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The Impact of Small Modular Reactors on Nuclear Non-Proliferation and IAEA Safeguards

Nicole Virgili*

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Biography: Nicole Virgili completed an internship at the Vienna Center for Disarmament and Non-Proliferation (VCDNP) where she focused on the analysis of the impact of small modular reactors on non-proliferation and the safeguards of the International Atomic Energy Agency (IAEA). Prior to this experience she completed an internship at the IAEA's Incident and Emergency Center (IEC) in the Department of Nuclear Safety and Security. In this role, Ms. Virgili supported IEC staff in the implementation of projects related to the Emergency Preparedness and Response Information Management System, implementation of capacity building activities and assistance in developing and implementing a catalogue of exercise information. She holds a MS in Nuclear Engineering and a BS in Energy Engineering from the La Sapienza University of Rome, Italy. She wrote her thesis on radiation protection, specifically on radioactive gasses emissions from the TR19PET cyclotron installed at the Department of Health Physics at A. Gemelli Hospital in Rome. The main focus was on Flourine-18 monitoring as a marker for the potentially hazardous radioactive gas Argon-41. The research provided her experience and insights into current debates in the scientific community on how to best protect patients and hospital staff during routine operations. Following graduation, she attended the Nuclear Innovation Bootcamp at the University of Berkeley (California) as an innovator and member of the Test and Irradiation of Materials Team, which won the Bootcamp Pitch Competition for the best research project.

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Keywords: Small modular reactors (SMRs), IAEA safeguards, non-proliferation, reactor designs

Abstract

Generation IV reactors are a set of nuclear reactor designs currently being researched for commercial applications by the Generation IV International Forum, with technology readiness levels varying between demonstration to economically competitive implementation. The focus on their development is linked to their anticipated economical affordability, enhanced safety, minimal waste and proliferation resistance. Moreover, these reactors are seen as essential tools for climate change mitigation, considering the low-carbon nature of nuclear energy.[1]

In this general framework, small modular reactors (SMRs) are gaining worldwide interest. A major factor of such an increasing focus is the governmental preference to reduce the total capital costs associated with construction and operation of nuclear power plants.

SMRs are emerging as an efficient and effective way to satisfy growing energy demands worldwide meanwhile promising benefits for safety and security. That being said, new physical layouts, procedural design, and increased digitization of SMRs are likely to challenge traditional approaches to nuclear security, safety, and safeguards, as well as long-established regulatory regimes and procedural norms.

The paper presents an up-to-date analysis of advances in SMR designs, including European companies. The aim of the project is to evaluate challenges and opportunities presented by SMRs to the nuclear non-proliferation regime, and to compare safeguards applied to conventional reactors currently in operation and to SMRs, taking into account varying approaches to the design and licensing processes depending on the fuel used in each SMR design.

[1] Global Nexus Initiative Where Climate, Nuclear, and Security Meet, June 2019, *Advancing Nuclear Innovation, Responding to Climate Change and Strengthening Global Security* https://globalnexusinitiative.org/http://globalnexusinitiative.org/wp-content/uploads/2019/05/PGS_ThoughtLeadershipReport_052419_FINAL_Pages.pdf

Table of Contents

List of abbreviations and acronyms

ASN	French Nuclear Safety Authority
BWR	Boiling Water Reactor
C&S	Containment and surveillance
DIQ	Design Information Questionnaire
FNR	Fast Neutron Reactor
Gen IV	Generation IV
GFR	Gas-cooled fast reactor
GIF	Generation IV International Forum
HTGR	High-temperature gas-cooled reactor
IAEA	International Atomic Energy Agency
IEC	Incident and Emergency Center
IFNEC	International Framework for Nuclear Energy Cooperation
INL	Idaho National Laboratory (United States)
ITV	International Target Value
HEU	High-enriched uranium
iPWR	Integral Pressurized Water SMR
LEU	Low-enriched uranium
LFR	Lead-cooled fast reactor
LWR	Light water reactor
MDEP	Multinational Design Evaluation Program
MOX	Mixed oxide
MSFR	Molten salt fast reactor
MSR	Molten salt reactor
NDA	Non-Destrucive Analysis

NSSPI	Nuclear Security Science and Policy Institute
NNWS	Non-Nuclear-Weapon State
NRC	Nuclear Regulatory Commission (United States)
NPT	Non-proliferation Treaty
ORNL	Oak Ridge National Laboratory (United States)
PIV	Physical Inventory Verification
PR&PP	Proliferation resistance and physical protection
R&D	Research and Development
PWR	Pressurized Water Reactor
RMS	Remote Monitoring Systems
SCWR	Supercritical Water-Cooled Reactor
SMR	Small Modular Reactor
SFR	Sodium-cooled Fast Reactor
SSAC	State Systems of Accounting and Control
SSBD	Safeguards and Security by Design
TRISO	Tristructural isotropic
VHTR	Very High Temperature Reactor

Units of measure

kW	Kilowatt
MPa	Megapascal
MW	Megawatt
MWe	Megawatt electrical
MWth	Megawatt thermal

Elements and compounds

Ar	Argon
Be	Berillium
Bi	Bismuth
F	Fluorine
Li	Lithium
P	Plutonium
Pb	Lead
Th	Thorium
U	Uranium
UF	Uranium Fluoride
UO_2	Uranium dioxide

Introduction

Increasing access to electricity and powering economies while minimizing greenhouse gas emissions are central goals of many governments. Advanced nuclear power reactor designs, including small modular reactors (SMRs), have the potential to play a crucial role in meeting these goals. The Generation IV International Forum (GIF) was created for the purpose of coordinating the international endeavour in this field. GIF defined four goals in its 2002 Technology Roadmap to move nuclear energy forward: sustainability, safety and reliability, economic competitiveness, proliferation resistance and physical protection.

Thirteen countries are involved in GIF where nuclear energy is widely used now and is also seen as vital for the future: Argentina, Brazil, Canada, France, Japan, South Korea, the South Africa, the United Kingdom, the United States, Switzerland, China, the Russian Federation and Australia.[2] The GIF members are mostly committed to sharing research and development (R&D) for the purpose of developing six Generation IV nuclear reactor technologies and their deployment after 2030. The six reactor technologies selected by the GIF in late 2002 are believed to represent the future of nuclear energy and considered clean, safe and cost-effective means to meeting increased energy demands on a sustainable basis, while also being resistant to diversion of materials for weapons proliferation and secure from terrorist attacks. Below are the reactor systems technologies under development by GIF:

- Gas-cooled fast reactor (GFR);
- Lead-cooled fast reactor (LFR);
- Molten salt reactor (MSR);
- Sodium-cooled fast reactor (SFR);
- Supercritical water-cooled reactor (SCWR);
- Very high temperature gas reactor (VHTR).

Table 1. Generation IV reactor designs under development by GIF[3]

	Neutron spectrum (fast/thermal)	Coolant	Temperature (°C)	Pressure*	Fuel	Fuel cycle	Size (MWe)	Use
Gas-cooled fast reactors	fast	helium	850	high	U-238 +	closed, on site	1200	electricity & hydrogen
Lead-cooled fast reactors	fast	lead or Pb-Bi	480-570	low	U-238 +	closed, regional	20-180** 300-1200 600-1000	electricity & hydrogen
Molten salt fast reactors	fast	fluoride salts	700-800	low	UF in salt	closed	1000	electricity & hydrogen

[2] Generation IV International Forum, GIF Membership. https://www.gen-4.org/gif/jcms/c_9492/members
[3] World Nuclear Association, *Generation IV Nuclear Reactors, May 2019.* https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

Molten salt reactor - advanced high-temperature reactors	thermal	fluoride salts	750-1000		UO_2 particles in prism	open	1000-1500	hydrogen
Sodium-cooled fast reactors	fast	sodium	500-550	low	U-238 & MOX	closed	50-150 600-1500	electricity
Supercritical water-cooled reactors	thermal or fast	water	510-625	very high	UO_2	open (thermal) closed (fast)	300-700 1000-1500	electricity
Very high temperature gas reactors	thermal	helium	900-1000	high	UO_2 prism or pebbles	open	250-300	hydrogen & electricity

*high = 7-15 MPa
+ with some U-235 or Pu-239
** 'battery' model with long cassette core life (15-20 years) or replaceable reactor module

All six systems operate at higher temperatures than today's reactors. Four are fast neutron reactors.[4] Most of the six systems employ a closed fuel cycle[5] to maximize the resource base and minimize high-level wastes to be sent to a repository. Only one is cooled by light water, two are helium-cooled and the others have lead-bismuth, sodium or fluoride salt coolants. The latter three operate at low pressure, which presents a significant safety advantage. The last has an uranium fuel dissolved in the circulating coolant. Temperatures range from 510°C to 1000°C, compared with less than 330°C for today's light water reactors (LWRs)[6], and this means that four of them can be used for thermochemical hydrogen production.[7]

Generation IV technology also involves assessment of a broad variety of reactor coolants. The appropriate choice of coolant for reactor systems is a very important factor to gain high performance.

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[4] A fast-neutron reactor or simply a fast reactor is a category of nuclear reactor in which the fission chain reaction is sustained by fast neutrons (carrying energies above 0.5 MeV or greater, on average), as opposed to thermal neutrons used in thermal-neutron reactors. Such a reactor needs no neutron moderator, but requires fuel that is relatively rich in fissile material when compared to that required for a thermal-neutron reactor.

[5] Nuclear Fuel Cycle: If spent fuel is not reprocessed, the fuel cycle is referred to as an open fuel cycle (or a once-through fuel cycle); if the spent fuel is reprocessed and the resulted fissile material is reused in the production of fresh fuel, it is referred to as a closed fuel cycle. The open fuel cycle does not include reprocessing. Spent fuel is thus considered to be waste that should eventually be placed in geological repositories. The open nuclear fuel cycle is the predominant choice of civilian fuel cycle worldwide.

[6] The light-water reactor (LWR) is a type of thermal-neutron reactor that uses normal water, as opposed to heavy water, as both its coolant and neutron moderator – furthermore a solid form of fissile elements is used as fuel. Thermal-neutron reactors are the most common type of nuclear reactor, and light-water reactors are the most common type of thermal-neutron reactor.

[7] Hydrogen production is the family of industrial methods for generating hydrogen gas. As of 2009, the majority of hydrogen (~95%) is produced from fossil fuels by steam reforming of natural gas, partial oxidation of methane, and coal gasification. Other methods of hydrogen production include biomass gasification and electrolysis of water.
The production of hydrogen plays a key role in any industrialized society, since hydrogen is required for many essential chemical processes. As of 2019, roughly 70 million tons of hydrogen are produced annually worldwide for various uses, such as, oil refining, and in the production of ammonia (Haber process) and methanol (reduction of carbon monoxide), and also as a fuel in transportation.

The thermophysical and thermohydraulic properties of coolants are one of the fundamental determinants of reactor design and, to a certain extent, have a significant impact on the technical and economic characteristics of power plants.

In January 2014, a new GIF Technology Roadmap Update[8] was published. It confirmed the choice of the six systems and focused on the most relevant developments in order to define the R&D goals for the next decade. It suggested that the Generation IV technologies that are most likely to be deployed first are the sodium-cooled fast reactor, the lead-cooled fast reactor and the very high temperature reactor technologies. The molten salt reactor[9] and the gas-cooled fast reactor were shown as furthest from demonstration phase.

The third GIF symposium took place in Japan in May 2015 and considered progress with the six systems in three methodology working groups.[10] The US Nuclear Regulatory Commission (NRC) has proposed a three-stage process culminating in an international design certification for new reactor types. In relation to Generation IV reactors, the NRC called for countries involved in their development to establish common design requirements so that regulatory standards can be harmonized.[11] The NRC has also published its draft design requirements.

Closely related to the GIF is the Multinational Design Evaluation Program (MDEP) set up by regulators with an aim to develop multinational regulatory standards for Generation IV reactors. It was launched in 2006 by the NRC and the French Nuclear Safety Authority (ASN) with an initial purpose of developing innovative approaches to leverage the resources and knowledge of national regulatory authorities reviewing new reactor designs. The programme currently involves the International Atomic Energy Agency (IAEA) and fourteen 14 national regulators. Its secretariat is with the Organisation for Economic Co-operation and Development’s Nuclear Energy Agency.

The MDEP pools the resources of its members for the purpose of reviewing the safety of designs of nuclear reactors that are under construction or undergoing licensing in several countries, and exploring opportunities for harmonization of regulatory requirements and practices. The MDEP also produces reports and guidance documents that are shared internationally beyond the MDEP membership. It has five design-specific working groups (EPR, AP1000, APR1400, VVER and ABWR), and three issue-specific ones (digital I&C, mechanical codes and standards, and vendor inspection cooperation).

Regarding nuclear governance structure, traditionally, the dominant suppliers of nuclear technology have had significant influence on these issues. It is not clear at this point which advanced reactors, or which countries will lead the market competition.

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[8] Generation IV International Forum, Technology Roadmap Update for Generation IV Nuclear Energy Systems, 2014. https://www.gen-4.org/gif/jcms/c_60729/technology-roadmap-update-for-generation-iv-nuclear-energy-systems?details=true

[9] A molten salt reactor (MSR) is a class of nuclear fission reactor in which the primary nuclear reactor coolant and/or the fuel is a molten salt mixture.

[10]GEN IV International Forum. https://www.google.com/search?sxsrf=ALeKk03pNlkGGf0o24gH98gcV_4WBXFuKg:1590705337518&source=univ&tbm=isch&q=GIF+SYMPOSIUM+2015+JAPAN&sa=X&ved=2ahUKEwi339aUz9fpAhXIepoKHWk-BHEQsAR6BAgJEAE

[11] World Nuclear Association, *Generation IV Nuclear, May 2019.* https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors.aspx

1. Small Modular Reactors

There is today a fairly high degree of uniformity in nuclear plans and programs among major nuclear countries, and nuclear power is one of the most highly globalized of all industries. The nuclear power plant supply industry is dominated by Russia, China, South Korea, France and the United States, all of whom are large global suppliers of light water reactor equipment and technology.[12]

Advanced nuclear reactors - often smaller, more flexible, and more innovative nuclear technologies of the future - are gaining interest as the global community grapples with the vital challenges of cutting carbon emissions, supporting the global demand for electric power, and ensuring the continued peaceful use of nuclear energy in the 21st century. Small modular reactors (SMRs) are planned to fulfil the need for flexible power generation for a wider range of users and applications, thus replacing ageing fossil-fuelled units, enhancing safety performance, and offering better economic affordability.

SMRs are newer generation reactors designed to generate electric power up to 300 MWe[13], whose components and systems can be constructed in a factory and then transported as modules to the sites of installation as demand arises. SMRs are attractive as viable alternatives to conventional reactors due to the projected advantage they offer in terms of a significant relative cost reduction, through modularization and assembly-line factory construction. Other advantages include vastly reduced meltdown risks[14] and greater flexibility in terms of where they can be located. SMRs can be deployed to closely match increasing energy demand, which results in a moderate financial commitment for countries or regions with smaller electricity grids.

Electricity plays a big part in our daily lives and is important for all the things that go on in the world around us, such as communications and transport. In the area of wider applicability, SMR designs and sizes are better suited for partial or dedicated use in non-electrical applications such as providing heat for industrial processes, hydrogen production or sea-water desalination.[15] Processed heat, as part of cogeneration, results in significantly improved thermal efficiencies leading to a better return on investment. Some SMR designs may also serve niche markets as nuclear waste burners.

1.1 Small Modular Reactor Designs and Major Technology Development Planning

Strong interest in the potential global market of SMRs has led many companies to offer their own individual reactor designs. There are already a number of designs available. Before long, a shakeout is likely to occur. In particular, in the US, there is currently no clarity regarding the length of time required for licensing new reactor designs that lack any commercial track record. This situation thus creates a lot of regulatory uncertainty.

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[12] Richard K. Lester and Robert Rosner, Daedalus, 2009, The growth of nuclear power: drivers & constraints. https://www.amacad.org/publication/growth-nuclear-power-drivers-constraints

[13] Megawatts electric or MWe is one of the two values assigned to a power plant, the other being megawatts thermal or MWt. Megawatts electric refers to the electricity output capability of the plant, and megawatts thermal refers to the input energy required. Power plants are assigned two values as most contain heat engines, and therefore cannot turn 100% of their input energy into electricity.

[14] A nuclear meltdown (core meltdown, core melt accident, meltdown or partial core melt) is a severe nuclear reactor accident that results in core damage from overheating.

[15] Desalination is a process that takes away mineral components from saline water.

There are some examples of SMRs in more advanced development stages, as the first US advanced SMR is on track to become operational by the mid-2020s.[16] The project took a crucial step forward when the company behind it, NuScale, secured an important security certification from the NRC.

Most SMRs are now in the output range between 50 and 200 MWe. There are designs for even smaller "mini" or "micro-reactors" that generate as few as 4 MWe. But today, it is unclear what SMR-generated power will cost. That will probably remain the case for at least the next 10 to 15 years until a few designs are actually built and operating. Some experts foresee SMRs achieving levels that could be higher than for large reactors which generally cost more to build and operate than other options, like natural gas, for the same amount of power.[17] Some observers also fear that reactor owners might cut corners to reduce costs, compromising safety or security.[18]

SMRs expected planning is as follows:

• Micro-reactor development by 2020s; commercial deployment by 2025;

• SMRs begin operation 2025-2026;

• Versatile Test Reactor operating beginning 2025-2026;

• Non-LWR demonstration reactor by 2030.

Table 2. Small reactors operating[19]

Name	Capacity	Type	Developer
CNP-300	300 MWe	PWR	SNERDI/CNNC, Pakistan & China
PHWR-220	220 MWe	PHWR	NPCIL, India
EGP-6	11 MWe	LWGR	at Bilibino, Siberia (three units are currently operating)
KLT-40S	35 MWe	PWR	OKBM, Russia
RITM-200	50 MWe	Integral PWR, civil marine	OKBM, Russia

[16] Office of Nuclear Energy, *Nation's First Small Modular Reactor Plant to Power Nuclear Research at Idaho National Laboratory, 2019.* https://www.energy.gov/ne/articles/nations-first-small-modular-reactor-plant-power-nuclear-research-idaho-national

[17] The Conversation, *The nuclear industry is making a big bet on small power plants, 2018.* https://theconversation.com/the-nuclear-industry-is-making-a-big-bet-on-small-power-plants-94795

[18] The Conversation, *The nuclear industry is making a big bet on small power plants*, 2018. https://theconversation.com/the-nuclear-industry-is-making-a-big-bet-on-small-power-plants-94795

[19] World Nuclear Association, 2020, *Small Nuclear Power Reactors.* https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

Table 3. Small reactor designs under construction[20]

Name	Capacity	Type	Developer
CAREM-25	27 MWe	Integral PWR	CNEA & INVAP, Argentina
HTR-PM	210 MWe	Twin HTR	INET, CNEC & Huaneng, China
ACPR50S	60 MWe	PWR	CGN, China

Table 4. Small reactors for near-term deployment – development well advanced[21]

Name	Capacity	Type	Developer
VBER-300	300 MWe	PWR	OKBM, Russia
NuScale	60 MWe	Integral PWR	NuScale Power + Fluor, USA
SMR-160	160 MWe	PWR	Holtec, USA + SNC-Lavalin, Canada
ACP100/Linglong One	125 MWe	Integral PWR	NPIC/CNPE/CNNC, China
SMART	100 MWe	Integral PWR	KAERI, South Korea
BWRX-300	300 MWe	BWR	GE Hitachi, USA
PRISM	311 MWe	Sodium FNR	GE Hitachi, USA
ARC-100	100 MWe	Sodium FNR	ARC with GE Hitachi, USA
Integral MSR	192 MWe	MSR	Terrestrial Energy, Canada
BREST	300 MWe	Lead FNR	RDIPE, Russia
RITM-200M	50 MWe	Integral PWR	OKBM, Russia

[20] World Nuclear Association, 2020, *Small Nuclear Power Reactors.* https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

[21]World Nuclear Association, *Small Nuclear Power Reactors*, 2020. https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx)

Table 5. Small reactor designs at earlier stages (or shelved)[22]

Name	Capacity	Type	Developer
EM2	240 MWe	HTR, FNR	General Atomics (USA)
VK-300	300 MWe	BWR	NIKIET, Russia
AHWR-300 LEU	300 MWe	PHWR	BARC, India
CAP200 LandStar-V	220 MWe	PWR	SNERDI/SPIC, China
SNP350	350 MWe	PWR	SNERDI, China
ACPR100	140 MWe	Integral PWR	CGN, China
IMR	350 MWe	Integral PWR	Mitsubishi Heavy Ind, Japan
Westinghouse SMR	225 MWe	Integral PWR	Westinghouse, USA*
mPower	195 MWe	Integral PWR	BWXT, USA*
Rolls-Royce SMR	220+ MWe	PWR	Rolls-Royce, UK
PBMR	165 MWe	HTR	PBMR, South Africa*
HTMR-100	35 MWe	HTR	HTMR Ltd, South Africa
Xe-100	75 MWe	HTR	X-energy, USA
MCFR	large?	MSR/FNR	Southern Co, USA
SVBR-100	100 MWe	Lead-Bi FNR	AKME-Engineering, Russia*
Westinghouse LFR	300 MWe	Lead FNR	Westinghouse, USA
TMSR-SF	100 MWt	MSR	SINAP, China
PB-FHR	100 MWe	MSR	UC Berkeley, USA
Integral MSR	192 MWe	MSR	Terrestrial Energy, Canada
Moltex SSR-U	150 MWe	MSR/FNR	Moltex, UK
Moltex SSR-W global	150 MWe	MSR	Moltex, UK
Thorcon MSR	250 MWe	MSR	Martingale, USA
Leadir-PS100	36 MWe	Lead-cooled	Northern Nuclear, Canada

[22] World Nuclear Association, *Small Nuclear Power Reactors*, 2020. https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

Table 6. Very small reactor designs being developed (up to 25 MWe)[23]

Name	Capacity	Type	Developer
U-battery	4 MWe	HTR	Urenco-led consortium, UK
Starcore	10-20 MWe	HTR	Starcore, Quebec
USNC MMR-5&10	5 MWe	HTR	UltraSafe Nuclear, USA
Gen4 module	25 MWe	Lead-bismuth FNR	Gen4 (Hyperion), USA
Sealer	3-10 MWe	Lead FNR	LeadCold, Sweden
eVinci	0.2-5 MWe	Heatpipe FNR	Westinghouse, USA
Aurora	1.5 MWe	Heatpipe FNR	Oklo, USA
NuScale micro	1-10 MWe	Heatpipe	NuScale, USA

** Well-advanced designs understood to be on hold or abandoned*

1.2 SMR Designs in the Context of Non-Proliferation Regime and IAEA Safeguards

The peaceful use of nuclear energy has resulted in 452 nuclear reactor units in 32 countries, most of them in Europe, North America, East Asia, and South Asia. Most of them are LWR units that may produce up to 1650 MWe of electricity each.[24] This has significantly contributed to and accelerated economic development in a number of countries.

The increase in peaceful nuclear activities has determined the production of more enriched uranium[25] (U-235) as a fuel for nuclear power plants and Pu-239 as a by-product in spent fuel.[26] U-235 and Pu-239 are fissile materials used to manufacture nuclear weapons and other nuclear explosive devices, rendering their control essential to ensure that these materials are not diverted from peaceful to weapons purposes.

As such, the proliferation resistance of a reactor is an important consideration in reactor design. Proliferation resistance is defined by the IAEA as "…characteristic of a Nuclear Energy System that impedes the diversion or undeclared production of nuclear material or misuse of technology by the

[23] World Nuclear Association, *Small Nuclear Power Reactors*, 2020. https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

[24] IAEA, Power Reactor Information System (PRIS). https://www.iaea.org/resources/databases/power-reactor-information-system-pris

[25] Enriched uranium is a type of uranium in which the percent composition of U-235 has been increased through the process of isotope separation. Naturally occurring uranium is composed of three major isotopes: U-238 (with 99.2739–99.2752% natural abundance), U-235 (0.7198–0.7202%), and U-234 (0.0050–0.0059%). U-235 is the only nuclide existing in nature (in any appreciable amount) that is fissile with thermal neutrons.

[26] Spent nuclear fuel, occasionally called used nuclear fuel, is nuclear fuel that has been irradiated in a nuclear reactor (usually at a nuclear power plant). It is no longer useful in sustaining a nuclear reaction in an ordinary thermal reactor and depending on its point along the nuclear fuel cycle, it may have considerably different isotopic constituents.

Host State seeking to acquire nuclear weapons or other nuclear explosive devices".[27] Proliferation resistance has both intrinsic components, such as the attractiveness of the nuclear material for diversion or the potential of its operation for undetected and undeclared uses, and extrinsic components, such as the suitability of its design to inspection and safeguards implementations.

The Treaty on the Non-Proliferation of Nuclear Weapons (NPT)[28] is the centrepiece of global efforts to prevent the further spread of nuclear weapons. Article III.1 of the NPT mandates that each non-nuclear-weapon State (NNWS) Party must conclude agreements with the IAEA on the application of safeguards to "all source or special fissionable material in all peaceful nuclear activities within the territory of such State, under its jurisdiction, or carried out under its control anywhere".[29]

IAEA safeguards are a central part of international efforts to stem the spread of nuclear weapons. In implementing safeguards, the IAEA plays an independent verification role, which is essential for ensuring that States' safeguards obligations are fulfilled. The IAEA can apply safeguards at any type of nuclear facility or location outside facility (LOF). IAEA safeguards are embedded in legally binding agreements concluded between States and the IAEA. These agreements provide the legal basis for the implementation of safeguards.

A great majority of the world's States have concluded comprehensive safeguards agreements (CSAs) with the IAEA pursuant to the NPT, and many States have also signed additional protocols (AP) to their agreements.

It is in the interest of both States and the IAEA to cooperate to facilitate the implementation of safeguards. This cooperation on safeguards is in the interest of States because it is often considered a prerequisite to receiving access to technical cooperation from the IAEA. It's in the interest of the IAEA because it is part of the mandate of the organization and, the fewer countries that have nuclear weapons, the better for global security. In addition, effective cooperation between States, the IAEA, and other stakeholders can facilitate a more cost effective and efficient implementation of safeguards that also minimizes the impact on nuclear facility operations. The intensity of safeguards measures chosen by the IAEA is evolving over time, adjusted and maintained by the IAEA Department of Safeguards.

Because many SMRs designs are still conceptual, designers have a unique opportunity to incorporate updated design basis threats and emergency preparedness requirements to fully integrate safety, physical security, safeguards and material control and accounting into their designs. Integrating safety, physical security, and safeguards is often referred to as integrating the 3Ss, and early consideration of safeguards and security in the design of a facility is often referred to as safeguards and security by design (SSBD).

Safeguards by design is the process of including the consideration of international safeguards throughout all phases of a nuclear facility project, from the initial conceptual design to facility construction and into operations, including design modifications and decommissioning.[30] The 'by

[27] IAEA Nuclear Energy Series, *Technical Features to Enhance Proliferation Resistance of Nuclear Energy Systems, 2010.*
[28] United Nations, Treaty on the Non-Proliferation of Nuclear Weapons (NPT). https://www.un.org/disarmament/wmd/nuclear/npt/
[29] United Nations, Treaty on the Non-Proliferation of Nuclear Weapons (NPT). https://www.un.org/disarmament/wmd/nuclear/npt/text/
[30] Nuclear decommissioning is the process whereby a nuclear facility is dismantled to the point that it no longer requires measures for radiation protection. The presence of radioactive material necessitates processes that are potentially

design' concept encompasses the idea of preparing for the implementation of safeguards in the management of the project during all of these stages. The safeguards by design concept does not introduce new requirements but rather presents an opportunity to facilitate the cost-effective implementation of existing requirements.

Familiarity with the processes, layout, equipment and other characteristics of a given nuclear facility is essential for developing and maintaining an optimal safeguards approach.

Facility design information can be provided to the IAEA before a decision takes place to construct a nuclear facility and can be revised as the design becomes more detailed.

Both the IAEA and the reactor designers should take steps in the design phase to facilitate effective international safeguards.

Designers of SMRs are requested to consider aspects of the designs safeguardability. The analysis of the safeguardability of a particular SMR design takes into consideration the overall approach safeguards developed for that type of facility.

The notion of safeguardability was introduced early in the development of the proliferation resistance and physical protection (PR&PP) methodology owing to the challenge of computing the probability of detecting diversion or misuse for a design concept in its early stage.

1.3 Improvements Posed by SMR Designs in the Context of Non-Proliferation and IAEA Safeguards

Increased proliferation resistance is a goal of advanced nuclear reactor designs and is one of the technology goals of GIF. SMRs have innovative design features and technologies that may require new tools and measures for safeguards. The technical data discussed below describe the improvements posed by SMR designs in the context of non-proliferation and IAEA safeguards.

- **Lower physical footprints:** SMRs are physically smaller than traditional reactor designs, which can potentially lead to fewer needs for surveillance reducing the target area size.

- **Lower fissile inventories**: SMRs have smaller radiological inventories and thus potentially smaller releases during off-normal conditions. The critical mass of a fissile isotope is the minimum mass needed to sustain a chain nuclear reaction, which is important for nuclear weapons design. In SMRs these critical masses are much smaller than what is available in a traditional nuclear reactor, but SMRs still contain significant amounts of other special fissionable material. Therefore, it is imperative to give SMRs the same attention as large nuclear reactors receive with regard to safeguards and non-proliferation.[31]

- **High burn-up:** The longer the fuel is used to produce power, the higher is its burn-up.

occupationally hazardous, expensive, time-intensive, and present environmental risks that must be addressed to ensure radioactive materials are either transported elsewhere for storage or stored on-site in a safe manner. The challenge in nuclear decommissioning is not just technical, but it is also economical and social.

[31] Nonproliferation improvements and challenges presented by small modular reactors Shikha Prasad, Ahmed Abdulla, M. Granger Morgan, Ines Lima Azevedo Indian Institute of Technology e Kanpur, Kanpur, UP 208016, India b Carnegie Mellon University, Pittsburgh, PA 15213, USA, 2014.

With a higher burn-up, the suitability of nuclear material from SMRs for weapons purposes declines, improving proliferation resistance.

- **Sealed core and long refuelling design concepts:** SMRs that operate without refuelling during the whole service period or require the refuelling only after a long period of operation are capable of providing an enhanced proliferation resistance. The sealed core concept proposes that the nuclear fuel is loaded to the core and sealed at the reactor-manufacturing site. The long refuelling design concepts propose refuelling as long as 300 months after the initial loading, challenging the current practice for nuclear materials accountancy. A long-life reactor core, possibly sealed, reduces core access and refuelling frequency making misuse of operation and diversion of spent fuel much more difficult.
  For sealed cores, reliable monitoring of authenticated sensor data may be provided through virtual access. A fuel cycle that represents an increase in proliferation resistance may allow a less stringent safeguards approach, provided that the IAEA safeguards objectives are still met. The implementation of international safeguards on such reactor systems will require a significant change to the current standard verification procedures for nuclear reactors, given the challenges associated with the nuclear material verification and the transfer of responsibility of the core fuel.[32]

- **Remote monitoring:** Remote monitoring is suitable for unattended and remotely controlled operations, adding to both safeguards efficiency and system complexity. It is used more and more frequently by the IAEA for safeguards. Considering the potential difficulty in accessing the locations of SMRs, as in the case of remote islands or sparsely populated regions, remote monitoring is a key tool to enhance both intrinsic and extrinsic PR&PP. Remote monitoring makes use of cameras, instruments, components or seals, and could monitor physical parameters that indicate diversion, misuse or sabotage. This could be complemented by reliable yearly off-site monitoring of redundant authenticated sensors. An analysis of the PR&PP characteristics of more than 45 innovative SMRs shows that some of the designs consider remote monitoring as a proliferation resistance option.[33] PR&PP experts, with the help of designers, could identify sensitive processes, instruments, components or areas that could be vulnerable to diversion, misuse or sabotage. This is an area of current development that builds upon the IAEA's growing experience with remote process monitoring, which has direct applications for fuel processing installations.

- **Remote location:** There is a concern regarding the implications of the remote location of facilities without established electricity grid infrastructures to support industrial as well as electric power operations. However, at the same time, difficulty in accessing a site enhances proliferation resistance by increasing the cost and difficulty of diversion or covert misuse.

[32] Marco Marzo, Sukesh Aghara, and Odera Dim Integrated Nuclear Security and Safeguards Laboratory University of Massachusetts Lowell, One University Avenue, Lowell, MA, USA, *Challenges on implementing safeguards to small modular reactors*, 2015.
[33] IAEA Nuclear Energy Series, *Options to Enhance Proliferation Resistance of Innovative Small and Medium Sized Reactors, 2014.*
https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1632_web.pdf

- **Enrichment (< 20%):** Nuclear reactor fuel can be low-enriched uranium, with a concentration of less than 20% of fissile U-235. This low quantity, non-weapons-grade uranium makes the fuel less desirable for weapons production. Fission products mixed with the fissile materials are highly radioactive and require special handling to remove safely (i.e. a "radiation barrier"), another non-proliferation feature.
  Many SMRs designs use higher enrichment levels to increase fissile content in their small core in the effort to decrease size and increase fuel life. Fast-neutron reactor designs will require higher enrichments than traditional thermal-neutron reactors. Designs that will use enrichment above 20% will be more proliferation prone due to the higher suitability of their fuels for weapons applications than the traditional reactors, and will require increased safeguards activities even though many SMRs are designed to lessen the danger of materials being stolen or diverted.

- **Thorium fuel cycle:** A further increase in proliferation resistance is offered by light water reactors designed to run on the thorium fuel cycle, due to the presence of U-232[34] and its strong gamma emitting daughter products, in comparison to the uranium cycle.[35]

- **Number of units per site:** One of the potential advantages of SMRs is that multiple individual reactor units can be added sequentially to one larger station, possibly sharing a single control room. It is possible that a common spent fuel pool might be used. These characteristics will need to be considered by the IAEA in determining its inspection approach and inspection frequency, including Physical Inventory Verification (PIV),[36] if an increase in inspection resources is to be avoided or minimized.

1.4 Challenges Posed by SMR Designs in the Context of Non-Proliferation and IAEA Safeguards

- **On-load refuelled reactors:** These reactors require safeguards considerations of the increased frequency in spent fuel handling compared to off-load refuelled reactors. Frequent movements of the relatively small, irradiated direct use items offers an opportunity for non-destructive assay instrumentation to be installed within the primary containment to

[34] Jungmin Kanga and Frank N. von Hippelb, *U-232 and the Proliferation Resistance of U-233 in Spent Fuel, 2001.*

[35] The factors influencing the level of U-232 contamination in U-233 are examined for heavy-water-moderated, light-water-moderated and liquid-metal cooled fast breeder reactors fuelled with natural or low-enriched uranium and containing thorium mixed with the uranium or in separate target channels. U-232 decays with a 69-year half-life through 1.9-year half-life Th-228 to Tl-208, which emits a 2.6 MeV gamma ray upon decay. We find that pressurized light-water-reactors fuelled with LEU-thorium fuel at high burnup (70 MWd/kg) produce U-233 with U-232 contamination levels of about 0.4 percent. At this contamination level, a 5 kg sphere of U-233 would produce a gamma ray dose rate of 13 and 38 rem/hr at 1 meter one and ten years after chemical purification respectively. The associated plutonium contains 7.5 percent of the undesirable heat-generating 88-year half-life isotope Pu-238. However, just as it is possible to produce weapon-grade plutonium in low-burnup fuel, it is also practical to use heavy-water reactors to produce U-233 containing only a few ppm of U-232 if the thorium is segregated in "target" channels and discharged a few times more frequently than the natural-uranium "driver" fuel. The dose rate from a 5-kg solid sphere of U-233 containing 5 ppm U-232 could be reduced by a further factor of 30, to about 2 mrem/hr, with a close-fitting lead sphere weighing about 100 kg. Thus, the proliferation resistance of thorium fuel cycles depends very much upon how they are implemented.

[36] Marco Marzo, Sukesh Aghara, and Odera Dim, Integrated Nuclear Security and Safeguards Laboratory, University of Massachusetts Lowell, One University Avenue, Lowell, MA, USA, *Challenges on implementing safeguards to small modular reactors, 2015.*

facilitate IAEA activities, but can require a designer to consider the utilization of unattended systems that are remotely monitored or that require periodic servicing on-site by inspectors. Spent fuel verification within the spent fuel pool can pose a challenge to designers that need to consider methods for minimizing spent fuel movements, especially if the irradiated fuel to be verified is stacked in layers. Since re-verification of the nuclear material inventory can be disruptive and costly, additional measures such as redundancy or subdivision of sealed enclosures can be considered to mitigate issues resulting from a potential loss of surveillance or to shorten the re-verification process. Safeguards considerations include provision for maintaining continuity of knowledge of the core using radiation sensor-based core discharge monitors and bundle counters. The aim is to facilitate IAEA verification and maintain continuity of knowledge of irradiated fuel placed in layers for storage and for remote monitoring of IAEA equipment to verify its proper operation.

- **Remote location:** The difficulty of access also applies to safeguards inspectors, increasing the cost and reducing the potential for unannounced inspections.

- **Enrichment (> 20%):** Designs that will use enrichment above 20% will have fission products mixed with the fissile materials and will be highly radioactive and thus require special handling to ensure safety. This is relevant for spent fuel. At the same time, HEU is more appealing for use in nuclear weapons or theft by non-State actors, requiring increased safeguards activities. These features will increase the costs of safeguards.

- **Excess reactivity:** A SMR reactor designed for low refueling frequency would likely have core design start with high excess reactivity and burnable absorbers. Such a core might tolerate target irradiation without affecting key operational parameters that can be monitored. From an independent observer's viewpoint, neutronic management with burnable absorbers would look similar to neutronic management with target material. A design requirement is needed to verify that there is no possible access for target insertion or removal. Potentially, these concerns can be mitigated with a pre-operation design verification activity by the IAEA coupled with reliable sealing and surveillance measures.

- **Coolant opacity:** Use of non-transparent coolants other than water, such as molten sodium or lead-bismuth, does not allow for traditional optical viewing of the fuel in the core or in the spent fuel storage. The IAEA can potentially benefit from access to new operator viewing systems for these routine inspection tasks. Authentication of these systems should be considered early on in the design process as it might be technically challenging to implement them afterwards.[37]

- **Low thermal signature:** Having a thermal footprint similar to other small-scale energy technologies currently deployed in remote locations implies that it will be challenging to use satellite or other forms of remote sensing to verify operations.

[37] IAEA Nuclear Energy Series, Options to Enhance Proliferation Resistance of Innovative Small and Medium Sized Reactors, 2014.
https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1632_web.pdf

- **Breeders:** Many SMRs are fast-neutron reactor designs. Fast reactors can be particularly useful for conversion of the abundant U-238 in the fuel to Pu-239, which could be used for the production of a weapons-useable material. Therefore, SMR designs which utilize fast spectra need to be cautious and should include safeguards by design elements, so that during its time of operation an SMR cannot be used to produce material for nuclear weapons.[38]

- **Advanced fuel cycle:** Advanced reactors can employ innovative fuel designs, the use of minor actinides, fast reactor designs, or some combination of these fuel cycles. In general, the nature of a non-LWR based SMR operating in an advanced fuel cycle will almost certainly be unfamiliar to the safeguards inspectors and require significant analysis to understand the most effective and efficient safeguards approach. This creates a need for safeguards experts to collaborate with the design team.

- **Fuel element size:** Small reactors will have smaller cores and shorter fuel elements that may also contribute to proliferation and safeguards concerns. They might have two opposing impacts on diversion issues: obtaining a significant useful quantity requires diverting more items, yet the small size tends to facilitate item concealment for those planning on diverting their use. This provides another incentive for the international safeguards regime to develop monitoring methods specifically for SMRs.[39]

- **Spent fuel storage geometry:** Smaller fuel elements would possibly need to be stored vertically for cooling purposes, with a strong economic incentive to stack fuel and reduce the storage footprint. This geometry potentially challenges the current safeguards inspection activities owing to the lack of a direct line visibility of the fuel elements from above. In one current approach, the operator packages a group of elements in a basket for ease of handling and transport, and the IAEA places the seals on the baskets at the packaging location instead of at the storage location.

[38] Shikha Prasad, Ahmed Abdulla, M. Granger Morgan, Ines Lima Azevedo Indian Institute of Technology e Kanpur, Kanpur, Indian Carnegie Mellon University, Pittsburgh, USA, Nonproliferation improvements and challenges presented by small modular reactors modular reactors, 2014.

[39] IAEA Nuclear Energy Series, Options to Enhance Proliferation Resistance of Innovative Small and Medium Sized Reactors, 2014.
https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1632_web.pdf

2. Light Water Reactors and IAEA Safeguards

The second part of the paper will analyze the application of IAEA safeguards to each advanced reactor design compared to the processes and approaches for safeguarding traditional LWRs[40], which represent a major type of nuclear power reactors currently used for the production of electricity. LWRs typically use LEU[41] [42], which is categorized as indirect-use material from the standpoint of its potential use in the manufacturing of nuclear weapons. After LEU has been used in the reactor core, the spent fuel produced usually contains plutonium – direct use material. Plutonium contained in spent fuel, as well as fresh MOX fuels[43], represent a strategic material from a safeguards standpoint.[44] This is one of the determining factors that affects the safeguards approach and the inspection goal for a facility.

The main SMR-LWR designs worldwide under consideration presently are summarized in Table 8[45], in which their fuel features, designed refueling period (varying from 14 – 300 months), and initial LEU fuel (varying from 2.4 to < 20%) are also indicated.

Table 7. Main SMR-LWR designs and their fuel features.[46]

SMR	Country	Power (MWe)	Enrichment	Burnup (MWd/t)	Core Fuel Assemblies	Refueling (months)
mPower	USA	180	<5.0	>40,000	69	48
NuScale	USA	45	<4.95	N/A	37	24
Westinghouse SMR	USA	225	<5.0	>62,000	89	24
SMR-160	USA	160	4.95	32,000	N/A	36-48
Flexblue	France	160	4.5		77	40
ACP-100	China	100	2.4 – 3.0	<45,000	57	24
KLT-40S	Russia	35	<20	45,400	121	28
VBER-300	Russia	325	4.95	50,000	85	72

[40] Neil Harms, Perpetua Rodriguez *Safeguards at light-water reactors: Current practices, future directions, 1996.* https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull38-4/38402051619.pdf

[41] Low enriched uranium (LEU) has a lower than 20% concentration of U-235; for instance, in commercial light water reactors (LWR), the most prevalent power reactors in the world, uranium is enriched to 3 to 5% U-235. High-assay LEU is enriched from 5-20%. Fresh LEU used in research reactors is usually enriched 12% to 19.75% U-235, The latter concentration is used to replace HEU fuels when converting to LEU.

[42] National Research Council, Division on Earth and Life Studies, Nuclear and Radiation Studies Board, Committee on Medical Isotope Production, *Medical Isotope Production Without Highly Enriched Uranium, 2009.*

[43] Union of Concerned Scientists, *What Is MOX Fuel, 2011.* https://www.ucsusa.org/resources/what-mox-fuel

[44] MOX fuel, short for mixed-oxide fuel, is a mixture of uranium and plutonium oxide. Most reactors use uranium fuel. As uranium fuel burns, some of it is converted into plutonium, so all operating reactors have plutonium in their core. The manufacture, transportation, and storage of MOX fuel increase the risk of its diversion or theft. In fact, MOX fuel is as great a terrorist and proliferation concern as plutonium itself. MOX fuel does not contain the highly radioactive components that make spent fuel dangerous, and the plutonium can be separated from the uranium by a straightforward chemical process

[45] World Nuclear Association, 2020, *Small Nuclear Power Reactors*. https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

[46] World Nuclear Association, 2020, *Small Nuclear Power Reactors*. https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

ABV-6M	Russia	6	19.7	N/A	121	120-144
RITM-200	Russia	50	<20	>51,200	199	54-84
VVER-300	Russia	300	3.3 – 4.79	>38,000	85	18-24
VK-300	Russia	250	4.0	41,400	313	72
UNITHERM	Russia	6.6	19.75	1150	265	200
RUTA-70	Russia	~25	3.0	>25,000	91	36
SHELF	Russia	6	<20	N/A	N/A	56
ELENA	Russia	0.068	15.2	57,600	109	300
SMART	South Korea	100	<5	60,000	57	36
CAREM-25	Argentina	27	3.1	24,000	61	14
IRIS	International Consortium	335	4.95	65,000	89 UO2/MOX	48
DMS	Japan	300	4.3	45,000	400	24
IMR	Japan	350	4.8	>40,000	97	26

Safeguards approaches are, in large part, based on an analysis of all technical possible diversion paths taking into account all safeguards-relevant information about that State.[47]

These approaches are also designed to counter possible undeclared production of direct-use material. It refers to the system of nuclear material accountancy, containment and surveillance (C&S), and other measures chosen for implementation of safeguards. For this purpose, other features including measurement methods and techniques used by the IAEA, the design of the facility, form and accessibility of the nuclear material, potential existence of unsafeguarded nuclear activities and inspection experience are also considered.

In the case of LWRs, two of the tools used for safeguards approaches are: item accountancy, including item counting and identification, non-destructive analysis (NDA) measurements and examination to verify the continued integrity of the item; and C&S measures**,** used to complement the accountancy verification methods for safeguarding the spent fuel. Since LWR cores are usually not opened more than once per year, it is often possible to seal the reactor pressure vessel head. The installation of a surveillance system in an area where spent fuel is stored, allows the IAEA to detect undeclared movements of nuclear material and potential tampering with other safeguards devices.

LWRs are refueled during outage periods, during which the inventory of nuclear material in the reactor and storage areas can be verified by visual inspection, NDA measurements, and containment and surveillance measures.

Activities performed to achieve IAEA inspection goals are:

- Audit of accounting records and comparison with reports submitted to the IAEA;
- Examination of operating records and reconciliation with accounting records;
- Verification of fresh fuel before core loading. In order to detect possible diversion of fresh fuel, the verification is carried out by item counting, serial number identification, NDA and other methods. For facilities using fresh MOX fuel, the verification activities are carried out by item counting, serial number identification and seal verification, assuming that the fuel is received from an IAEA safeguarded facility. However, in the case where fresh MOX fuel is

[47] John Carlson, Victor Bragin, John Bardsley, and John Hill (Nonproliferation Review/Winter 1999) *Nuclear Safeguards as an Evolutionary System, 1999.*

received from unsafeguarded facilities, additional NDA measurements are performed and the fuel is maintained under seal if kept in a dry store, or under surveillance if kept in a wet store. Seal verification and/or surveillance evaluation is also carried out on a monthly basis in addition to the usual accountancy verification methods.

• The fuel in the core is verified by item counting and serial number identification following refueling and before the reactor vessel[48] is closed. For facilities using fresh MOX fuel in the core, loading is either maintained by on-site or underwater surveillance. Soon after verification, C&S measures are applied to ensure that the reactor core remains unchanged.

• Spent fuel ponds are verified after sealing the transfer canal gate or upon closure of the reactor core. In addition to evaluating the C&S measures, inspectors verify the spent fuel by observing and evaluating the Cherenkov glow[49] with the use of NDA techniques.

Remote Monitoring Systems (RMS) have been introduced as a step towards the IAEA's objective of reducing inspection costs at LWRs while improving safeguards efficiency and effectiveness. RMS are based on an all-digital approach which facilitates image and data handling (for example, information on IAEA seals), transmission, processing, and storage. The communication system is independent of the monitoring system. The communication system provides near-real-time information, depending on how images and data acquisitions are set up. The use of RMS at a LWR facility is anticipated to be in conjunction with a reduced number of interim inspections, either announced or unannounced.

[48] A reactor pressure vessel in a nuclear power plant is the pressure vessel containing the nuclear reactor coolant, core shroud, and the reactor core.

[49] Cherenkov radiation is electromagnetic radiation emitted when a charged particle (such as an electron) passes through a dielectric medium at a speed greater than the phase velocity of light in that medium. A classic example of Cherenkov radiation is the characteristic blue glow of an underwater nuclear reactor. The phenomenon is named for Soviet physicist Pavel Cherenkov, who shared the 1958 Nobel Prize in Physics for its discovery.

3. Integral Pressurized Water SMRs

An Integral Pressurized Water SMR (iPWR) is a supercritical water-cooled reactor (SCWR). It is a conceptualized Generation IV reactor, mostly designed as a LWR, which operates with coolant pressurized above the thermodynamic critical point of water (374ºC, 22.1 MPa)[50] to give a thermal efficiency[51] about one-third higher than today's LWRs from which the design evolves.

The water heated in the reactor core becomes a supercritical fluid above the critical temperature of 374 °C, transitioning from a fluid resembling liquid water to a fluid resembling saturated steam, which can be used in a steam turbine without going through the distinct phase transition of boiling. The supercritical steam generator is a proven technology.[52] Two design options are currently under consideration: pressure vessel and pressure tube. Passive safety features are similar to those of simplified boiling water reactors.[53]

The development of SCWR systems is considered a promising advancement for nuclear power plants because of its higher thermal efficiency (~45 % vs. ~33 % for current LWRs) and simpler design. Today's supercritical coal-fired plants use supercritical water, which have pressures around 25 MPa[54] and steam temperatures of 500 to 600ºC resulting in 45% thermal efficiency. The supercritical water at higher values of pressure and temperature (25 MPa and 510-550°C) directly drives the turbine, without any secondary steam system, simplifying the plant. At ultra-supercritical levels (30+ MPa), 50% thermal efficiency may be attained.
This reactor type is fueled by uranium oxide, which has to be enriched when using an open fuel cycle option. The core may use thermal neutron spectrum with light or heavy water moderation[55], or be a fast reactor with full actinide[56] recycled based on conventional reprocessing.

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[50] Supercritical fluids are those above the thermodynamic critical point, defined as the highest temperature and pressure at which gas and liquid phases can co-exist in equilibrium. They have properties between those of gas and liquid. For water the critical point is at 374°C and 22 MPa, giving it a steam density one-third that of the liquid so that it can drive a turbine in a similar way to normal steam.

[51] In thermodynamics, the thermal efficiency is a dimensionless performance measure of a device that uses thermal energy, such as in an internal combustion engine, a steam turbine or a steam engine, a boiler, furnace, or a refrigerator.

[52] M. Ricotti, M. Santinello, *Integral PWR for a sea-based SMR: steam generator and passive safety system, 2016.* https://www.politesi.polimi.it/bitstream/10589/120481/3/2016_04_Iacopini.pdf

[53] C. Spitzer, U. Schmocker, V. N. Dang, 2004, *Probabilistic Safety Assessment and Management*.

[54] MPa is megapascal. The pascal (Pa) is the SI derived unit of pressure used to quantify internal pressure, stress, Young's modulus (it is a mechanical property that measures the stiffness of a solid material. It defines the relationship between stress (force per unit area) and strain (proportional deformation) in a material in the linear elasticity regime of a uniaxial deformation) and ultimate tensile strength. The unit, named after Blaise Pascal, is defined as one newton per square metre. The unit of measurement called standard atmosphere (atm) is defined as 101325 Pa.

[55] A neutron moderator is a medium that reduces the speed of fast neutrons, ideally without capturing any, leaving them as thermal neutrons with only minimal (thermal) kinetic energy. These thermal neutrons are immensely more susceptible than fast neutrons to propagate a nuclear chain reaction of U-235 or other fissile isotope by colliding with their atomic nucleus. Light water is the most commonly used moderator (roughly 75% of the world's reactors) although the term is slightly ambiguous, usually meaning natural fresh water, but could also refer to actual light-water. Solid graphite (20% of reactors) and heavy water (5% of reactors) are the main alternatives. Beryllium has also been used in some experimental types, and hydrocarbons have been suggested as another possibility.

[56] The actinide series encompasses the 15 metallic chemical elements with atomic numbers from 89 to 103, actinium through lawrencium. All actinides are radioactive and release energy upon radioactive decay; naturally occurring uranium and thorium, and synthetically produced plutonium are the most abundant actinides on Earth. These are used in nuclear reactors and nuclear weapons. Uranium and thorium also have diverse current or historical uses, and americium is used in the ionization chambers of most modern smoke detectors.

Since the SCWR builds both on the experience from boiling water reactors and that from hundreds of fossil-fueled power plants operating with supercritical water, it can readily be developed, and the operation of a 30 to 150 MWe technology demonstration reactor is targeted for 2022.[57]

3.1 Challenges to IAEA Safeguards and Non-Proliferation Posed by Integral Pressurized Water SMRs

The light water moderated and cooled designs will most likely be exported first due to their similarity to the current pressurized water reactors (PWRs)[58] that are the most popular around the world. The integral pressurized water reactor is a class of SMRs currently being expedited for licensing to the NRC.

iPWR designs are similar to deployed designs and follow the safeguards approaches for traditional LWRs. They are item facilities, with all nuclear material being itemised both upon arrival as fresh fuel and when departing as spent fuel. Since all nuclear material is kept in item form and remains unaltered during its time in the facility, it is possible to conduct accurate item counting and identification. Although the material's composition will change during the fission process, the uranium and plutonium stay contained in the fuel rod. At the same time, source data will provide detailed information on the unirradiated fuel and will be available after irradiation, including the burn-up and post-irradiation isotopic composition that is assigned to each fuel assembly.
Integral PWRs are refueled during outage periods, during which the inventory of nuclear material in the reactor and storage areas can be verified by visual inspection, NDA measurements, and C&S methods.

iPWRs pose challenges to safeguards and non-proliferation that will be discussed below.

iPWR designs are similar to deployed designs, but if vendors plan to export them to non-nuclear-weapons States (NNWS), those iPWRs will be subject to IAEA safeguards under Article III.2 of the NPT.

Measures under comprehensive safeguards agreements need to consider the differences in the iPWR facility designs that deviate from traditional designs enough to require additional coverage through the concept of safeguards-by-design (SBD). The problem is that the current LWR SMRs, which are most likely to get licensed soon, do not mention SBD in their preliminary designs.[59] [60]

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[57] J. Moralez Pedraza, *Small Modular Reactors for Electricity Generation, 2017.*

[58] Pressurized water reactors (PWRs) constitute the large majority of the world's nuclear power plants (notable exceptions being Japan and Canada) and are one of three types of light-water reactor (LWR). The other types being boiling water reactors (BWRs) and supercritical water reactors (SCWRs). In a PWR, the primary coolant (water) is pumped under high pressure to the reactor core where it is heated by the energy released by the fission of atoms. The heated water then flows to a steam generator where it transfers its thermal energy to a secondary system where steam is generated and flows to turbines which, in turn, spin an electric generator. In contrast to a boiling water reactor, pressure in the primary coolant loop prevents the water from boiling within the reactor. All LWRs use ordinary water as both its coolant and neutron moderator.

[59] Coles, G.A., et al., *Trial Application of the Facility Safeguardability Assessment Process to the NuScale SMR Design*, PNNL-22000 Rev. 1, Pacific Northwest National Laboratory, 2012.

[60] Bari, R.A., et al., *Overview of the Facility Safeguardability Analysis (FSA) Process,2011.*

Moreover, there is no established procedure for such verification, as a reactor manufacturing plant is not considered a nuclear facility under current IAEA safeguards agreements.[61] Therefore, it has been proposed that LWR SMRs core fuel is treated as difficult-to-access fuel items.

For this purpose, the introduction of a Design Information Questionnaire (DIQ) for such reactor factories may be required. At each inspection the LWR fresh fuel assemblies foreseen for shipping since the previous inspection would need to be verified at the fuel fabrication plant and held to the same standards as at a PIV in accordance with current safeguards approaches and criteria.

This means they would be verified with low detection probability (10%) for gross and partial defects and by serial number identification, where possible. Data stored on fuel assemblies would be made available to the IAEA via a mailbox system.

Once the fuel assemblies arrive at the reactor site, they would be counted and verified with medium detection probability (50%) for gross defects or by serial number identification. Only in few cases the seals are removed at the reactor site to maintain continuity of knowledge about the fuel assemblies, challenging current safeguards approaches and criteria.

The very long fuel service cycle also presents challenges to the current practice for nuclear materials accountancy. A sealed reactor core seems to limit C&S measures. The current IAEA safeguards criteria for LWRs requires periodic verification of the spent fuel that should not exceed an 18 months period. Long fuel service cycles, due to exceptional circumstances like accidents or extended shutdowns[62], are considered on a case-by-case basis by the IAEA Department of Safeguards that can waive the requirement under certain conditions.

SMRs should not be treated as an exceptional case, as they are designed to operate for long periods under a closed core.

SMRs with sealed cores that are transferred to a different country need to be further investigated. The question of who has legal jurisdiction over the fuel must be established in the supply agreement between the two countries and in consultation with the IAEA.[63]

Finally, from a safeguards standpoint, the iPWR spent fuel is more sensitive than the standard PWR spent fuel in terms of the amount of U-235, and equally sensitive in terms of the amount of Pu-239.[64][65]

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[61] Marco Marzo, Sukesh Aghara, and Odera Dim, Integrated Nuclear Security and Safeguards Laboratory, University of Massachusetts Lowell, One University Avenue, Lowell, MA, USA *Challenges on implementing safeguards to small modular reactors, 2015.*

[62] In a nuclear reactor, shutdown refers to the state of the reactor when it is subcritical by at least a margin defined in the reactor's technical specifications. Further requirements for being shut down may include having the reactor control key be secured and having no fuel movements or control systems maintenance in progress.

[63] Regarding INFCIRC/153: "all source or special fissionable material in all peaceful nuclear activities within its territory, under its jurisdiction or carried out under its control anywhere". https://www.iaea.org/sites/default/files/publications/documents/infcircs/1972/infcirc153.pdf

[64] Marco Marzo, Sukesh Aghara, and Odera Dim Integrated Nuclear Security and Safeguards Laboratory, University of Massachusetts Lowell, One University Avenue, Lowell, MA, USA, *Challenges on implementing safeguards to small modular reactors, 2015*

[65] It has been shown the 235U depletion for the SMR designs are significantly lower than for the standard PWR. After 1000 days of irradiation time the SMR fuel assemblies will contain much more 235U than the standard PWR (50% more for Westinghouse SMR and 100% more for mPower SMR). It has also been shown that the Pu-239 production with the

There are unique aspects of light water iPWR designs that can cause deviation from conventional IAEA inspection practices for LWRs as covered below.

Based on dual C&S evaluations, the IAEA has proposed[66] that the special criteria for difficult-to-access fuel items be applied to SMR core fuel. That means that the verification requirements at a PIV take into account applied C&S measures, and allow for no interruption of the continuity of knowledge since the previous verification.

Since a non-acceptable result of a dual C&S system evaluation will require re-measurement of the core fuel, it is important that reliable dual C&S systems are applied to the closed core. It is highly recommended that the dual C&S systems incorporate remote transmission capability, at least to confirm the state-of-health of the system.

Similar conditions apply to verification requirements at interim inspections for timely detection purposes. The inspection frequency should be determined, as usual, to comply with the timeliness goals.

The conventional methods of safeguarding LWRs will need to be rethought for advanced designs. As a result, the implementation of international safeguards on iPWR will require a significant change to the current standard verification procedures for LWRs.

irradiation time for mPower SMR is quite similar with the standard PWR. The Pu-239 production for Westinghouse SMR is approximately 10% smaller than that of the standard PWR after 1000 days of irradiation.

[66] Joseph A. Cuadrado-Medina, Mark Pierson, Virginia Polytechnic Institute and State University, *Providing Effective International Safeguards for Light-water Small Modular Reactors, 2014*.

4. Molten Salt Reactors

Molten salt reactors (MSRs) are seen as a promising technology today, in principal as part of a prospective thorium fuel cycle or for using spent LWR fuel.

The fuel consists of fissile materials dissolved in a salt. The salt is solid at room temperature, but a molten liquid during the operation of the reactor.
This is in itself not a radical departure from cases where the fuel is solid and fixed, but by extending the concept to dissolving the fissile and fertile fuel in the salt is what makes it innovative.

The design has no fuel units (such as fuel rods or assemblies), and the fissile elements (uranium or thorium) are mixed with the coolant.

MSRs operate with a uranium fuel enrichment up to (but less than) 20% of thorium based fuel.
Much of the interest today in reviving the MSR concept relates to using thorium to breed fissile U-233, where an initial source of fissile material such as Pu-239 needs to be provided.

In a reactor with thorium-based fuel, Th-232 in the initial fuel inventory is converted during operation to the fissile isotope U-233, which is then consumed as fuel. The renewed interest in thorium-based fuels is based on the need for proliferation resistance, longer fuel cycles, higher burnup and improved waste characteristics.

MSRs are typically refueled online, allowing for extended, continuous reactor operation.
Fission products are removed continuously and the actinides are fully recycled, while plutonium and other actinides can be added along with U-238, without the need for fuel fabrication.

Coolant temperature is 700°C at very low pressure, with 800°C envisaged. A secondary coolant system is used for electricity generation, and thermochemical hydrogen production is also feasible.
MSRs designs can range in size from 10s of MWe to 100s of MWe.

Removal of unwanted fission products and the addition of fresh fuel enables the reactor to run for long periods without major refueling outages.

MSRs can be either thermal reactors, burning the fuel, or fast reactors which may (but do not have to) produce more new fissile material than they consume in operation, i.e. breeder reactors.
Focused on the thermal-spectrum, thorium-fuelled systems contain two major design variants:

- a molten salt breeder reactor (MSBR) with multiple configurations that could breed additional fissile material or maintain self-sustaining operation; and
- a denatured molten salt reactor (DMSR) with enhanced proliferation resistance.

Compared with solid-fuelled reactors, MSR systems have lower radiological inventories, no radiation damage constraint on fuel burn-up, no requirement to fabricate and handle solid fuel or solid used fuel, and a homogeneous isotopic composition of fuel in the reactor.

These and other characteristics may enable MSRs to have unique capabilities and competitive economics for actinide burning and extending fuel resources.

Other attractive features of the MSR fuel cycle concept include: the high-level waste comprising fission products only, hence shorter-lived radioactivity; small inventory of weapons-fissile material (Pu-242 being the dominant Pu isotope); low fuel use (the French self-breeding variant claims 50kg of thorium and 50kg U-238 per billion kWh[67]); increased safety due to passive cooling up to any size.

It now has two baseline concepts:

- The Molten Salt Fast Neutron Reactor (MSFR) that will use the thorium fuel cycle, which includes recycling of actinides, closed Th/U fuel cycle with no uranium enrichment, enhanced safety and minimal waste.
- The Advanced High-Temperature Reactor (AHTR) – also known as the fluoride salt-cooled high-temperature reactor (FHR) – with the same graphite and solid fuel core structures as the VHTR and molten salt as a coolant instead of helium, enabling power densities four-to-six times greater than HTRs and power levels up to 4000 MWt with passive safety systems. The Thorium-based Molten Salt Reactors (TMSR) Research Centre is constructing a small solid-fuel simulator (TMSR-SF0) at Shanghai Institute of Nuclear Applied Physics (SINAP, under the China Academy of Sciences) with a 2020 target for operation. It will be followed by a 10 MWt prototype, TMSR-SF1.[68]

According to the GIF 2014 Roadmap a lot of work needs to be done on salts before demonstration reactors become operational, with the year 2025 suggested as the end of the viability R&D phase. Yet, according to the China Academy of Sciences, which is a global leader in R&D on MSRs, the main research needs are fuel treatment, materials and reliability.[69]

Table 9 lists the initial design intents of the publicly described reactors including their associated fuel cycle. Other MSR companies exist with non-publicly disclosed design intents and are therefore not included in the table.

[67] The kilowatt-hour is a unit of energy equal to 3600 kilojoules (3.6 megajoules). The kilowatt-hour is commonly used as a billing unit for energy delivered to consumers by electric utilities.
[68] World Nuclear Association, Molten Salt Reactors, 2018, https://www.world-nuclear.org/information-library/current-and-future-generation/molten-salt-reactors.aspx
[69] World Nuclear Association, Molten Salt Reactors, 2018. https://www.world-nuclear.org/information-library/current-and-future-generation/molten-salt-reactors.aspx

Table 8.[70] Currently proposed molten salt reactors and fuel cycles. The proposed technologies are shown in relation to their main design characteristics (solid fuel vs. liquid fuel, fast vs. thermal spectrum). The figure shows that most designs use salt for both the fuel and coolant, use thorium, and have either onsite or offsite fissile material separations capabilities.

Fuel Cycle	Reactor/Developer
Thermal Th-232/U-233 Breeder	FLiBe Inc., Copenaghen Atomics, Thoreact, Alpha Tech Research
Thermal Two Fluid Th-232/U-233 Breeder	Indian Molten Salt Breeder Reactor
Thermal Th-232/U-233 Breeder with Multistage Separations	Chinese TMSR-LF
Thermal Denatured Mixed Thorium and LEU Burner	ThorCon Power
Denatured Thermal U-235 Burner	Terrestrial Energy
Fast Fluoride U-238/Pu-239 Breeder	MOSART – Russian Federation
Fast Fluoride Mixed Thorium and Uranium Breeder	MSFR
Fast Chloride U-238/Pu-239 Breeder	TerraPower, Elysium Industries
Spectral Shift Actinide Burner	TransAtomic
Mixed Spectrum Thorium Enhanced Actinide Burner	Seaborg Waste Burner
Fast Plutonium Chloride Burner – Fluoride Salt Cooled	Moltex
Fast Chloride Burner – Lead Cooled	Dual Fluid Reactor
Pebble bed solid fuel U-235 Burner	Kairos Power

4.1 Challenges to IAEA Safeguards and Non-Proliferation Posed by Molten Salt Reactors

The large variation in MSRs fuel cycles and reactor technologies causes a deep impact on safeguards and non-proliferation with significant differences between the two MSRs sub-categories: liquid-fuelled MSRs or solid-fuelled MSRs.

4.1.1 Liquid-fuelled MSRs

The unique core poses unique challenges to safeguards approaches such as:

- homogeneous high radiation mixture of fuel, coolant, fission products, and actinides;

[70] Donald N. Kovacic, Louise G. Worrall, Andrew Worrall, George F., Flanagan, and David E. Holcomb – Oak Ridge National Laboratory, Robert Bari and Lap Cheng - Brookhaven National Laboratory, David Farley and Matthew Sternat - Sandia National Laboratorie, *Safeguards Challenges for Molten Salt Reactors, 2018.*

- high operating temperature of the fuel salt, always kept above the melting point of the salt and highly corrosive environment of the fuel salt;
- presence of frozen fuel potentially requiring different safeguards compared to that of liquid salt fuel;
- fuel salt with potential low fissile concentration in the salt mixture; and
- fuel reprocessing and refuelling.

The existing IAEA inspection regime is based on the fuel cycle where items are counted for in each nuclear reactor or facility. But in the case of MSRs, a bulk material accountancy is needed for the front and back end of the nuclear fuel cycle. The problem is that the techniques and associated instrumentation for bulk accountancy, developed predominantly for enrichment, fuel fabrication and aqueous reprocessing, cannot be directly applied to liquid fuelled MSRs. MSR fresh fuel contains many significant quantities of nuclear materials. These are manufactured on site and then shipped to an external facility, which requires safeguards during transport to the reactor site and during any potential online processing. Therefore, multiple material balance areas will be needed with attention to material in-process or material unaccounted for, since liquid and some solid fuel are likely to require bulk material accountancy methods. There are currently no safeguards approaches for nuclear power reactors that have to take into consideration the nominal MSR fuel form as a homogeneous mixture of fuel, coolant, fission products, and actinides.[71] This homogeneous mixture, not contained in the form of assemblies, makes it impossible to perform traditional item counting and visual accountability of the salt fuel. A unique combination of high temperature (from 400 °C to > 800°C) with high radiation and corrosive environments poses challenges both for measurement techniques and for instrumentations.

Yet another consideration is the potential presence of frozen fuel which requires a different safeguards approach to that of liquid salt fuel.[72]

In cases of potentially low fissile concentration in the fissile mixture, relatively large volumes of salt would need to be diverted to produce a significant quantity of nuclear material, potentially being a proliferation risk.

4.1.2 Solid-fuelled MSRs

Only some MSRs designs use solid fuel forms and given that they are more conventional designs, traditional safeguards can be consequently applied. Yet some new safeguards considerations should also be included.

Because of the variety of fuel forms, an issue that has to be considered is to determine what constitutes an item. A potential theft of solid fuel could involve either many items (TRISO fuel particles and/or pebbles, described in part 4 of this paper) or bulky items (rods or fuel assemblies). As the flow sheet of TRISO fuel reprocessing in industrial cycle is unknown, there is no safeguards experience.

LEU fuel could potentially be enriched to levels greater than 5%. Safeguards implications of MSRs designs will be different depending on the use of thorium. If the thorium fuel cycle is employed, there

[71] Donald N. Kovacic, Louise G. Worrall, Andrew Worrall, George F., Flanagan, and David E. Holcomb – Oak Ridge National Laboratory, Robert Bari and Lap Cheng - Brookhaven National Laboratory, David Farley and Matthew Sternat - Sandia National Laboratorie, *Safeguards Challenges for Molten Salt Reactors, 2018.*

[72]U.S. Department of Energy Office of Scientific and Technical Information, *Safeguards Challenges for Molten Salt Reactors, 2018*.
https://www.osti.gov/servlets/purl/1474868

will be additional complications since the resulting radiation signatures will be different from those of the uranium-based fuel cycle. The existing IAEA inspection regimes are based on the uranium-plutonium fuel cycle.

Another concern for non-proliferation is the possibility of reactor misuse for the production of more U-233 by modifying its fuel salt composition.

It is important to verify how the MSR fuel cycles introduce fissile[73] and fertile[74] materials in terms of location and distribution of the nuclear material inventory, production rate and consumption rate of these materials, and their chemical, physical and isotopical changes. As a result of these changes, each MSR design will have different signatures based on the different salt chemistries and fuel processing techniques, and will depend on how much fissile material is being created. This poses a new challenge to safeguards.

Spent nuclear fuel does not accumulate as a consequence of online processing. Thus, there is the problem of determing the fissile material content in the fuel when it is in the reactor, in storage tanks or in separation processing. This also poses a challenge to safeguards.

The presence of high-dose, short-lived fission products in the salt could pose challenges related to measurement instrumentation in safeguarding reactors while they are online.

Nuclear material accountancy is expected to verify that any material unaccounted for is within the range allowable by the IAEA. This means that for the detection of diversion of those materials high accuracy measurement systems could be needed for MSRs. According to the international target values (ITVs), measurement uncertainties that do not satisfy IAEA requirements could require more frequent PIVs for safeguards measures.

Current safeguards must be enhanced in order to adapt to the variation in MSR fuel cycles and reactor technologies.

[73] Fissile material is material capable of sustaining a nuclear fission chain reaction. By definition, fissile material can sustain a chain reaction with neutrons of thermal energy. The predominant neutron energy may be typified by either slow neutrons (i.e., a thermal system) or fast neutrons. Fissile material can be used to fuel thermal-neutron reactors, fast-neutron reactors and nuclear explosives.

[74] Fertile material is a material that, although not itself fissionable by thermal neutrons, can be converted into a fissile material by neutron absorption and subsequent nuclei conversions.

5. Very High Temperature Reactors

The very-high-temperature reactor (VHTR) is one of the six classes of Generation IV reactors. VHTRs under development will be capable of delivering high temperature helium (700-950ºC and eventually up to about 1000°C) either for industrial application via heat exchangers, or to make steam conventionally in a secondary circuit via a steam generator. VHTR has also been considered to directly drive a Brayton cycle[75] gas turbine for electricity with almost 50% thermal possible efficiency, increasing around 1.5% with each 50°C increment.

These reactors, having a negative temperature coefficient of reactivity[76], are inherently safe, do not require any containment building for safety and will usually be installed below ground level. They can range in size from 10 to over 100 MWe.Their fuel is in the form of TRISO (tristructural-isotropic)[77] unidentifiable microsphere particles less than a millimeter in diameter. Each particle has a kernel[78] (*ca.* 0.5 mm) of uranium oxycarbide (or uranium dioxide), with U-235 enriched up to 20% (between 3% and 19%[79]). Fuel is surrounded by layers of carbon and silicon carbide, giving a containment for fission products which is stable to over 1600°C. Microsphere particles are dispersed in either graphite, billiard-ball-sized pebbles in pebble-bed modular reactors (PBMR) or in blocks of graphite, hexagonal prisms, each with about 15,000 fuel particles and 9 grams of uranium. The fuel is designed not to crack due to the stress from very high temperatures.

Some VHTRs are helium-cooled designs with thermal neutron spectrum, and some are molten fluoride, salt-cooled designs. The coolant circulates through the spaces between the fuel pebbles to carry heat away from the reactor.

These reactors are refueled online, including PBMRs, or when fuel is unloaded, as is the case with reactors utilizing the graphite prisms. Used pebbles are taken out of the core, and unirradiated pebbles, or pebbles that have not reached the desired burn-up, are added to the core. Prismatic designs will require regular refueling every 1 to 3 years.

The reactor is shutdown periodically (about every 6-10 years) for replacement of in-core graphite structures.

Source data is available for each unit, as for LWR fuel. But the problem is that data after irradiation may not be able to be assigned to an individual unidentifiable pebble. Therefore, further analysis with access to more detailed information on the fuel for specific reactor designs will be required (e.g. information related to the feed of pebbles during online refueling C&S methods).

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[75] The Brayton cycle is a thermodynamic cycle that describes the workings of a constant-pressure heat engine. A supercritical CO_2 Brayton-cycle system can reach 50 percent conversion efficiency. Typically, you only get 30 percent conversion with an [air-based] steam engine.

[76] Negative temperature coefficient of reactivity means that the fission reaction slows as temperature increases.

[77] The tristructural-isotropic (TRISO) type coated fuel particle, which has been commonly used in the current VHTR consists of a microspheric UO_2 fuel kernel surrounded by four coated layers: a porous buffer pyrolysis carbon layer (buffer PyC), an inner dense pyrolysis carbon layer (IPyC), a silicon carbide layer (SiC) and an outer dense pyrolysis carbon layer (OPyC).

[78] World Nuclear News, *Kernel formation marks progress towards TRISO restar*t, 2020. https://www.world-nuclear-news.org/Articles/Kernel-formation-marks-progress-towards-TRISO-rest

[79] HALEU is enriched between 5% and 20% and is required for most U.S. advanced reactors to achieve smaller designs that get more power per unit of volume. HALEU will also allow developers to optimize their systems for longer life cores, increased efficiencies and better fuel utilization.

5.1 Challenges to IAEA Safeguards and Non-Proliferation Posed by VHTRs

VHTRs are reactor types that defy the traditional safeguards approach based on item accountancy applied to LWRs.[80]

The large number of low-inventory items (5-9g of uranium per element) that circulate through the PBMR system, gives this reactor characteristics that are between bulk and item facilities.

The challenge posed by these reactors stems from the fact that they consist of a large number of pebbles produced without individual serial numbers. They reside in a safeguards grey area, having properties that qualify them for both item and bulk accountancy safeguards options. Because there is a lack of a clear safeguards approach for VHTRs/PBMRs, this area represents a safeguards approach gap.

To date, the difficulties associated with traditional item counting for VHTRs/PBMRs have given rise to the IAEA safeguards approaches that rely upon maintaining continuity of knowledge of C&S data throughout the operational lifetime of the reactor. Therefore, new safeguards approaches are required for these reactor types to mitigate the vulnerability in continuity of knowledge.

The difficulties associated with traditional item counting are increased by the online refueling capability of this reactor type. A given reactor holds hundreds of thousands of small fuel spheres containing gram-quantities of nuclear material that are not uniquely identifiable when moving into or out of the reactor during online refueling.

Moreover, as the number of reactors posing safeguards challenges associated with systems that do not permit traditional item accountancy will increase in the coming years, now is the time to consider viable safeguards approaches to overcome the excessive dependence on C&S continuity of knowledge. Unique safeguards approaches should be developed by the IAEA for this reactor type, considering the bulk nature of the fuel.

The ideal safeguards approach appears to be a hybrid approach[81] employing fuel flow monitoring, redundant advanced containment and surveillance, and bulk nuclear material accountancy and verification techniques. This layered approach[82] would provide safeguards "defense in depth" that item facility or bulk facility approaches cannot provide alone.

The IAEA originally considered nuclear material in spent PBMR fuel irrecoverable because of the highly refractory nature of the fuel.[83] However, reprocessing of similar PBMR fuel has been demonstrated in the United States at the Idaho Chemical Processing Plant. Instead of shutting down for weeks to replace fuel rods, pebbles are placed in a bin-shaped reactor. A pebble is recycled from

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[80] David H. Beddingfield U.S. Department of Energy/National Nuclear Security Agency Office of Global Security Engagement and Cooperation, *Nuclear Safeguards Challenges at Reactors Types That Defy Traditional Item Counting, 2007.*

[81] Lance K. Kim, Center for International & Security Studies, U. Maryland, *Safeguards-by-design for advanced nuclear systems, 2017.*

[82] David H. Beddingfield U.S. Department of Energy/National Nuclear Security Agency Office of Global Security Engagement and Cooperation, *Nuclear Safeguards Challenges at Reactors Types That Defy Traditional Item Counting*, 2007.

[83] U.S. Department of Energy Office of Scientific and Technical Information, *Nuclear Safeguards Considerations For The Pebble Bed Modular Reactor (PBMR)*, 2009 https://www.osti.gov/servlets/purl/968683

the bottom to the top about ten times over a few years, and tested each time it is removed. When the fuel pebble is spent, it is removed to the nuclear-waste area, and a new pebble is inserted.

As far as proliferation risk is concerned, current IAEA safeguards practices does not categorize PBMRs under LWRs. Consequently, for these reactors a random inspection for uranium, plutonium, and/or thorium content does not seem feasible.

The potential presence of separated plutonium in unirradiated fresh fuel is a higher proliferation risk than those that contain LEU.

The recovery of plutonium and uranium from PBMR spent fuel must be considered possible, although technically challenging. This has been confirmed by a separate Idaho National Laboratory (INL) report on the subject.[84]

Therefore, a potential diversion scenario of fresh fuel and core fuel, and/or undeclared introduction of specially designed fuel for target irradiation, spent fuel and possible substitution with fake fuel balls and/or undeclared removal of specially designed fuel for target irradiation via broken-ball storage is an important issue of concern.

VHTRs have very high proliferation resistance[85] due to low fissile volume fractions and the refractory characteristics of the TRISO fuel particle coating system that assures a containment from which it is difficult to retrieve fissile materials. VHTR fresh fuel and spent fuel have higher resistance to diversion and proliferation than the fuel for any other reactor option.

The quantity of plutonium content per spent fuel block of VHTR, the material of most proliferation concern, is exceedingly low due to high fuel burn-up. The discharged plutonium isotopic mixture is degraded well beyond LWR spent fuel and becomes unattractive for use in weapons. To obtain the same quantity of Pu-239, 50 times more volume of spent VHTR fuel would need to be diverted than from a LWR fuel element. These features provide high proliferation resistance.

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[84] David L. Moses, Michael H. Ehinger *Oak Ridge National Laboratory, 2010, Supplemental Report on Nuclear Safeguards Considerations for the Pebble Bed Modular Reactor (PBMR).* https://info.ornl.gov/sites/publications/Files/Pub26683.pdf

[85] Kenneth D, Kok, *Nuclear Engineering Handbook,* 2009. https://books.google.it/books?id=EMy2OyUrqbUC&pg=PA225&lpg=PA225&dq=triso+ptoliferation+risk&source

6. Fast Neutron Spectrum Reactors

Fast reactors use a fast neutron spectrum[86] that can enable high fuel utilization and recycling. Reactors with fast neutron spectrum are called fast breeder reactors (FBR), to be differentiated from reactors with thermal neutron spectrum, called thermal breeder reactors and typically utilizing Th-232 as fuel.

Fast breeder reactors with closed fuel cycles are important to the sustainability, reliability, and security of the world's long-term energy supply. Their attractiveness is due to several features such as the conversion of the abundant fertile isotope U-238 into fissile material Pu-239 at rates faster than it is consumed (breeding); a hundred-fold energy extraction potential[87] from the same amount of mined uranium compared to its use in thermal reactors; and the possibility of incinerating all long-lived heavy elements during the reactor cycle.

FBRs typically utilize U-238 as fuel. Fast neutrons are ideal for plutonium production because they are easily absorbed by U-238 to create Pu-239 and cause less fission than thermal neutrons.

The high fuel-efficiency of breeder reactors could greatly reduce concerns about fuel supply or energy used in mining. Breeder reactors, by design, have extremely high burnup compared to a conventional reactor, as breeder reactors produce much more of their waste in the form of fission products, while most or all of the actinides are meant to be fissioned and destroyed.

All current fast neutron reactor designs use liquid metal as the primary coolant to transfer heat from the core to steam used to power the electricity generating turbines.

In contrast to most conventional nuclear reactors, however, a fast reactor uses a coolant that is not an efficient moderator, such as liquid sodium, so its neutrons remain high-energy. This plutonium isotope can be reprocessed and used for more reactor fuel or in the production of nuclear weapons. Reactors can be designed to maximize plutonium production, and in some cases they actually produce more fuel than they consume. Some fast reactors are being designed to operate for an estimated period of 10 to 40 years without refueling.

Three of the proposed generation IV reactor types are fast breeder reactors, all with closed fuel cycles:

- Gas-cooled fast reactor (GFR) cooled by helium.
- Sodium-cooled fast reactor (SFR) based on the existing liquid-metal FBR and integral fast reactor designs.
- Lead-cooled fast reactor (LFR) based on Soviet naval propulsion units.

[86] Neutrons produced by fission have high energies and move extremely quickly. These so-called fast neutrons do not cause fission as efficiently as slower-moving ones so they are slowed down in most reactors by the process of moderation. A liquid or gas moderator, commonly water or helium, cools the neutrons to optimum energies for causing fission. These slower neutrons are also called thermal neutrons because they are brought to the same temperature as the surrounding coolant. Although fast neutrons are not as good at causing fission, they are readily captured by an isotope of uranium (U-238), which then becomes plutonium (Pu-239). This plutonium isotope can be reprocessed and used as more reactor fuel or in the production of nuclear weapons. Reactors can be designed to maximize plutonium production, and in some cases they actually produce more fuel than they consume. These reactors are called breeder reactors.

[87] Breeder reactors can extract almost all of the energy contained in uranium or thorium, decreasing fuel requirements by a factor of 100 compared to widely used once-through light water reactors, which extract less than 1% of the energy in the uranium mined from the earth.

6.1 Gas-cooled fast reactor

The gas-cooled fast reactor (GFR) system is a nuclear reactor design which is currently in development. Classified as a Generation IV reactor, it features a fast-neutron spectrum and closed fuel cycle for efficient conversion of fertile uranium and management of actinides. The reference reactor design is a helium-cooled system operating with an outlet temperature of 850 °C using a direct Brayton closed-cycle gas turbine for high thermal efficiency.

They use uranium fuel in silicon carbide fuel rods. Some fast reactors are being designed to operate for an estimated period of 10 to 40 years without refueling. They employ reactor technology similar to the VHTR, suitable for power generation, thermochemical hydrogen production or other process heat.

The reference GFR unit is 2400 MWt/1200 MWe, large enough for breakeven breeding[88], with thick steel reactor pressure vessel and three 800 MWt loops.

For electricity, an indirect cycle with helium will be on the primary circuit, in the secondary circuit the helium gas will directly drive a gas turbine, and a steam cycle will comprise the tertiary circuit. They have a self-generating (breeding) core with fast neutron spectrum and no fertile blanket.[89]

Nitride or carbide fuels would include depleted uranium[90] and any other fissile or fertile materials as ceramic pins or plates, with plutonium content of 15 to 20%. As with the SFRs, used fuel would be reprocessed on site and all the actinides recycled repeatedly to minimize production of long-lived radioactive waste.

6.2 Lead-cooled Fast Reactor

The LFR is a flexible fast neutron reactor which can use depleted uranium or thorium fuel matrices, and burn actinides from LWR fuel.

Lead-cooled fast reactors utilize either molten lead or a lead-bismuth mixture as the coolant, which are relatively inert in relation to water or air but are highly corrosive, requiring more robust piping or vessel materials. Lead-cooled designs typically use uranium metal or nitride fuels, with full actinide recycling from regional or central reprocessing plants.

A wide range of unit sizes is envisaged, from factory-built battery with 15-20 year life-span for small grids, to modular 300-400 MWe units and large single plants of 1400 MWe. An operating temperature of 550°C is readily achievable but 800°C is envisaged with advanced materials to provide lead corrosion resistance at high temperatures, which would enable thermochemical hydrogen production.

A two-stage development program leading to industrial deployment is envisaged: by 2025 for reactors operating with relatively low temperature and power density; and by 2040 for more advanced

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[88] Breakeven is achieved when the conversion ratio (one measure of a reactor's performance defined as the ratio of new fissile atoms produced to fissile atoms consumed) reaches 1.0 and the reactor produces as much fissile material as it uses.

[89] Since the ability to breed fuel is the principal feature that distinguishes fast reactors, it is appropriate to ask how fertile and fissile fuels should be arranged to optimize breeding potential. Two basic choices exist regarding where the breeding takes place:(1) In the external breeding concept, all the fertile material is contained in the blanket surrounding the core in which all breeding takes place external to the core; and (2)in the internal, or in-core breeding concept, some fertile fuel is mixed within the core fuel assemblies.
Alan E. Waltar, Donald R. Todd, Pavel V. Tsvetkov, *Fast Spectrum Reactors, 2012*

[90] Depleted uranium is uranium with a lower content of the fissile isotope U-235 than natural uranium. Natural uranium contains about 0.72% U-235, while the depleted uranium used by the U.S. Department of Defense contains 0.3% U-235 or less. Uses of depleted uranium take advantage of its very high density of 19.1 g/cm3 (68.4% denser than lead). The less radioactive and non-fissile uranium-238 constitutes the main component of depleted uranium.

higher-temperature designs. This corresponds with Russia's BREST fast reactor technology which is lead-cooled and builds on 80 reactor-years' experience of lead or lead-bismuth cooling, mostly in submarine reactors. However, these propulsion reactors were small, operated at low capacity, featured an epithermal (not fast) neutron spectrum and operated at significantly lower temperatures than those anticipated in Generation IV LFRs.

For the LFR, no system arrangements have been signed, and collaborative R&D is pursued by interested GIF members under the auspices of a provisional steering committee led by Japan and Euratom, joined by Russia in 2011.

A technology pilot plant is envisaged to be in operation by 2021, followed by a prototype of a large unit and deployment of small transportable units.

6.3 Sodium-cooled Fast Reactor

SFRs use liquid sodium as the reactor coolant, allowing high power density with low coolant volume at low pressure. It builds on close to 390 years of reactor experience with sodium-cooled fast neutron reactors over five decades and in eight countries, and was initially the main technology of interest in GIF.[91] It remains at the forefront despite needing a sealed coolant system to counter the chemical volatility of sodium.

A variety of fuels are possible. Most SFR plants so far have had a core plus blanket configuration, but new designs are likely to have all the neutron action in the core. The SFR utilizes depleted uranium as the fuel matrix and has a coolant temperature of 500-550°C enabling electricity generation via a secondary sodium circuit, the primary one being at near atmospheric pressure.

Three variants are proposed: (1) a 50-150 MWe modular type with actinides incorporated into a uranium-plutonium metal fuel requiring electrometallurgical processing (pyroprocessing) integrated on site; (2) a 300-1500 MWe pool-type version of this; and (3) a 600-1500 MWe loop-type with conventional MOX fuel, potentially with minor actinides, and advanced aqueous reprocessing in central facilities elsewhere.

Early in 2008, the USA, France and Japan signed an agreement to expand their cooperation on the development of sodium-cooled fast reactor technology. The agreement relates to their collaboration in the International Framework for Nuclear Energy Cooperation (IFNEC) (formerly Global Nuclear Energy Partnership) aimed at closing the nuclear fuel cycle through the use of advanced reprocessing and fast reactor technologies, and seeks to avoid duplication of effort.

Two significant large SFRs are starting up: the BN-800 at Beloyarsk in Russia (operational since 2015) and the Kalpakkam PFBR of 500 MWe in India (expected in 2020). The BN-800 is largely an experimental reactor for fast reactor fuels. GIF observes that the technology is deployable in the very near-term for actinide management. Much of the ongoing R&D focus will be on fuels.

6.4 Challenges to IAEA Safeguards and Non-Proliferation Posed by Fast Reactors

Knowing its vast potential, research activities on the fast breeder reactor designs with closed fuel cycles have rejuvenated worldwide. Presence of three such nuclear systems among the total six systems proposed by GIF further marks the importance of fast reactor fuel cycle systems in the future.

[91]World Nuclear association, *Fast Neutron Reactors, 2020.*
https://www.world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx

The safeguards approach considers fast reactors close to the LWR model. Fuel assemblies are similar to those in a LWR. As for LWRs, source data is available for each unit and there is potential for very long operating periods.

Fast reactors are refueled during outage periods, during which the inventory of nuclear material in the reactor and storage areas can be verified by visual inspection, NDA measurements, and C&S methods.

But fast reactors pose a relevant challenge to safeguards by virtue of the potential presence of separated plutonium in unirradiated fresh fuel. This proliferation risk, which is higher than in reactors that contain LEU, signifies that IAEA safeguards may require considerably more effort than for a LWR. The breeding of high purity Pu-239 isotope and its envisaged use in large quantities in fast breeder reactor designs with closed fuel cycles is a major safeguards concern because of the vulnerability of spent nuclear material (SNM) diversion from peaceful uses.

In addition to current operating situations where production of low burn-up plutonium cannot be avoided, there will potentially be a large-scale buildup of low burn-up plutonium in the blanket material derived from fast breeder reactors. Since, in the future, production of blanket material will be the major reason for operating fast breeder reactors (i.e. to obtain plutonium for reuse), it is not practical to proscribe the production of such plutonium in irradiated blanket material.

Creating extra fuel in nuclear reactors is also not without its concerns: one is that the plutonium produced can be removed and used in nuclear weapons; another is that, to extract the plutonium, the fuel must be reprocessed, creating radioactive waste and potentially high radiation exposure.[92] Hence, it is prudent to assess the proliferation resistance of these facilities to find weak links, so as to ensure enhanced safeguards for the spent nuclear material.

Towards meeting this objective, the Nuclear Security Science and Policy Institute (NSSPI) at the Texas A&M University is carrying out pre-conceptual design studies for the integration of modern safeguards directly into the planning and building of FBRFC facilities.[93] A broad three step safeguards approach is adopted consisting of several tasks: developing a quantitative flow diagram of spent nuclear material present at each of the FBRFC facilities; developing a tool for the quantitative proliferation resistance assessment of intrinsic and extrinsic barriers for a set of spent nuclear material diversion scenarios; and designing a safeguards system by arriving at optimized material balance areas, material balance period, key measurement points and the C&S program based on the risk informed data obtained from the proliferation resistance assessment.

The results of the project study are expected to identify the possible weak links in the FBRFC that could lead to nuclear material proliferation and suggest ways to strengthen them by integrating modern safeguards. Finally, it should aid the IAEA to effectively and efficiently monitor and verify spent nuclear material in a manner that provides minimal intrusion into normal plant or facility operations.

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[92] Radiation exposure is a measure of the ionization of air due to ionizing radiation from photons; that is, gamma rays and X-rays. It is defined as the electric charge freed by such radiation in a specified volume of air divided by the mass of that air. The SI unit of exposure is the coulomb per kilogram (C/kg), which has largely replaced the roentgen (R). One roentgen equals 0.000258 C/kg; an exposure of one coulomb per kilogram is equivalent to 3876 roentgens. As a measure of radiation damage exposure has been superseded by the concept of absorbed dose, which takes into account the absorption characteristic of the target material.

[93] NSSPI, Center for Nuclear Security Science and Policy Initiatives, *Risk Informed Safeguards Approaches for Fast Reactor Fuel Cycle Utilizing MAUA based Proliferation Resistance Assessment*, 2010. https://nsspi.tamu.edu/risk-informed-safeguards-approaches-for-fast-reactor-fuel-cycle-utilizing-maua-based-proliferation-resistance-assessment-3384/

The risk of nuclear weapon proliferation from civilian use of nuclear energy stems mainly from two different stages of the nuclear fuel cycle: enrichment and reprocessing. These processes can create fissile material for use in nuclear weapons, which is why they need to be safeguarded against diversion.

Enrichment is a process that increases the share of the fissile isotope U-235 from 0.7% in natural uranium, which is composed mostly of U-238, to 3–5% to be used in LWRs as fuel. The same process can be used for creating weapons-grade material simply by enriching uranium to much higher levels. The commonly accepted definition of weapon usable material, or HEU, is 20% or more enriched U-235, and material containing more than 90% is called weapons grade. There is no technical fix for proliferation risk stemming from enrichment, and political controls are needed. Fast reactors operating on mixed uranium-plutonium fuel do not require a uranium enrichment technology.[94] There is no long-term storage of spent nuclear fuel in a closed fuel cycle.

In the context of reactor fuel production as opposed to military applications, the purpose of reprocessing is to separate the fissile plutonium that accumulates during reactor operation from spent fuel for further use as a fuel. The separated plutonium can also, however, be used for making weapons and for this purpose itis needed in smaller quantities than HEU.[95]

Plutonium for purely weapons purposes is typically produced in smaller dedicated reactors with shorter operating periods, in the range of a month, which creates a high yield of Pu-239, the most suitable plutonium isotope for creating weapons. Therefore, the main barrier against proliferation is controlling the plutonium isotope composition. The range from 6 to 8% of Pu-238 is sufficient[96] to make material non-weapon usable. One of the most studied breeder designs, FBRs with blankets of U-238, produce plutonium with a very low share of Pu-238 (0.01%).[97] No general agreement, however, on the proliferation resistance stemming from plutonium's isotopic combination has been reached.[98]

To provide an extra measure against possible material diversion and use for weapons, alternative reprocessing methods have been proposed that would simultaneously extract other transuranic elements together with plutonium, making the separation of plutonium more difficult.[99] It has been claimed[100] that even with these technologies a cessation of reprocessing will always be more

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[94] E.N. Avrorin, A.N. Chebeskov, Nuclear Energy and Technology, *Fast reactors and nuclear nonproliferation problem, 2015.*
https://doi.org/10.1016/j.nucet.2015.11.001
[95] Highly enriched uranium (HEU) has a 20% or higher concentration of U-235. The fissile uranium in nuclear weapon primaries usually contains 85% or more of U-235 known as weapons-grade material. Though, theoretically, for an implosion design a minimum of 20% could be sufficient (called weapon(s)-usable material), although it would require hundreds of kilograms of material and "would not be practical to design". Even lower enrichment is hypothetically possible, but as the enrichment percentage decreases the critical mass for unmoderated fast neutrons rapidly increases, with for example, an infinite mass of 5.4% U-235 being required. For criticality experiments, enrichment of uranium to over 97% has been accomplished.
[96] G. Kessler, Nuclear Science and Engineering, *Plutonium Denaturing by ^{238}Pu*, 2017. https://www.tandfonline.com/doi/abs/10.13182/NSE07-A2644
[97] Y. Meiliza, M. Saito, H. Sagara, Journal of Nuclear Science and Technology, 2010, *Denaturing Generated Pu in Fast Breeder Reactor Blanket, 2010.*
https://www.researchgate.net/publication/254276937_Denaturing_Generated_Pu_in_Fast_Breeder_Reactor_Blanket
[98] M. Lehetveer, F. Hedenus, *Nuclear power as a climate mitigation strategy – technology and proliferation risk, 2014.*
https://www.tandfonline.com/doi/full/10.1080/13669877.2014.889194
[99] IAEA, TECDOC-1587, *Spent Fuel Reprocessing Options.*
https://www-pub.iaea.org/MTCD/publications/PDF/te_1587_web.pdf
[100] F. N. von Hippel, Arms Control Association, *South Korean Reprocessing: An Unnecessary Threat to the Nonproliferation Regime, 2020.*
https://www.armscontrol.org/act/2010_03/VonHippel

proliferation resistant because plutonium can be separated from the reprocessing product with extra effort, and because of the protection that highly radioactive fission products provide against material diversion.

Nevertheless, it has been assumed that some nuclear fuel cycles that include reprocessing can provide an early warning of weapon program intentions and can thus be employed with a high level of confidence if a robust safeguards regime is in place.[101]

To summarize, although several different methods for making reprocessing of spent fuel more proliferation resistant have been proposed, we still do not know to what extent these proposed technologies will be used in the future and if they will succeed in their goal of making nuclear weapon acquisition more difficult.[102]

[101] M. Yim, Progress in Nuclear Energy, 2006, *Nuclear nonproliferation and the future expansion of nuclear power.* https://www.researchgate.net/publication/222429030_Nuclear_nonproliferation_and_the_future_expansion_of_nuclear_power

[102]M. Lehetveer, F. Hedenus, 2014, *Nuclear power as a climate mitigation strategy – technology and proliferation risk.* https://www.tandfonline.com/doi/full/10.1080/13669877.2014.889194

Conclusions

SMR designs promise an affordable, safe, viable, and non-greenhouse gas emitting energy.
Due to their unique features, SMRs do not easily fit into the international safeguards regime posing potential proliferation challenges.

In some cases, SMR designs can provide improvements even in the field of non-proliferation. Already identified[103] areas where technical improvements will help the deployment of SMRs include:

- reduction of service and maintenance requirements for reactor parts to ensure that the reactor does not need to be shut down for maintenance between outages;
- development of effective wireless communication systems for automated monitoring;
- development of in-vessel sensors for integral reactor vessels, which contain the entire primary cooling circuit;
- development of radiation detectors for the passively safe designs with very large water inventories;
- sealed design development, such that the fuel remains sealed from factory fabrication to the fuel handling facility at the back end of the fuel cycle;
- development of designs with infrequent refueling while keeping enrichment levels low; and
- new detection systems for opaque coolants, where visual inspections are infeasible.

These developments will allow the SMR community to be more confident and prepared in order to face potential proliferation challenges.

SMR designs, in particular, pose new challenges for IAEA safeguards because of their fuel types, coolants, and configurations. Therefore, they should be subjected to scrutiny through the lens of non-proliferation and safeguards guidelines.

None of the advanced reactor design categories can be safeguarded in the same manner as LEU-fueled LWR.

PBMRs and MSRs offer new challenges in verifying items in the reactor and fuel cycle.
Fast reactors are closer to the LWR model but present some unique problems and have the added complication of the potential for separating plutonium.

But there is high confidence that any of the advanced reactor concepts can be safeguarded to prevent nuclear weapon proliferation.

SMR designs will require more effective tools which IAEA safeguards should identify.
Therefore, the IAEA is called to work on the new types of reactors including those with long-life cores. Tools could include new C&S techniques and non-destructive measurements of enrichment and nuclear material quantities in circumstances such as online refueling of a reactor.

Moreover, an interactive process between the IAEA and the designers should be initiated at an early date. This interaction will allow the safeguards system to be more robust since safeguards-challenging elements of technology could be identified and explained at the onset. Steps should be taken to

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[103] S. Prasad, A. Abdulla, M. Granger Morgan, I. L. Azevedo, Progress in Nuclear Energy, *Nonproliferation improvements and challenges presented by small modular reactors*, 2014.
https://irgc.org/wp-content/uploads/2018/09/Prasad-et-al_Nonproliferation-SMRs.pdf

facilitate international safeguards in the design phase of the reactor, ensuring cost-efficient and operationally effective safeguards by design.

Finally, designers should conduct a review of the new reactor designs with reference to the efficient, well established IAEA safeguards system for LWRs. Such a review should evaluate the possibility of turning the advanced reactor into an item facility, noting that the definition of an item may need to evolve in new and untraditional ways.

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