrum like (SFR). The GFR design aims to operate safely and reliably, achieving sustainability, economic competitiveness, and enhanced proliferation resistance and security [25]. In addition, being a fast reactor will allow the usage of recycled plutonium, which will play a crucial role in the long-term strategy for nuclear power development [26].

The proposed Generation IV GFR design is a 2400 MW_{th} plant operating with a coolant outlet temperature of 850 °C. The power density of the core is comparable to that in PWRs, while the coolant pressure is comparable to the BWRs. GFR technology is still in the R&D stage. Moreover, the design represents a significant step toward developing large-scale, high-temperature gas-cooled fast-spectrum reactors.

2.1.8. Molten Salt Reactor

Molten Salt Reactors (MSRs) come in two distinct designs regarding fuel geometry. The first design is when the fuel and the coolant are mixed in one homogeneous fluid. In the second one, the fuel is confined to traditional fuel rods. These two designs have some differences in the operating environment. This study uses the salt-fueled design as a reference for the comparison. The fuel movement, salt chemistry, higher power density, and elevated temperatures significantly differ from the currently operating reactors.

In the United States, liquid fuel nuclear reactors got an attraction in the 1950s by initiating the Molten Salt Reactor Program (MSPR) at Oak Ridge National Laboratory (ORNL). Two MSRs were built and operated: the Aircraft Reactor Experiment (ARE) and the Molten Salt Reactor Experiment (MSRE) [27], [28]. The ARE was successfully operated for over four days, while the MSRE was for 4.5 years [29]. Nevertheless, no commercial deployment of this reactor type was achieved.

In the United States, research is conducted on molten salt reactor development and deployment efforts. Construction is underway for a Molten Salt Research Reactor (MSRR) located on the Abilene Christian University (ACU) campus in Texas. The primary purpose of the Reactor will be to facilitate research and provide training opportunities within the Molten Salt Reactor (MSR) environment.

2.2. Comparison of Reactor Environments

Coolant temperature and pressure, neutron spectrum, and corrosive environment are the most important parameters regarding the compatibility of new sensors and instrumentation technologies with an advanced reactor environment. Although sensors and instrumentation that would be placed in-core may exhibit slightly higher temperatures than coolant outlet temperatures, this temperature can indicate the temperature range in which the sensors and instrumentation should be able to operate. The operating pressure measurement is necessary to prevent instrumentation failures, damage, or compromised performance. The knowledge of the type of neutron spectrum in a particular reactor indicates the radiation damage and material degradation with time. The coolant material describes the corrosion environment that may face the sensors and instrumentation. A summary of the operating parameters that may make challenges to the currently available sensors and instrumentation in current and advanced reactors is listed in Table 1.

Table 1. Comparison of operating parameters for different types of reactors.

Reactor type (Design)	Neutron spectrum	Coolant type	Coolant outlet temperature (°C)	Pressure (MPa)	Power density (MW_{th}/m^3)
PWR (AP1000)	Thermal	Light water	330	15.5	98
BWR (ABWR)	Thermal	Light water	288	7.07	49.2
SCWR*	Thermal	Light water	500	25	97.6
VHTR*	Thermal	Helium	1000	7	6
SFR*	Fast	Sodium	550	0.1 (Ambient)	350
LFR*	Fast	Lead	480	0.1 (Ambient)	69

GFR*	Fast	Helium	850	7	100
MSR*	Fast	Sodium	700	0.1 (Ambient)	500

*Designs provided by the Generation IV International Forum.

The above table shows that advanced nuclear reactors will operate at temperatures higher than what sensors and instrumentation have experienced serving in currently available nuclear reactors. In addition, higher levels of power density, fast neutron spectrum, and the corrosive environment in these reactors may pose a challenge for the available sensors and instrumentation.

In terms of neutron flux, the overall neutron flux level will be comparable for all reactor designs. However, only the type of neutron spectrum and the activation of the coolant material and the associated gamma-ray field may play a role in the compatibility of the sensors and instrumentation. Studying each parameter's impact on the compatibility of the sensors and instrumentation can indicate the effect of this parameter on all advanced reactor designs. The proposed advanced reactor types are compared with LWRs in terms of the operating parameters that may affect the sensors and instrumentations. This comparison is shown in Table 2.

Table 2. Advanced reactors environments in comparison with LWRs.

Reactor type	Operating parameters (In comparison with LWRs)			
	High temperature	Corrosive environment	High pressure	Fast spectrum
SCWR	✓	×	✓	×*
VHTR	✓	×	×	×
SFR	✓	✓	×	✓
LFR	✓	✓	×	✓
GFR	✓	×	×	✓
MSR	✓	✓	×	✓

* Some SCWRs are available with fast spectrum design.

It can be concluded that advanced reactors environments will differ from the currently available LWRs by the increase in the operating temperature (from the range of 300-350 ℃ up to around 1000 ℃ in VHTR), the harsh chemical environment caused by the usage of molten salts and liquid sodium and lead, and the exposure to fast neutrons in fast reactors. In addition, it can be demonstrated that high pressure is not a significant concern in advanced reactor designs. Only the SCWR design has an elevated operating pressure than the currently available reactor designs.

3. Assessment Methodology

The previous section discussed the main differences in the operating environment of several nuclear reactors. Commercially available nuclear reactors have attained enough operating experience with various sensors and instrumentations. Thus, the first step to discovering the problems that sensors and instrumentation would face in advanced reactors is to study the differences in the operational environments between the commercially available reactors and the proposed advanced reactor.

An approach was adopted to investigate nuclear sensor and instrumentation technology's R&D needs. This approach analyzed the available nuclear sensors and instrumentation used in current reactor designs. The technological gaps and the needed improvements were highlighted. Then, the compatibility of these sensors and instrumentation with the advanced reactor environments was investigated.

Sensors and instrumentation that would not face any problem in the advanced reactor environment and are commercially available can be used in advanced reactor designs. Thus, the instrumentation technology can be assessed as mature. Therefore, R&D is not a priority. If the sensor and instrumentation technology is compatible with the advanced reactor environment but is not commercially available, an R&D program is essential to commercialize the technology. Commercial availability of several types of sensors and instrumentation can be investigated by searching for the availability of the technology within companies of the Nuclear Suppliers Association (NSA). NSA comprises approximately 73 companies specializing in manufacturing and distributing services and products for nuclear energy users [30].

Sensors and instrumentation facing problems in the advanced reactor environment require significant R&D programs to fill the technological gaps. In either case, where R&D is needed based on the defined approach, the availability of initiated research projects on the sensor and instrumentation technology was further investigated. The investigation was based on the availability of research projects supported by the DOE NEET ASI program. Although the availability of funded projects on a particular type of technology does not mean that the technology is mature, it indicates that sensors and instrumentation with no current research projects have priority for future R&D programs. The adopted approach for determining the need for R&D programs for specific instrumentation is summarized in Figure 3.

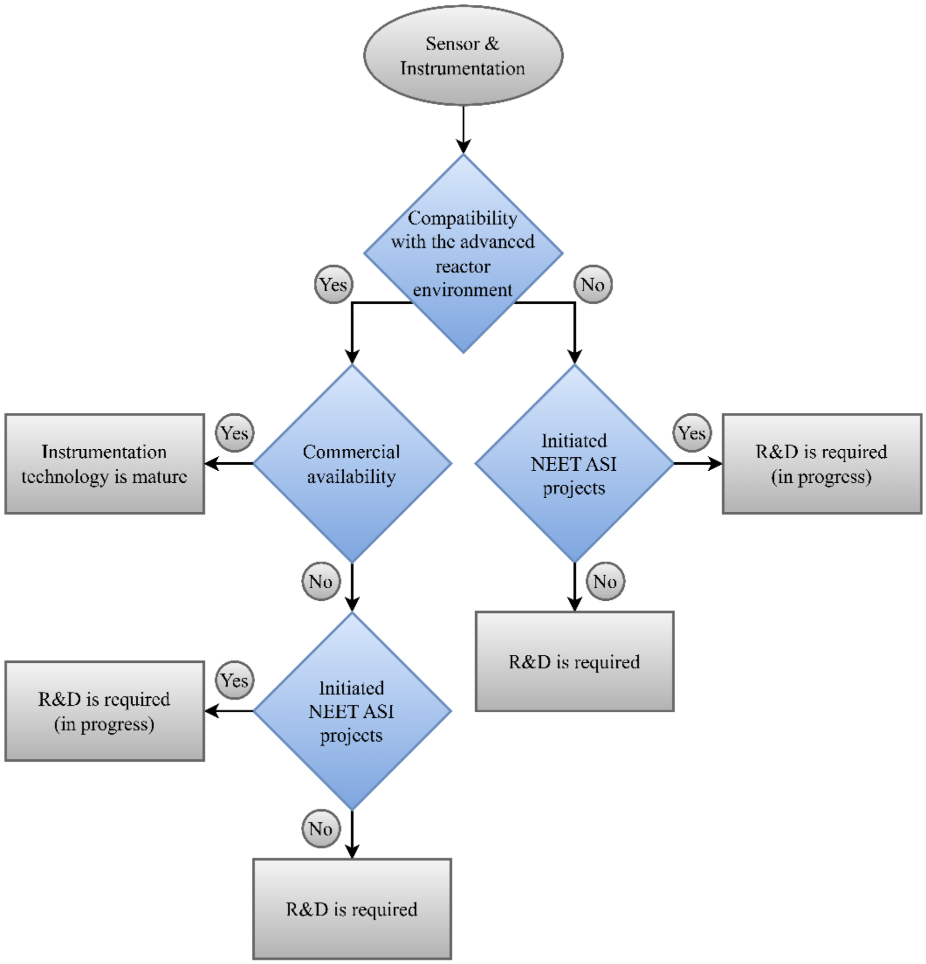

Figure 3. Sensors and instrumentation maturity assessment approach.

In the future development of this approach, the Technology Readiness Levels (TRLs) approach can be used to assess the maturity of a particular instrumentation technology. NASA first proposed the TRL in the 1980s. The TRLs are divided into nine technology readiness levels starting from TRL 1 (The lowest where the basic principles for a specific technology are observed and reported) and ending in TRL 9 (The highest where the existing system was proven to be successful for mission operations) [31].

4. Nuclear Sensors and Instrumentation

Various sensors and instrumentation are required in a nuclear reactor to operate it safely and efficiently. These sensors and instrumentations represent the information suppliers to the reactor operators about the reactor status. Based on their deployment location, they are needed for the reactor core or other nuclear reactor components. These include nuclear instrumentation required to monitor the neutron flux and the associated reactor power, process instrumentation to measure non-nuclear processes such as temperature distribution in the core, pressure and flow measurements of the coolant, radiation instrumentation systems for radiation monitoring and dose levels measurements, and some other specific instrumentation for specific purposes [32]. A summary of nuclear reactor sensors and instrumentation groups is shown in Figure 4.

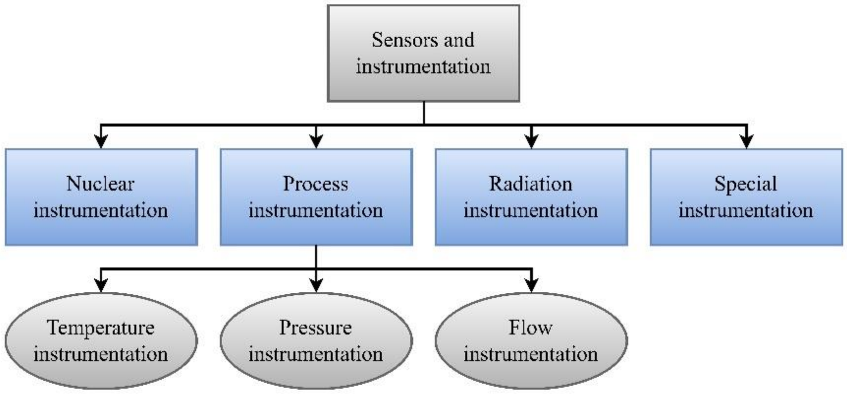

Figure 4. Sensors and instrumentation groups of a nuclear reactor.

Process instrumentation is crucial in monitoring and controlling various parameters within a nuclear reactor. It involves using sensors, detectors, and other measurement devices to gather data and provide real-time information about the reactor's temperature, pressure, flow, and other essential parameters. Radiation instrumentation systems include the sensors and instrumentation required to monitor the site radiation level (area radiation monitoring), gas effluents, and main steam pipes. These instrumentation systems are essential to protect personnel from radiation exposure, and they can indicate abnormal reactor conditions. Special instrumentation systems are reactor-type targeted. Based on the reactor type, such as the boric acid concentration instrumentation in PWRs, these sensors and instrumentation are required.

Nuclear sensors and instrumentation play a significant role in reactor control and safety. They measure the neutron flux and the associated reactor power level during various reactor conditions. These are: during the approach to criticality and reactor startup, intermediate power operation, and full-power reactor operation [33]. In the Advanced Pressurized water-cooled reactor (AP1000) designed by Westinghouse Electric Company, several types of neutron detectors are used to monitor the neutron flux from zero to 120 percent of full power [34].

In the currently operating reactors, various neutron detection systems are being used. These sensors and instrumentation can be installed inside the reactor core (in-core) or outside the reactor core (ex-core) based on their design purpose. They provide diversity and redundancy in the obtained information about the reactor status. Fission chambers, Ionization chambers, gamma thermometers, proportional counters, and self-powered neutron detectors (SPNDs) are among this nuclear instrumentation [35]. Furthermore, other nuclear instrumentation systems are used in specific reactor types, such as the aeroball measurement system used in EPR reactors. In addition, research is ongoing to apply new reactor flux and power measurement methods, such as the Cerenkov monitoring systems for in-core power measurement. The typical flux ranges covered by nuclear instrumentations in LWRs are illustrated in Figure 5 [33]. Note that the nuclear instrumentations should be able to overlap between the operating flux ranges.

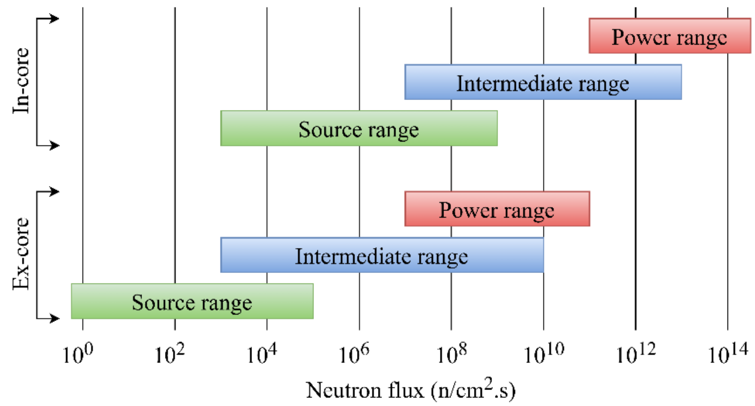

Figure 5. The covered typical flux ranges by nuclear instrumentation systems in LWRs.

A group of fixed in-core and ex-core neutron detectors in nuclear reactors monitors the neutron flux and reactor power. In AP1000 reactors, fixed in-core and ex-core neutron detectors are used to monitor the neutron flux and reactor power [36]. The choice of detector location is made based on the detector's purpose and ability to withstand the harsh environment in the reactor core. These in-core and ex-core nuclear instruments should be able to measure the neutron flux over the entire range from the source start-up range up to the full power range.

In-core instrumentation should be able to operate at the operating conditions of the nuclear reactor. Ex-core instrumentation would be exposed to lower temperature, pressure, and neutron and gamma flux values. In commercial nuclear reactors, self-powered neutron detectors and gamma thermometers are the in-core nuclear instrumentation. Ionization chambers and proportional counters are the ex-core nuclear instrumentation. Fission chambers are used as both in-core or ex-core nuclear instrumentation. Classification of nuclear instrumentation based on their location regarding the reactor core is shown in Figure 6.

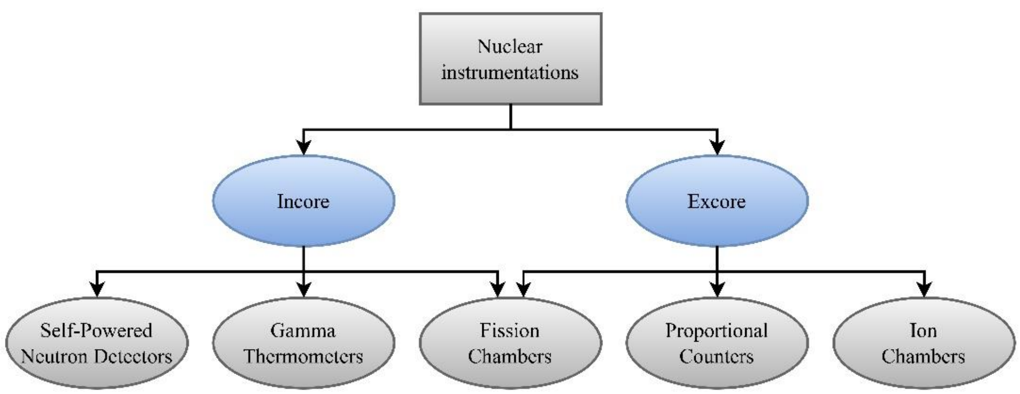

Figure 6. Classification of nuclear instrumentation by deployment location.

Regarding the movability of the installed nuclear sensors and instrumentation, they can be fixed in the reactor core or movable on-demand systems. The aeroball measurement system is an example of a system used as on-demand in-core nuclear instrumentation.

4.1. Self-Powered Neutron Detectors

Self-Powered Neutron Detectors (SPNDs) are the most common detectors used in commercial nuclear power plants [37]. These detectors attained this wide usage due to their advantages over other detector types in the reactor operating environments. Simple structure, tiny volume, no need for a power supply, and high temperature and radiation resistance are among the advantages of this type of detector [38].

In a nuclear reactor, several SPNDs are located axially within a channel in several channels inside the core. Thus, SPNDs can continuously measure the neutron flux in fixed positions inside the reactor core from low power level up to full power. However, they are unsuitable for startup range measurements. A SPND comprises four main components: emitter, insulator, collector (sheath), and lead wire [39]. A schematic drawing of a SPND is shown in Figure 7.

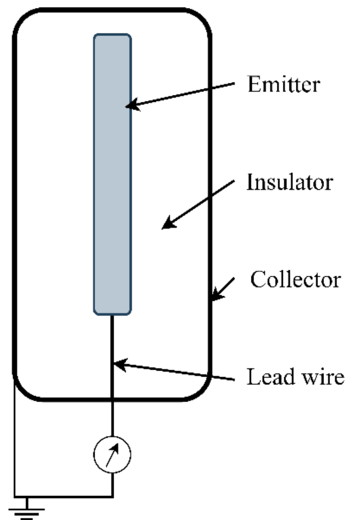

Figure 7. Schematic drawing of a SPND.

The emitter material is selected to have a high neutron absorption cross section that undergoes betas decay directly or indirectly following the neutron absorption. The insulator's function is to provide temperature and electric resistance. It must have an optimized thickness so that the produced electrons in the emitter can reach the sheath (collector). The sheath works as a collector of the electrons from the emitter. The lead wire's function is to transmit the electrical current. A current meter will read the current value, which will be proportional to the emitted electrons from the emitter material. After equilibrium, the registered electric current will be proportional to the incident neutron flux from the reactor core. Thus, the reactor power is measured by measuring the output current in the SPND induced by the decay resulting from the neutron capture reactions [40].

The selection of the emitter material determines the response of the SPND. The response of a SPND is dependent on the radioactive decay of the radionuclide resulting from the neutron capture by the emitter material. SPNDs can be classified as prompt response and delayed response SPNDs. The emitter material can produce electrons directly following the neutron absorption reaction, such as in the case of rhodium (^{103}Rh) and vanadium (^{51}V) emitters. The disadvantage of using such emitters is that these materials decay with characteristic half-lives (0.7 and 3.76 minutes, respectively) [41]. Thus, the registered neutron flux is delayed; they are named delayed-response SPNDs.

Prompt SPNDs were designed to overcome this delay issue and obtain an instantaneous measurement of the neutron flux in the reactor core. Following the absorption of a neutron, the emitter nucleus will emit gamma rays which will interact with the emitter material to produce electrons. The time from the neutron absorption until the emission of electrons is extremely short. Thus, a prompt measurement of the neutron flux is obtained with such materials. Cobalt and cadmium are the main types of emitter materials in prompt SPNDs.

The selection of the emitter material for a SPND has been an important research topic. The half-life of the resulted radionuclide and thus the response required, the neutron absorption cross section and therefore the burnup of the emitter material in the reactor core, the natural abundance of the isotope of interest and the ease in manufacturing it, and their adaptively to the high-temperature environment are the critical factors in the selection process.

From the above description of the main components of the SPND, it is clear that the SPND has several components that must be designed to operate in advanced reactors. One of the issues with the SPNDs is that they have a lifetime. This lifetime is affected by the degradation of the insulator material, to a lesser extent, the burnup of the emitter material with time. In addition, one of the issues is that the housing material should be compatible with the reactor coolant, which does not undergo corrosion.

The maximum working temperature for the SPNDs depends on the emitter material and the housing material properties. Typically, it is around 550°C [42]. SPNDs have not been used in high-temperature reactor environments or fast reactors (beyond light water reactors environments). However, deploying SPND in advanced reactors can improve the accuracy of power distribution measurements and hence the core operating LOCA and DNBR margin values [43]. The commercially available technology for LWRs is expected to have no problem in a high-pressure environment. However, a further study on the effects of the high-pressure environment on SPNDs is required.

The commercially available SPNDs cannot be used in fast reactors [44]. This problem can be explained by the drop in the absorption cross section of the emitter material at higher neutron energies (absorption cross section decreases with the increase in the incident neutron energy). For this reason, research is ongoing to select a proper material for the emitter to get good results in fast reactors [45], [46]. In molten salts, SPNDs require modifications in the housing material (exterior sheath) to be compatible with the salt [47].

Several funded projects by the NEET ASI program recently initiated the development of SPNDs for High-Temperature environments. However, R&D projects are needed to modify the external housing material for the SPNDs if they are used in a chemically corrosive environment. In addition to that, the possibility of deployment of SPNDs in fast reactors is shown to be high. R&D programs can accelerate these efforts.

4.2. Gamma Thermometers

Reactor power measurement sensors are based on detecting neutrons, gammas, or both. Gamma thermometers measure the reactor power by measuring the gamma-ray flux in the reactor core. In addition to that, gamma thermometers can be used to get information about core cooling in nearby channels. Furthermore, they can be used outside the reactor vessel.

The start of deployment of gamma thermometers goes back to the beginning of the 1950s in heavy water-moderated reactors. They were used because they are simple in design, very rugged, and insensitive to neutron fluence. They have the advantage over SPNDs that they do not deplete with time. Thus, they can operate longer than SPNDs and other in-core neutron detectors. Gamma thermometers are not suitable for startup or low power levels. At intermediate power level and up to full power, the gamma-ray flux is proportional to the reactor power level, and thus gamma thermometers can be used.

The design structure of gamma thermometers is similar to the thermocouples used in temperature measurement. A gamma thermometer is composed of a rod material, gap, and sheath [48]. The rod (inner body) is usually made of stainless steel. A gap filled with gas surrounding the inner body is used for heat insulation. The gas is selected with proper thermal conductivity, depending on the level of gamma-ray heating inside the core. For low levels of gamma-ray heating (< 2 W/g), xenon is a proper gap material.

Argon is used for intermediate gamma-ray heating levels (~ 10 W/g), while helium is used for high levels of gamma-ray heating (~20 W/g) [49].

When inserted in the reactor core, incident gamma-ray flux heats the rod, which is transferred along the sensor axis. The gap filled with the gas will interrupt the heat flow. Two thermocouples measure the difference between the sheath and the steel rod regions. This difference is proportional to the gamma flux incident on the sheath and, thus, the power of nearby fuel rods. Several thermocouples can be used along the gamma thermometer to get the axial power distribution. Using gamma thermometers in several channels provides the radial power distribution. A simple schematic drawing of a gamma thermometer is shown in Figure 8.

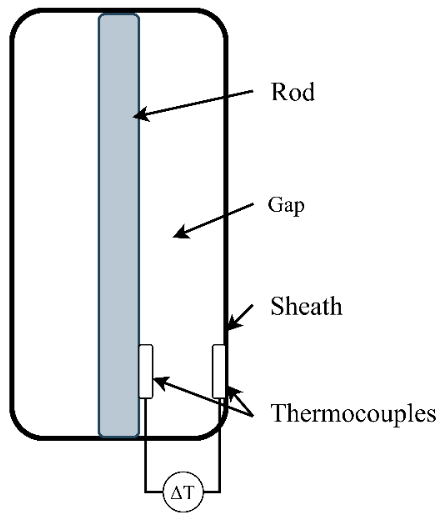

Figure 8. Schematic drawing of a gamma thermometer.

Gamma thermometers have yet to achieve widespread, long-term deployment within U.S. commercial nuclear power plants [50]. In-plant tests as part of a joint research program were initiated to use gamma thermometers at commercial nuclear power plants in the U.S. and Japan [51]. In the U.S., research supported by the NEET ASI program is ongoing to develop an optical fiber-based gamma thermometer [52]. Deployment of gamma thermometers in nuclear power plants can enhance safety and core monitoring while reducing other systems' operational and maintenance costs. In the Economic Simplified Boiling Water Reactor (ESBWR), gamma thermometers as in-core monitoring sensors are considered an essential feature over the previous BWRs [53].

Gamma thermometers have not been demonstrated at the higher temperatures of VHTRs. A significant redesign is needed to function at higher temperatures [54]. However, with their simplicity in design, it is promising that they would perform well at higher temperatures. For MSRs, customization effort would be required to develop a version suitable for the reactor environment. High pressure can exert mechanical stress on the components of gamma thermometers. This stress may cause deformation, cracking, or failure of structural elements. Thus, this high pressure may reduce the lifetime of such components. R&D programs must be initiated to study the effect of a high-pressure environment on gamma thermometers.

4.3. Fission Chambers

Fission chambers are a type of ionization chamber. Unlike SPNDs, fission chambers require the application of an electric voltage between the cathode and the anode. The chamber is filled with a gas (commonly argon) at high pressure. Fission chambers can be used as in-core or ex-core nuclear instrumentation. A schematic drawing of a fission chamber is shown in Figure 9.

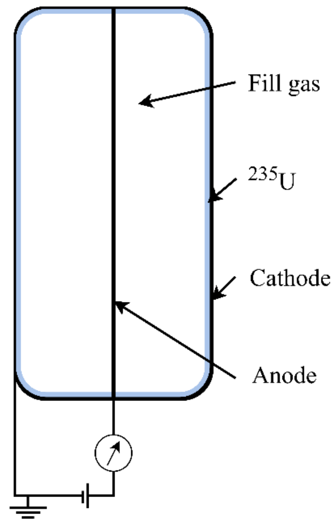

Figure 9. Schematic drawing of a fission chamber.

By placing a fission chamber in a neutron field, incident neutrons will be absorbed by the fissile material lined on the fission chamber housing. Usually, the housing material is steel or aluminum, while the fissile material is uranium highly enriched in a ^{235}U isotope. Using highly enriched uranium increases the fission reaction rate and thus enhances the ionization current.

Upon ^{235}U fission, two ionized fission products will be produced with a total kinetic energy of around 160 MeV. These two fission fragments will travel in opposite directions. One of the two fission fragments will be traveling into the gas chamber. For this reason, the thickness of the fissile material should be optimized to allow the fission fragment to reach the gas without affecting the fission rate [55]. The fission fragment will ionize the fill gas atoms along its path, producing positive ions and negative electrons. An external voltage is applied to the cathode and anode, causing the positive ions to move toward the cathode while the electrons are collected on the anode. The current produced from this process is proportional to the fission rate in the fissile material and, thus, to the reactor core's neutron flux [56].

The depletion of the fissile material is the leading cause of the limited operating time for fission chambers as in-core nuclear instrumentation. The sensitivity of a fission chamber decreases with time because of the neutron fluence. Combining fissile and fertile materials can be a solution to such a problem.

Commercial fission chambers are available for the operating environment of LWRs. However, no commercial fission chamber is available for high-temperature reactors environment (above 550 °C). Locating the chambers ex-core will reduce the temperature to those that commercially available fission chambers can withstand. The housing material and the internal gas pressure determine the operating temperatures of fission chambers [57].

High pressure may affect the sealing and containment of a fission chamber. The fission chamber must be appropriately sealed to prevent pressure leakage, which could compromise its functionality. Specialized sealing materials and techniques capable of withstanding high-pressure differentials may be required. There is no available research on the effect of a high-pressure environment on fission chambers.

A fission chamber that would operate at high temperatures of 550 °C and beyond is named High-Temperature Fission Chamber (HTFC). Previous research programs have developed such chambers that run up to 800 °C. However, these chambers are not commercially available. Developing HTFCs and demonstrating their sensitivity and mechanical and thermal robustness in the high-temperature environment will pave the way for developing high-temperature reactors. Several DOE NEET ASI projects have been initiated to design, fabricate, and demonstrate High-Temperature Fission Chambers (HTFCs). They aim to provide HTFC for HTRs, MSRs, and fast reactors.

Micro-pocket fission chambers are pancake-style, highly miniaturized fission chambers that employ sealed alumina plates as their structural backings and coatings of uranium or thorium as their neutron-sensitive element [58]. Micro-pocket fission chambers are a promising technology used in a high-temperature environment. The technology has yet to be commercially available. Several funded projects by DOE NEET ASI were initiated to develop it.

4.4. Ionization Chambers

In PWRs, the core power density distribution can be measured using ex-core detectors. These detectors can be installed outside the reactor vessel in several axial locations. The measured neutron flux in these detectors is then used to get the axial power distribution in the reactor core.

Ionization chambers are neutron detectors that can be used outside the reactor vessel for neutron flux measurements. They are gas-filled radiation detectors that can be designed to measure several types of ionizing radiation. The principle of operation is similar to fission chambers. Compared to fission chambers, ionization chambers use ^{3}He or ^{10}B nuclides as the filling gas instead of ^{235}U to produce the charged particles. A schematic drawing of an ionization chamber is shown in Figure 10.

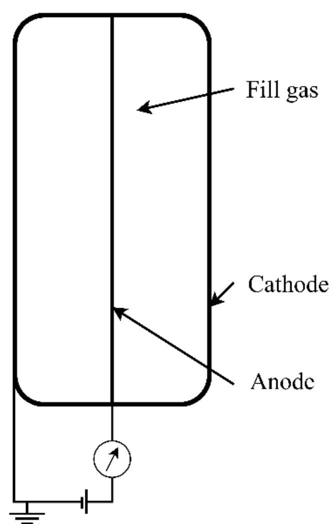

Figure 10. Schematic drawing of an ionization chamber.

Compensated and uncompensated ionization chambers are used as ex-core nuclear instrumentation. Uncompensated ionization chambers are used as a power-range monitoring system. Compensated ionization chambers are used for intermediate power range. The compensated ionization chamber comprises two distinct chambers: one is coated with boron, while the other is uncoated. The coated chamber exhibits sensitivity to gamma and neutrons, whereas the uncoated chamber only detects gamma rays. The detector output is the difference between the two currents generated from the chambers. This difference in current represents the neutron response of the compensated ionization chamber. Therefore, the compensated ionization chamber cancels the current resulting from the gamma rays' interaction. This compensation technique proves valuable in the intermediate power range, ensuring that the detector response is only due to neutron flux.

Several types of compensated and uncompensated ionization chambers are used in LWRs and high-temperature reactors. Thus, no significant challenge is expected in deploying the currently available technology in the advanced high-temperature reactors environment. In a fast reactor environment, ex-core moderation is required to achieve better sensitivities in the measurements or to use more giant ionization chambers.

In MSRs, ionization chambers are expected to be compatible and thus have no problem deploying such detectors [59]. This compatibility can be explained by the fact that these detectors will be used as ex-core nuclear instrumentation. In fact, in the only two MSRs built, no neutron instrumentation was employed in the core. Only ex-core detectors were used. However, for the proposed advanced MSRs, employing in-core neutron detectors that can withstand their harsh environment is necessary for high-sensitivity measurements.

4.5. Proportional Counters

Proportional counters are gas-filled detectors used as a source-range neutron flux monitoring system. They are used as ex-core nuclear instrumentation during the first criticality or for start-up after a very long shutdown. Their principal mode of operation is quite similar to the ionization chamber. However, the applied voltage to the cathode and anode is higher than in ionization chambers.

Some proportional counters are based on the (n, α) reaction with ^{10}B in the boron trifluoride gas (BF_3) filled in the detector's chamber. Boron-lined proportional counters have been used in High-Temperature Engineering Test Reactor (HTTR) for temperatures up to 600 °C. In gas-cooled reactors, proportional counters have been used as neutron sensors [60]. Thus, no temperature problem is expected to arise in high-temperature reactor environments. Therefore, commercially available proportional counters technology is mature enough, and R&D is not a priority for such a type of detector.

Proportional counters can be used to detect thermal neutrons or fast neutrons. For fast-spectrum reactors, proportional counters are less efficient due to the ^{10}B capture cross-section drop with increased neutron energy. Using more giant detectors can solve this problem to compensate for this drop in cross section. In addition to that, helium or a gas with a low atomic number can be used in the chamber to moderate the neutrons. In molten salt reactors, proportional counters are expected to operate with no problem since they are deployed out of the corrosive environment of the reactor core.

4.6 On-Demand Nuclear Instrumentation

Some nuclear instrumentation systems are on-demand operation. That is, the system is not in a continuous mode of operation and may not be installed in fixed core positions [61]. One of the examples of such a system is the Aeroball Measurement System (AMS) used in the Evolutionary Power Reactor (EPR). The system measures the neutron flux in predetermined three-dimensional positions in the reactor core. In addition to that, AMS is used to calibrate SPNDs and predict power density distribution in the reactor core [62].

The AMS is composed of several steel balls that contain vanadium. These balls move in specific vertical tubes in the reactor core by a nitrogen gas driving mechanism. The aeroballs enter the reactor core using nitrogen gas pressure. In the reactor core, the thermal neutron flux will irradiate the aeroballs, and many of the ^{51}V atoms will capture neutrons resulting in ^{52}V in an excited state with a half-life of 3.74 minutes. ^{52}V will undergo beta decay with the emission of about 1.43 MeV gamma-ray.

After irradiation, the aeroballs are transported to waiting positions before they are transported to a measuring system. The measuring system consists of several planar silicon detectors that measure the gamma-ray intensity resulting from the decay of the activated atoms. Information about the relative neutron flux values in the reactor core and, thus, power distribution can be calculated using software using these measured intensities from the aeroballs [63]. Because of the short half-life of the produced ^{52}V, this measurement process can be repeated every 15 minutes allowing for the reuse of the aeroballs [64].

Even though such on-demand nuclear instrumentation systems may be installed in the reactor core, they will face a different reactor operation environment than other in-core nuclear sensors and instrumentation. This results from the fact that they will not be exposed to the harsh in-core environment for the same duration. Therefore, they may be treated like ex-core nuclear sensors and instrumentation. In addition, unlike fission chambers or gamma thermometers, such systems are mainly used in certain reactors and not widely used in other reactor designs. For these reasons, the on-demand nuclear instrumentation systems are not discussed further.

5. Overall Assessment

The compatibility of the nuclear sensors and instrumentation with the advanced reactors environments was assessed. For in-core nuclear instrumentation, it is clear that some of the nuclear sensors and instrumentation technologies used in current LWRs may not be suitable for the advanced reactors environment. SPNDs are expected to have issues operating in a fast-spectrum environment, high temperature, and corrosive environment. Gamma thermometers are not ready to be used in high-temperature or corrosive environments. Fission chambers are compatible with the fast spectrum environment and high-temperature environment. However, the technology is not commercially available at high temperatures. The housing material must be modified to operate in a corrosive environment.

Overall, it can be demonstrated that the ex-core nuclear instrumentation is expected to have no issue when deployed in advanced nuclear reactors. This fact is mainly because, outside the reactor core, the neutron flux, temperature, and corrosion environment are several folds lower than that in the reactor core. Thus, the ex-core environment in the advanced reactors will be the same as in the currently operating reactors. Using ex-core nuclear instrumentation may be sufficient for reactor operation and safety. On the other hand, deploying in-core nuclear sensors and instrumentation may increase the sensitivity of the measurements and, thus, the overall safety. A cost/benefit analysis is required to assess the need to deploy the nuclear sensors and instrumentation in the in-core advanced reactor environments to decide whether an R&D is necessary to deploy the technology.

The compatibility of the above-discussed in-core and ex-core nuclear sensors and instrumentation with various reactor environments is summarized in Tables 3 and 4, respectively. Since LWRs have a long operating experience, the comparison was performed with the environment in LWRs.

Table 3. Compatibility of the in-core nuclear instrumentation with various reactor environments.

Reactor Environment	In-core nuclear instrumentation		
	SPNDs	Gamma thermometers	Fission chambers
LWR	**Compatible** They have been used in	**Compatible** Have been used since the 1950s.	**Compatible** Have been widely used.

	thermal nuclear reactors for more than 60 years.		
Fast spectrum	**Incompatible** The emitter material should be replaced.	**Compatible** Insensitive to neutron fluence.	**Compatible** Larger size detectors are used.
High temperature	**Incompatible** A maximum working temperature is around 550 ℃.	**Incompatible** A significant redesign is required to function at higher temperatures.	**Compatible** These chambers are not commercially available.
Molten salts	**Incompatible** The housing material should be modified for salt compatibility.	**Incompatible** A version suitable for the reactor environment is required.	**Incompatible** The housing material should be modified for salt compatibility.
High pressure	**Compatible** The effect of high pressure on its lifetime and structural integrity should be studied.	**Compatible** The effect of high pressure on its lifetime and structural integrity should be studied.	**Compatible** The effect of high pressure on its sealing and containment should be studied.

Table 4. Compatibility of the ex-core nuclear instrumentation with various reactor environments.

Reactor Environment	Ex-core nuclear instrumentation		
	Fission chambers	Ionization Chambers	Proportional Counters
LWR	**Compatible** Several types are being used worldwide.	**Compatible** Compensated and uncompensated types are being widely used.	**Compatible** They are being used.
Fast spectrum	**Compatible** Larger size detectors are usually used.	**Compatible** Larger size detectors are usually used.	**Compatible** Larger size detectors are usually used.
High temperature	**Compatible** Ex-core reactor environment would be the same as in LWRs.	**Compatible** They have been used in several gas-cooled reactors.	**Compatible** The commercially available counters can be used.
Molten salts	**Compatible** They were used as ex-core nuclear instrumentation.	**Compatible** They were used as ex-core nuclear instrumentation.	**Compatible** They were used as ex-core nuclear instrumentation.
High pressure	**Compatible** Ex-core reactor environment would be the same as in LWRs.	**Compatible** Ex-core reactor environment would be the same as in LWRs.	**Compatible** Ex-core reactor environment would be the same as in LWRs.

Although in-core nuclear instrumentation is expected to function at high pressure, the high-pressure environment may impact the in-core nuclear instrumentation. This influence can be by affecting the structural integrity of the instrumentation caused by the mechanical stresses applied by the high pressure. This stress may cause deformation, cracking, or failure of structural elements of the nuclear instrumentation over the operating time. Additionally, the high pressure may affect the sealing and containment of instrumentation filled with gasses. Thus, instruments must be appropriately sealed to prevent pressure leakage, which could compromise their functionality. Furthermore, the high pressure may influence the calibration standards used for pressure-sensitive instruments. For these reasons, the compatibility and durability of nuclear sensors and instrumentation with high-pressure reactor environments such as SCWR must be investigated.

Table 5 summarizes the technology gaps, commercial availability, and the R&D needs for the above-discussed in-core nuclear instrumentation in currently operating PWRs, BWRs, and generation IV reactors.

Table 5. Summary of in-core nuclear instrumentation R&D needs in current and advanced reactors.

Reactor Environment	In-core nuclear instrumentation		
	SPNDs	Gamma thermometers	Fission chambers
PWR	**The technology is mature.** Commercially available.	**The technology is mature.** Have been widely used and is commercially available.	**The technology is mature.** Have been widely used and is commercially available.
BWR	**The technology is mature.** Commercially available.	**The technology is mature.** Have been widely used and is commercially available.	**The technology is mature.** Have been widely used and is commercially available.
SCWR	**Requires R&D** The commercially available technology is expected to function well in a high-pressure environment. However, the durability and structural integrity may need to be studied in a high-pressure environment.		
VHTR	**Requires R&D** to operate at high temperatures. Not commercially available.	**Requires R&D** to operate at high temperatures. Not commercially available.	**Requires R&D** to operate at high temperatures. Not commercially available.
SFR	**Requires R&D** to operate at high temperatures with the fast spectrum environment. Not commercially available.	**Requires R&D** Not commercially available.	**Requires R&D** to operate at high temperatures. Not commercially available.
LFR	**Requires R&D** to operate in the fast spectrum environment.	**R&D is not a priority** Commercially available technology can be used.	**R&D is not a priority** Commercially available technology can be used.
GFR	**R&D is required** to operate in a fast-spectrum environment.	**Requires R&D** to operate at high temperatures. Not commercially available.	**Requires R&D** to operate at high temperatures. Not commercially available.
MSR	**R&D is required** to modify the emitter and housing materials and to operate in a fast-spectrum environment. Not commercially available.	**R&D is required** to function at high temperatures and to be salt compatible. Not commercially available.	**Requires R&D** to operate at high temperatures. Housing material should be modified. Not commercially available.

To assess the priorities in future research projects, the availability of funded research projects by the DOE NEET ASI program in advanced nuclear sensors and instrumentation was investigated [65]–[70]. An overview of the DOE NEET ASI program-funded projects on nuclear sensors and instrumentation is listed in Table 6.

Table 6. DOE NEET ASI program-funded research projects.

Nuclear instrumentation	**Project** Description	Project year(s)
Self-Powered Neutron Detector	**Nuclear Instrumentation - Neutron Flux Sensors** Demonstration and qualification of Self-Powered Neutron Detectors (SPNDs).	2020
	Flux Measurement Calibration processes were developed, focusing on their performance at high temperatures.	2020-2021
	Irradiation Testing of Neutron Flux Sensors in the Advanced Test Reactor Critical Facility The aim is to test neutron flux in a variety of reactor environments.	2020-2021
Fission Chambers	**Micro Pocket Fission Detectors** Development of Micro Pocket Fission Detectors.	2012-2014
	High-Temperature Fission Chamber Fabricate and test a high-temperature fission chamber for temperatures up to 800 °C.	2012-2014
	Enhanced Micro-Pocket Fission Detector for High-Temperature Reactors Demonstrate and deploy a high-temperature micro-pocket fission chamber for temperatures up to 800°C.	2014-2017
	Flux Measurement Calibration processes are being developed, focusing on their performance at high temperatures.	2020-2021
Gamma Thermometers	**Development of an Optical Fiber-Based Gamma Thermometer** Build an optical fiber-based gamma thermometer (OFBGT) and test it in two research reactors.	2018-2021

It can be observed that all nuclear sensors and instrumentation-funded projects were in-core sensors and instrumentation. This trend supports the conclusions of the study that R&D priorities are for the in-core nuclear reactor sensors and instrumentation. It is shown that nearly all research projects were focused on the high-temperature environment. Thus, R&D projects are required to study in-core nuclear instrumentation in fast-spectrum, high-pressure, and corrosive environments.

6. Summary

Advanced nuclear reactors (Generation IV) will have differences in operating environments from the currently operating nuclear reactors. These differences are mainly the higher operating temperature and pressure, the corrosive environment, and the fast neutron spectrum. Developing sensors and instrumentation systems capable of operating in these advanced reactors will play a significant role in their licensing and demonstration efforts.

It was demonstrated that the in-core reactor sensors and instrumentation are prioritized in future R&D projects. R&D is required mainly for SPNDs, gamma thermometers, and fission chambers. SPNDs have to be able to operate at higher temperatures, with a fast neutron spectrum, and in a molten salt reactor environment. Gamma thermometers require R&D projects to work in a fast neutron spectrum reactor and with a molten salt environment. Fission chambers that would be employed as in-core reactor instrumentation require R&D to commercialize the available technology of fission chambers to operate in a high-temperature reactor environment. In addition to that, they need R&D if they will be used in a molten salt environment. The durability and structural integrity of all these in-core instrumentation has to be further investigated in a high-pressure environment.

Ex-core nuclear instrumentation is expected to face the same operational environments as those in currently operating LWRs. Thus, R&D for ex-core nuclear instrumentation is not a priority. On-demand in-core nuclear instrumentation must be evaluated based on operating time in the reactor environment. In addition, some types of nuclear instrumentation are not used in the in-core reactor environment. Employment of such sensors and instrumentation in advanced reactors may increase the accuracy of the measurement and, thus, the reactor's safety. However, cost/benefit analysis is necessary for such R&D projects.

In the United States, the Department of Energy established many research programs to fill the technological gaps and assess the advanced reactor needs of a new generation of sensors and instrumentation. Many R&D projects have been initiated and supported by the NEET ASI program in the last few years. For this reason, where R&D is required based on the defined approach, the availability of initiated research projects on the sensor and instrumentation technology was further investigated. It was shown that the funded projects in the last few years were focused on in-core nuclear sensors and instrumentation. However, R&D projects for gamma thermometers at high temperatures are required. In addition, if SPNDs are planned to be used in MSRs, then R&D projects are necessary to design SPNDs compatible with the corrosive environment.

The assessment guides the most prior R&D needs in nuclear sensors and instrumentation technologies. Filling the gaps in the technology will enable advanced reactors to follow the proven safe and operational path of previously operated nuclear reactors.

References

[1] International Atomic Energy Agency, “Power Reactor Information System.” https://pris.iaea.org/pris/# (accessed Oct. 18, 2022).

[2] Generation IV International Forum, “When Will Gen IV Reactors Be Built?” https://www.gen-4.org/gif/jcms/c_41890/faq-2 (accessed Oct. 19, 2022).

[3] International Atomic Energy Agency, “Nuclear Power Plant Instrumentation and Control: A Guidebook,” 1984.

[4] R. Meininger, “Three Mile Island Technical Information and Examination Program Instrumentation and Electrical Summary Report,” 1985.

[5] J. Rempe and Knudson Darrell, “TMI-2 - A Case Study for PWR Instrumentation Performance during a Severe Accident,” 2013. [Online]. Available: http://www.inl.gov

[6] United States Nuclear Regulatory Commission, “Report to Congress: Advanced Reactor Licensing,” 2012.

[7] U.S. Department of Energy - Office of Nuclear Energy, “Light Water Reactor Sustainability (LWRS) Program.” https://www.energy.gov/ne/nuclear-reactor-technologies/light-water-reactor-sustainability-lwrs-program (accessed Oct. 27, 2022).

[8] U.S. Department of Energy - Office of Nuclear Energy, “Nuclear Energy Enabling Technologies (NEET).” https://www.energy.gov/ne/nuclear-energy-enabling-technologies-neet (accessed Jul. 24, 2022).

[9] G. Locatelli, M. Mancini, and N. Todeschini, “Generation IV nuclear reactors: Current status and future prospects,” *Energy Policy*, vol. 61, pp. 1503–1520, Oct. 2013, doi: 10.1016/j.enpol.2013.06.101.

[10] J. ’Lamarsh and A. ’Baratta, *Introduction to Nuclear Engineering*, Third edition. 2001.

[11] United States Nuclear Regulatory Commission, "Power Reactors." https://www.nrc.gov/reactors/power.html (accessed Oct. 23, 2022).
[12] S. Rippon, "History of the PWR and its worldwide development," *Energy Policy*, vol. 12, no. 3, pp. 259–265, 1984.
[13] M. H. Subki, "Water cooled small modular reactors (Integral PWR and BWR)," in *Encyclopedia of Nuclear Energy*, Elsevier, 2021, pp. 694–710. doi: 10.1016/b978-0-12-819725-7.00208-7.
[14] Westinghouse, "International Reactor Innovative and Secure (IRIS) Plant Overview," 2002.
[15] H. B. Ray, "U.S. options for licensing a new commercial power plant," in *Encyclopedia of Nuclear Energy*, Elsevier, 2021, pp. 168–174. doi: 10.1016/b978-0-12-409548-9.12159-1.
[16] D. A. Hamon, "Boiling Water Reactors," in *Encyclopedia of Nuclear Energy*, Elsevier, 2021, pp. 214–235. doi: 10.1016/B978-0-12-819725-7.00027-1.
[17] P. Wu, Y. Ren, M. Feng, J. Shan, Y. Huang, and W. Yang, "A review of existing SuperCritical Water reactor concepts, safety analysis codes and safety characteristics," *Progress in Nuclear Energy*, vol. 153. Elsevier Ltd, Nov. 01, 2022. doi: 10.1016/j.pnucene.2022.104409.
[18] J. Cai, C. Renault, and J. Gou, "Supercritical Water-Cooled Reactors," *Science and Technology of Nuclear Installations*, vol. 2014, 2014, doi: 10.1155/2014/548672.
[19] J. Wang, Q. Wang, and M. Ding, "Review on Neutronic/Thermal-Hydraulic Coupling Simulation Methods for Nuclear Reactor Analysis," *Annals of Nuclear Energy*, vol. 137. Elsevier Ltd, Mar. 01, 2020. doi: 10.1016/j.anucene.2019.107165.
[20] M. M. Rahman, J. Dongxu, N. Jahan, M. Salvatores, and J. Zhao, "Design concepts of supercritical water-cooled reactor (SCWR) and nuclear marine vessel: A review," *Progress in Nuclear Energy*, vol. 124. Elsevier Ltd, Jun. 01, 2020. doi: 10.1016/j.pnucene.2020.103320.
[21] P. V. Tsvetkov, T. G. Lewis, A. B. Alajo, and D. E. A. Ii, "VHTR-based systems for autonomous co-generation applications," *Nuclear Engineering and Design*, vol. 240, pp. 2451–2457, Oct. 2010, doi: 10.1016/j.nucengdes.2010.05.053.
[22] J. Scherr and P. Tsvetkov, "Reactor design strategy to support spectral variability within a sodium-cooled fast spectrum materials testing reactor," *Ann Nucl Energy*, vol. 113, pp. 15–24, Mar. 2018, doi: 10.1016/j.anucene.2017.10.049.
[23] T. Abram and S. Ion, "Generation-IV nuclear power: A review of the state of the science," *Energy Policy*, vol. 36, no. 12, pp. 4323–4330, Dec. 2008, doi: 10.1016/j.enpol.2008.09.059.
[24] B. Hatala, "Gas Cooled Fast Reactor System (GFR)," in *Encyclopedia of Nuclear Energy*, Elsevier, 2021, pp. 545–552. doi: 10.1016/b978-0-12-409548-9.12207-9.
[25] P. Tsvetkov, "Gas-cooled Fast Reactors (GFRs)," *Handbook of Generation IV Nuclear Reactors*, pp. 167–172, Jan. 2023, doi: 10.1016/B978-0-12-820588-4.00016-5.
[26] T. M. Abuqudaira and Y. V. Stogov, "Possibilities of Better Utilization of MOX fuel in VVER type reactors by optimizing neutron spectrum," in *Journal of Physics: Conference Series*, IOP Publishing Ltd, Dec. 2020. doi: 10.1088/1742-6596/1689/1/012023.
[27] E. S. Bettis, R. W. Schroeder, G. A. Cristy, H. W. Savage, R. G. Affel, and L. F. Hemphill, "The Aircraft Reactor Experiment -Design and Construction," *Nuclear Science and Engineering*, vol. 2, no. 6, pp. 804–825, Nov. 1957, doi: 10.13182/nse57-a35495.
[28] B. E. Prince, S. J. Ball, J. R. Engel, P. N. Haubenreich, and T. W. Kerlin, "Zero-power Physics Experiments on the Molten-Salt Reactor Experiment - ORNL-4233," 1968.
[29] J. Serp *et al.*, "The molten salt reactor (MSR) in generation IV: Overview and perspectives," *Progress in Nuclear Energy*, vol. 77, pp. 308–319, 2014, doi: 10.1016/j.pnucene.2014.02.014.
[30] NSA, "Nuclear Suppliers Association." https://nuclearsuppliers.org/ (accessed Jul. 19, 2022).
[31] NASA, "Technology Readiness Level." https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level (accessed Jul. 19, 2022).
[32] H. M. Hashemian, "Nuclear Power Plant Instrumentation and Control," in *Nuclear Power - Control, Reliability and Human Factors*, P. Tsvetkov, Ed., London, United Kingdom: IntechOpen, 2011.
[33] G. Knoll, *Radiation Detection and Measurement*, Fourth Edition. 2010.

[34] Westinghouse Electric Company LLC, “Chapter 7: Instrumentation and Controls, AP1000 Design Control Document,” 2011.
[35] Pacific Northwest National Laboratory, “Technical Readiness and Gaps Analysis of Commercial Optical Materials and Measurement Systems for Advanced Small Modular Reactors - PNNL-22622, Rev. 1,” 2013.
[36] U.S.NRC, “AP1000 Design Control Document, Chapter 4,” 2011.
[37] Y. Sang *et al.*, “Development and verification of a simulation toolkit for Self-Powered Neutron Detector,” *Ann Nucl Energy*, vol. 150, Jan. 2021, doi: 10.1016/j.anucene.2020.107784.
[38] X. Liu, Z. Wang, Q. Zhang, B. Deng, and Y. Niu, “Current compensation for material consumption of cobalt self-powered neutron detector,” *Nuclear Engineering and Technology*, vol. 52, no. 4, pp. 863–868, Apr. 2020, doi: 10.1016/j.net.2019.09.010.
[39] J. M. Harrer and J. G. Beckerley, *Nuclear Power Reactor Instrumentation systems Handbook*, vol. 1. 1973.
[40] T. Cui, Y. Yang, H. Xue, and H. Kuang, “A Monte-Carlo simulation method for the study of self-powered neutron detectors,” *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 954. Elsevier B.V., Feb. 21, 2020. doi: 10.1016/j.nima.2018.10.061.
[41] U.S. Department of Energy, *DOE Fundamentals Handbook Instrumentation and Control Volume 2 of 2*, vol. 2. 1992.
[42] A. ’ ’Goodings, “Experience with High-Temperature Radiation Detectors and Cables for Reactor Instrumentation Systems,” in *Nuclear Power Plant Control and Instrumentation, Proceedings of a Symposium*, Vienna: International Atomic Energy Agency, 1978, pp. 225–242.
[43] J. ’Mourlevat, D. ’Janvier, and H. ’Warren, “Industrial Tests of Rhodium Self-Powered Detectors: the Golfech 2 Experimentation,” in *Core Monitoring for Commercial Reactors: Improvements in Systems and Methods*, Stockholm, 1999, pp. 65–77.
[44] K. C. Goetz, S. M. Cetiner, and C. Celik, “Development of a Fast-Spectrum Self-Powered Neutron Detector for Molten Salt Experiments in the Versatile Test Reactor,” *EPJ Web Conf*, vol. 253, p. 05006, 2021, doi: 10.1051/epjconf/202125305006.
[45] V. Verma, L. Barbot, P. Filliatre, C. Hellesen, C. Jammes, and S. J. Svärd, “Self powered neutron detectors as in-core detectors for Sodium-cooled Fast Reactors,” *Nucl Instrum Methods Phys Res A*, vol. 860, pp. 6–12, Jul. 2017, doi: 10.1016/j.nima.2017.04.011.
[46] M. Angelone, A. Klix, M. Pillon, P. Batistoni, U. Fischer, and A. Santagata, “Development of self-powered neutron detectors for neutron flux monitoring in HCLL and HCPB ITER-TBM,” *Fusion Engineering and Design*, vol. 89, no. 9–10, pp. 2194–2198, 2014, doi: 10.1016/j.fusengdes.2014.01.077.
[47] D. E. Holcomb, R. A. Kisner, and S. M. Cetiner, “Instrumentation Framework for Molten Salt Reactors,” 2018. [Online]. Available: www.osti.gov
[48] A. Birri and T. E. Blue, “Methodology for inferring reactor core power distribution from an optical fiber based gamma thermometer array,” *Progress in Nuclear Energy*, vol. 130, Dec. 2020, doi: 10.1016/j.pnucene.2020.103552.
[49] R. Van Nieuwenhove and L. Vermeeren, “Nuclear heating measurements by gamma and neutron thermometers,” *EPJ Web Conf*, vol. 225, p. 04003, 2020, doi: 10.1051/epjconf/202022504003.
[50] Nuclear Regulatory Commission, “Instrumentation in VHTRs for Process Heat Applications,” 2010.
[51] R. Raghavan, C. L. Martin, A. L. Wirth, T. Itoh, Y. Goto, and R. Arai, “Application of the Gamma Thermometer as BWR Fixed In-Core Calibration System,” in *Proc. of the Specialists Meeting on Incore Instrumentation and Reactor Core Assessment*, Mito City, Japan, 1996.
[52] A. Birri, C. M. Petrie, and T. E. Blue, “Parametric Analysis of an Optical Fiber–Based Gamma Thermometer for University Research Reactors Using an Analytic Thermal Model,” *Nucl Technol*, vol. 207, no. 12, pp. 1865–1872, 2021, doi: 10.1080/00295450.2020.1844532.
[53] K. Theriault, “Boiling Water Reactors (BWRs),” in *Nuclear Engineering Handbook*, K. Kok, Ed., CRC Press, 2009, pp. 83–139.

[54] Oak Ridge National Laboratory, "HTGR Measurements and Instrumentation Systems - ORNL/TM-2012/107," 2012. [Online]. Available: http://www.osti.gov/contact.html
[55] Doug. Reilly, Norbert. Ensslin, Hastings. Smith, Sarah. Kreiner, Los Alamos National Laboratory (U.S.), and Etats-Unis. Nuclear Regulatory Commission., "Neutron Detectors," in *Passive Nondestructive Assay of Nuclear Materials*, US Department of Commerce, National Technical Information Service, 1991, pp. 379–406.
[56] J. Coburn, S. M. Luker, E. J. Parma, and K. R. DePriest, "Modeling, Calibration, and Verification of a Fission Chamber for ACRR Experimenters," in *EPJ Web of Conferences*, EDP Sciences, Feb. 2016. doi: 10.1051/epjconf/201610605001.
[57] R. 'Lamphere, "Fission Detectors," in *Fast Neutron Physics. Part 1. Techniques.*, J. 'Marion and J. 'Fowler, Eds., New York: Interscience, 1960.
[58] D. S. McGregor, M. F. Ohmes, R. E. Ortiz, A. S. M. Sabbir Ahmed, and J. Kenneth Shultis, "Micro-pocket fission detectors (MPFD) for in-core neutron flux monitoring," *Nucl Instrum Methods Phys Res A*, vol. 554, no. 1–3, pp. 494–499, Dec. 2005, doi: 10.1016/j.nima.2005.06.086.
[59] Oak Ridge National Laboratory, "Instrumentation Framework for Molten Salt Reactors - ORNL/TM-2018/868," 2018. [Online]. Available: www.osti.gov
[60] Oak Ridge National Laboratory, "Assessment of Sensor Technologies for Advanced Reactors - ORNL/TM-2016/337 R1," 2016. [Online]. Available: http://www.osti.gov/scitech/
[61] AREVA NP, "U.S. EPR Nuclear Incore Instrumentation Systems Report," 2006.
[62] A. M. Dias and F. C. Silva, "Determination of the power density distribution in a PWR reactor based on neutron flux measurements at fixed reactor incore detectors," *Ann Nucl Energy*, vol. 90, pp. 148–156, Apr. 2016, doi: 10.1016/j.anucene.2015.12.002.
[63] P. A. Glasow, "Aeroball System and Energy-dispersive Analysis: Important Industrial Applications of Silicon Detectors," *Nuclear Instruments and Methods in Physics Research*, vol. 226, pp. 17–25, 1984.
[64] J. Konheiser, S. E. Mueller, and M. Seidl, "Study of the influence of water gaps between fuel assemblies on the activation of an aeroball measurement system (AMS)," *Ann Nucl Energy*, vol. 136, Feb. 2020, doi: 10.1016/j.anucene.2019.107005.
[65] DOE-NE, "Advanced Sensors and Instrumentation Project Summaries," 2016.
[66] DOE-NE, "Advanced Sensors and Instrumentation Project Summaries," 2017.
[67] DOE-NE, "Advanced Sensors and Instrumentation Project Summaries," 2018.
[68] DOE-NE, "Advanced Sensors and Instrumentation Project Summaries," 2019.
[69] DOE-NE, "Advanced Sensors and Instrumentation Project Summaries," 2020.
[70] DOE-NE, "Advanced Sensors and Instrumentation Project Summaries," 2021.