ESARDA
European Safeguards Research & Development Association

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# Connector

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## EDITORIAL

by Mari Lahti (ESARDA President)

Dear ESARDA Community,

We have another busy safeguards year underway. We already met within the framework of the Editorial Committee, the Working Groups, and the Executive Board meetings in Geel, Belgium from 30 January to 1 February. Many thanks again to the colleagues in JRC Geel for hosting us at this hybrid meeting. All in all, we had eligible participation, both on spot and online. For the WG meetings, having many overseas participants, on-line meetings are becoming established as a way of working. The Editorial Committee and WG Chairs reported their group activities for the Executive Board on Wednesday afternoon and Thursday morning. By invitation, Irmie Niemeyer and Yetunde Aregbe provided a World Café report summary and outlook, with ideas on how to review the actions and gather feedback from the Working Groups. Results will be followed in the Annual Meeting to be held in May.

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## INDEX

In the afternoon, we continued with a closed EB meeting, with a more administrative agenda. Perhaps the topic that sparked the most discussion was JRC engagement in ESARDA, and how to guarantee ESARDA's functionality in the future. It is acknowledged that JRC is the heart and asset of the association and most of the work input, including the Secretariat, the Editorial Committee, and that the organisation of the Annual Course is the responsibility of the JRC staff. Understandably, it would be preferable if this burden were to be shared more within the community. The EB started to look for alternatives, but at the same time, recognised the challenges of finding ways to continue this much appreciated work elsewhere. Some functions may be easier to arrange in different ways than others. In particular, the Secretariat which needs the continuity and benefits from personal contacts and experience, was considered difficult to organise with a shorter rotation, such as the Presidency or EB membership. I imagine that we can affirm that we have a common challenge ahead of us, and that all the efforts to ensure the continuity of activities are of utmost value.

Next, I would like to briefly mention the ongoing review of the regulation. Many of us working with safeguards have surely come across the revision of the Euratom Safeguards Regulation. The Belgian Presidency of the Council of the EU and the European Commission, organised in late February and early March two online information sessions for stakeholders on the proposed Commission Regulation on the application of Euratom Safeguards, published in December 2023. The Regulation proposed considers new types of facilities and geological disposal of nuclear waste and spent fuel, reflecting the developments in the Member States. It also enhances facilitating safeguards by design for new builds, major modifications, and decommissioning. One aspect of the revision also regards clarification and reducing the administrative burden. We can surely all agree that this work is important. Especially ESARDA's Implementation of Safeguards WG is closely following the revision and reflecting feedback to be discussed within the community.

Now, on to recent and upcoming events. The 2024 ESARDA Course on Nuclear Safeguards and Non-Proliferation (22nd Edition) was organised on-line from 15 to 19 April and featured a full five-day programme with lectures, group exercises and virtual visits to some of the JRC Ispra research laboratories. The course is open and relevant for anyone working in the nuclear field, but especially for students and young professionals. This course provides a comprehensive review of the fundamentals of non-proliferation and the implementation of safeguards and is a great opportunity for professional networking.

In addition, I would like to recall that the 2024 ESARDA Annual Meeting will be held at the European Convention Centre, Luxembourg, from 13 to 16 May 2024, facilitated by DG ENER. This Annual Meeting is a closed event reserved for ESARDA Parties, all our Associated and Individual Members and of course, invited contributors. Monday afternoon will be dedicated to the Steering Committee and Executive Board Meetings. Tuesday, 14 May is the plenary day, with keynote speakers in the morning session and topical discussions in the afternoon. In the session themes we plan to continue the topic of Advanced and Small Modular Reactors, which was already initialised in the 2022 Annual Meeting Plenary. The Working Group meetings will take place on Wednesday and Thursday, before the Closing Session on Thursday afternoon.

I would also like to take the opportunity to remind you that one of the highlights of the year will be the INMM Annual Meeting 21-25 July to be held in Portland, Oregon, USA. Publication of preliminary program and notification of abstract status can be expected around the end of March.

I would like to wish everyone a pleasant spring and look forward to seeing you at the upcoming events.

Mari Lahti
ESARDA President

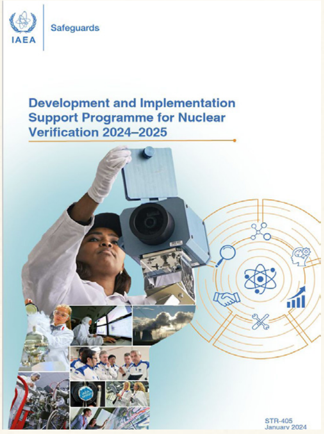
# news & events

Keeping you up to date with all the latest news of the association and its partners, as well as all the upcoming events in the near future.

# NEWS

### The IAEA Published the Development and Implementation Support Programme for Nuclear Verification 2024-2025

This publication provides a comprehensive overview of the Development and Implementation Support (D&IS) Programme for Nuclear Verification (hereafter “the D&IS Programme”) within the International Atomic Energy Agency’s Department of Safeguards. The D&IS Programme seeks to enhance nuclear verification capabilities through collaborative efforts with a diverse range of partners. Emphasizing the commitment to innovation and sustainability, this document is situated within the broader context of the IAEA’s nuclear verification mandate.




The primary objective of this publication is to communicate the 27 safeguards-relevant Development and Implementation Plans to current and potential partners to the Department of Safeguards (hereafter “the Department”). It seeks to engage partners in supporting the Department’s efforts to implement Safeguards effectively, efficiently, and innovatively. Additionally, the document aims to inform partners about the Department’s resource needs and facilitate discussions on collaborative initiatives that align with the overarching goal of strengthening nuclear verification capabilities.

Read more.

### The European Commission Proposes Revised Rules for the Application of Euratom Safeguards

The Commission has proposed revised rules on reporting by users of nuclear material in the EU within the framework of the ‘Euratom safeguards’ supervisory system. The proposal consists of a new regulation to update and replace the current Regulation 302/2005, taking into account the developments in recent years in the nuclear sector and in information technology. The aim is to ensure the continued effectiveness and efficiency of Euratom safeguards in guaranteeing the peaceful use of civil nuclear materials in the EU.

The proposal follows and fully implements the conclusions of an in-depth evaluation conducted in 2022 with the purpose of providing evidence to support legislative decisions in this policy area. In line with the Euratom Treaty, it is now for the Council to approve this new regulation.

Read more.

### Welcome to Helena Cedergren, New IS Working Group Vice-Chair

Marianne Calvez, IS WG Chair, has recently been joined by Helena Cedergren as new WG Vice-Chair. Since around 6 years back Helena is an inspector at the Section for Nuclear Non-Proliferation at the Swedish Radiation Safety Authority (SSM), with a responsibility for nuclear safeguards. She has a bachelor of science (BSc) in chemistry, with more than 20 years of experience in quality assurance, domestic and international inspections in different industries e.g. environmental control, pharmaceutical, steel and automotive. Among her current responsibilities at SSM is safeguards at small holders of nuclear materials and participating in safeguards inspections performed by the IAEA and Euratom. She has been the representative from SSM in ESARDA Working group for Implementation of Safeguards since 2019.

Read more.

## STUK published “Highlights of International Cooperation for Safety, Security and Safeguards in 2023”

In a world often beset by challenges and conflict, the international cooperation stands as a beacon of hope and progress. As we reflect on our achievements and commitments in the realm of global collaboration, it becomes evident that our collective efforts have yielded good results.

Today STUK - Säteilyturvakeskus published “Highlights of International Cooperation for Safety, Security and Safeguards in 2023”. Read more about our cooperation to support Ukraine and working together with African Commission on Nuclear Energy (AFCONE) and African countries and much more.

Read more.

## VERTIC partners with the US to provide nuclear safeguards implementation assistance to Lao PDR

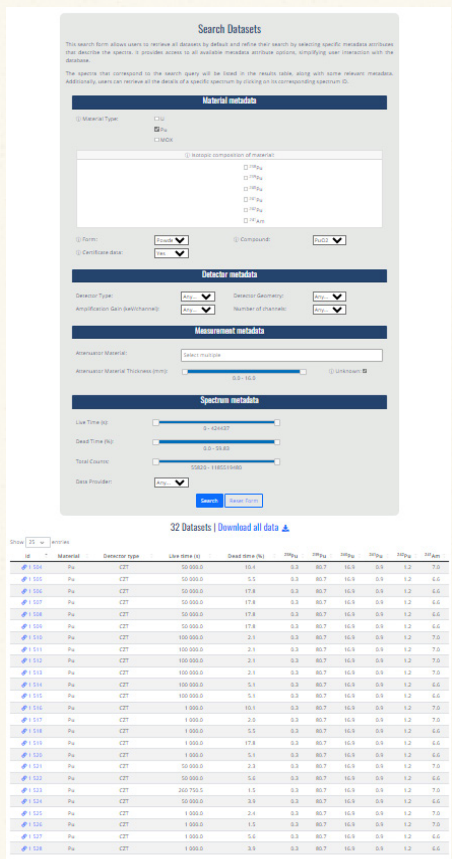
Senior Researcher Hugh Chalmers attended an IAEA safeguards implementation workshop in Lao PDR, where he explained how states fulfil their international safeguards commitments through domestic legislation. He presented a set of case studies that demonstrated the safeguards provisions typically captured in legislation, and the different structural approaches taken by states to achieve this.

The workshop was hosted by the Lao PDR Ministry of Education and Sport and delivered by the US National Nuclear Security Administration’s International Nuclear Safeguards Engagement Programme (INSEP).

Read more.

## IAEA Announces the International Database of Reference Gamma Spectrum (IDB)

The Nuclear Data Section of the IAEA announced that the International Database of Reference Gamma Spectrum (IDB) is available at https://nds.iaea.org/idb. The IDB currently contains over 1500 well characterized gamma datasets. The IAEA Department of Safeguards contributed to the IDB which was sponsored by the United States Support Program. The main customers of the IDB are expected to be the nuclear safeguards and nuclear security communities, but all are welcome. More information about the IDB can be found at https://www-pub.iaea.org/MTCD/Publications/PDF/Newsletters/nd76.pdf.




Two screengrabs of the International Database of Reference Gamma Spectrum (IDB) metadata-based search.

The entire database can be downloaded from the IDB homepage which also provides a link to contact information.

The IDB’s metadata-based search allows users to find spectra that match entered metadata values. For example, results of a search for spectra from Pu[2] material in powder form are shown below:

Details of a spectrum returned in a search can be viewed by clicking on the ID link in the table showing the returned spectra.

Read more.

# EVENTS

**2024**
**May**
**13-16**

13th - 16th May 2024

## ESARDA 46th Annual Meeting

**Luxembourg Congress Conference Centre, Luxembourg**

The 2024 ESARDA Annual Meeting is planned to be held at the Luxembourg Congress Conference Centre, Luxembourg, from 13-16 May 2024. This annual meeting is a closed meeting reserved to ESARDA Steering Committee, Executive Board and Working Groups' members,
[Read more]

**2024**
**June**
**16-20**

16th - 20th June 2024

## 7FP GENTLE intersemester course on nuclear safeguards and security

**European Commission JRC, Geel, Belgium**

This course focuses on providing fundamental principles for the peaceful use of nuclear energy and development of technology related to measurement and detection of nuclear materials.
[Read more]

**2024**
**July**
**21-25**

21st - 25th July 2024

## 2024 INMM Annual Meeting

**Portland Marriott, Downtown Waterfront, USA**

Join INMM in July for the 65th Annual Meeting. The INMM 65th Annual Meeting will discuss topics on Nuclear Materials Management.
[Read more]

# working group reports

This section of the Connector has the objective to inform the ESARDA Community about the latest undertaking of the Working Groups' activities during the last six months. Each Working Group Chair has been invited to provide a brief overview of findings in their fields of interest.

## CONTAINMENT AND SURVEILLANCE WORKING GROUP (C/S)

by Heidi Smartt
(C/S Working Group Chair), and
Vitor Sequeira
(C/S Working Group Vice-Chair)


Figure 1: (left) JRC, Ispra's Reusable Random Pattern Passive Seal (R2P2), (center) Sandia National Laboratories' Puck Loop Seal, (right) IAEA's Field Verifiable Passive Loop Seal (FVPS)

The Containment/Surveillance (C/S) working group's mission is to provide the safeguards community with expert advice on C/S instruments and methods and on their performance and act as a forum for the exchange of information on such instruments and methods, including unattended and remote monitoring systems. The group held two meetings during the last year. The first meeting took place in Vienna, Austria, at the end of the INMM & ESARDA Joint Annual Meeting, Friday, May 26. As the Annual Meeting took up much of the week, the C/S working group meeting was very short. Heidi Smartt (Sandia National Laboratories, Albuquerque, United States) took over as chairperson from Katarina Aymanns, and Vitor Sequeria (Joint Research Center (JRC), Ispra, Italy) took over as vice-chair from Heidi. Presentations were given on muon tomography for shielding casks and for verification of geological repositories; a new passive loop seal, R2P2, developed by JRC; and the IAEA provided seal and surveillance updates.

The working group met again at JRC, Geel, Belgium, on Tuesday, January 30 for a full day. There were approximately 27 participants with about 9 attending in person. Presentation topics included: a new passive loop seal "Puck" under development by Sandia National Laboratories; a related passive loop seal with RFID and ability to monitor wire loop continuity by Oak Ridge National Laboratories; an update by the IAEA on their new passive loop seal FVPS and new active loop seal AUAS; a talk by JRC, Ispra on point cloud segmentation for spinning laser sensors; another update by the IAEA on the Next-Next Generation Surveillance System; another JRC-Ispra talk on active learning for image retrieval; a talk on a new polymer material that can indicate the type of tamper attack (mechanical, chemical, thermal); an update from both STUK and JRC-Ispra on safeguards for Olkiluoto geological repository and the Resident Inspector (a quadruped robot deployed within the tunnels); and an update on the Sandia National Laboratories' Inspecta project (an AI-enabled smart digital assistant with Spot robotic support).

The working group will meet again at the ESARDA Annual Meeting, Luxembourg, on May 15, 2024.

## EXPORT CONTROL WORKING GROUP (EXP)

by Henri Niittymäki
(EXP Working Group Chair), and
Maggie Arno
(EXP Working Group Vice-Chair)

EXP-WG is now looking to the future, where emerging technologies and SMR's await. Development alone cannot be examined from the perspective of export control, but the whole must include e.g. SbD. EXP-WG has identified the need to get together and organise a workshop together with another ESARDA working group. This has already been planned with IS WG. The aim was to strengthen the impact and effectiveness of the Group's efforts in the coming years, especially in light of new technologies and small modular reactors (SMRs) that promise to profoundly shape the export control landscape.

EXP-WG convened remotely on Monday, January 29, 2024 using the TEAMS platform. The meeting offered an overview of the status and prospects of the EXP-WG key focus areas. Three presentations illuminated topics of relevance in the realm of export control. Firstly, the discussion centered on the inclusion of drone technology in supply chains that may ultimately support Russia's military operations. This topic sparked discussions and prompted considerations on enhancing oversight effectiveness. Thus far, there have been no reports of radiation measurement equipment being incorporated into drones.

Secondly, the meeting delved into the latest edition of the Peddling Peril Index (PPI). The presentation provided a comprehensive overview of the index's updates and country-specific rankings. Discussion ensued regarding the implications of the ranking changes, with an emphasis on enhancing the traceability and consistency of the index. The inaugural PPI was published in 2017.

As the final presentation, the group examined the current state of export control on the US research front. This review offered valuable insights into emerging trends and challenges.

In conclusion, the 17th meeting successfully provided in-depth insights into key topics, leaving participants with new knowledge and perspectives.

In addition, the EXP-WG discussed topics and prerequisites for the 18th meeting. EXP-WG chairs raised the issue of discussion and research on the emergence of new technologies and their impact on the adaptation of export controls to international protocols. This is an important subject in view of the similarities between nuclear and export controls. It was noted that a joint meeting with the IS Working Group would be an optimal solution for the upcoming ESARDA Annual Meeting, which will take place in Luxembourg on 14-16 May 2024.

## IMPLEMENTATION OF SAFEGUARDS WORKING GROUP (IS)

by Marianne Calvez
(IS Working Group Chair), and
Helena Cedergren
(IS Working Group Vice-Chair)

*The Implementation of Safeguards Working Group (IS WG) is a horizontal issues working group of ESARDA. Its objective is to provide the Safeguards Community with proposals and expert advice on the implementation of safeguards concepts, methodologies and approaches aiming at enhancing the effectiveness and efficiency of safeguards on all levels. This WG is also a forum for exchange of information and experiences on safeguards implementation.*

In 2023, the working group met three times. The first meeting was organised as part of the INMM-ESARDA annual meeting in May in Vienna as a special session in conjunction with the INMM ISD (International Safeguards Technical Division). This half-day face-to-face meeting focused, for example, on Safeguards by Design (SBD) and Small Modular Reactors (SMRs). The aim was to strengthen cooperation between ESARDA and INMM experts on certain topics related to safeguards implementation. The participants discussed the possibility to organise a special event on SMRs. Around 60 participants attended this half-day meeting.

The second meeting took place virtually in June. The central theme was State Level Approaches (SLA) and participants discussed how SLAs are implemented in their respective countries. Representatives from the IAEA and the EC shared their perspectives on this topic. During the round table, attendees delved into the current implementation of SLAs and challenges faced in different countries were highlighted. The meeting also included a brief session on bilateral nuclear cooperation between the EU and the UK. Participants found the meeting highly valuable and discussion on the evolution of SLAs will continue and how it affects to the practical safeguards implementation in the states.

The third meeting was held in hybrid form and hosted by STUK in September and over 40 participants attended, either in person or virtually. The focus was on current safeguards topics and approaches in Finland, especially on how spent nuclear fuel disposal project is advancing and the safeguards is implemented in the EPGR facilities (Encapsulation Plant and Geological Repository). The current status of decommissioning and safeguards implementation was presented and the meeting introduced ongoing Finnish SMR projects, emphasizing the role of Safeguards by Design (SBD). Participants shared updates on safeguards implementation in their respective countries.
In connection with the recent IS WG meeting, a half-day joint meeting with the ESARDA Final Disposal Working Group (FD WG) was organized. FD WG members presented the current approach to safeguards for final disposal and discussed ongoing research and development. The meeting concluded with a discussion on the challenge of passing knowledge to future generations.

In 2024, the ESARDA IS WG will meet twice. The first meeting will take place over a day and a half on 15 and 16 May, in conjunction with the annual meeting organised in Luxembourg in 2024. This meeting can only take place in person. For the second meeting the group will meet at the invitation of Swiss Federal Office of Energy in Switzerland in the autumn.

In January 2024, the Group's chair and vice-chair changed: M. Calvez succeeded M. Hämäläinen as chair and H. Cedergren became vice-chair. They had already been active members of the group for several years and intend to continue the group's work.

## MATERIAL BALANCE EVALUATION (MBE)

by Vincent Janin
(MBE Working Group Chair), and
Michael Whitaker
(MBE Working Group Vice-Chair)

The Material Balance Evaluation (MBE) Working Group was established to share best practices and knowledge related to MBE in large bulk handling facilities (e.g., reprocessing and uranium enrichment). The main objectives are to (1) establish guidelines on MBE, (2) provide robust methodologies for in-process inventory verification and MBE, (3) share best practices and knowledge, and (4) contribute to international reference through publishing guidelines and ESARDA publications. Four subgroups are facilitating the activities of the working group:

1. Regulations,
2. Methodologies and Statistical Assumptions,
3. Good Practices for Monitoring and Accuracy Improvements, and
4. Near-Real Time Accountancy (NRTA) Studies and Perspectives.

Last Fall, subgroups 2 and 3 held virtual meetings and the entire working group had an in-person + remote meeting in conjunction with the ESARDA Board meeting in January 2024. Subgroup 2 has organized 8 presentations on methodologies so far. Subgroup 3 distributed an 18-question survey on MBE practices and challenges in April 2023 and has received responses from 12 organizations. Subgroup 4 has been sharing work on NRTA systems and simulation tools. The working group is progressing towards producing an MBE Handbook with "bricks" addressing selected topics prepared by the subgroups. We will be reaching out to other ESARDA workings groups sharing common interests. The next In-person + remote meeting is being planned for May in Luxembourg and Orano is planning a visit of GBII and associated laboratory by the end of 2024.

## TRAINING AND KNOWLEDGE MANAGEMENT WORKING GROUP (TKM)

by Riccardo Rossa
(TKM Working Group Chair), and
Pierre Funk
(TKM Working Group Vice-Chair)

The ESARDA TKM Working Group (TKM WG) met on January 30th 2024 at the JRC site of Geel in Belgium with remote connection also possible.

The hybrid meeting attracted about 15 participants and featured 5 presentations. The activities of the GIF Education & Training Working Group (ETWG) were presented by Patricia Paviet (PNNL). An update on the ESARDA course, with a view on the medium term developments in terms of funding and organization was given by Kamel Abbas (JRC-Ispra). The brainstorm session on “Current and future needs to Education & Training (E&T)” was continued from the last meeting in May 2023 and was led by Riccardo Rossa (SCK CEN). The ABACC approach to E&T activities was presented by Sonia Fernández Moreno (ABACC). The IAEA approach to Knowledge Management was outlined by Sofya Hambaryan (IAEA).

Figure 1: Geographical location of participants of the TKM WG meeting.

The 22nd ESARDA course on nuclear safeguards and non-proliferation will be organized on-line from April 15th to April 19th 2024. The ESARDA course is co-organised by the JRC’s Nuclear Safety and Security directorate and the ESARDA Training and Knowledge Management working group.

The second edition of the First Level Specializing Master on Nuclear Safeguards, organized by the Politecnico di Milano and the European Nuclear Education Network (ENEN) in the frame of the SATE project (https://www.nuclearsafeguards.polimi.it/) started in November 2023. The second edition is scheduled to run until January 2025.

# featured articles

This section presents prominent articles on the latest news and topics of interest in the safeguards community

# KFKI ATOMIC ENERGY RESEARCH INSTITUTE TRANSFER TO HUN-REN

by Hedvig Eva Nagy
(HUN-REN Centre for Energy Research, Hungary)

Radiation Safety Laboratory at HUN-REN's Nuclear Security Department

The Nuclear Security Department (NSD) of the Centre for Energy Research (and its legal predecessor) plays an important role in Hungarian safeguards activities.

The Centre for Energy Research was established in January 2012 on the basis of two former independent institutions, the Research Institute for Atomic Energy and the Institute of Isotopes. From 2019, the research centre has been transferred to the Eötvös Loránd Research Network. From 2024 January the Centre for Energy Research continues to operate as the HUN-REN Centre for Energy Research, as part of the Hungarian Research Network.

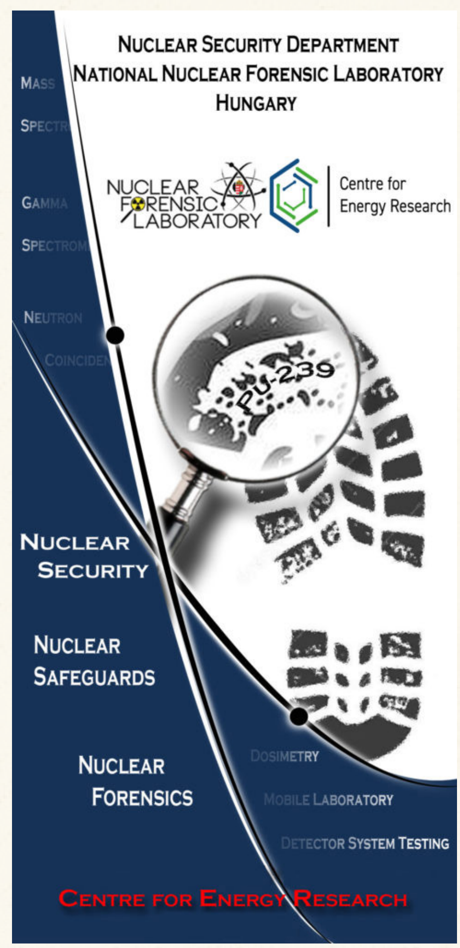
The aim of the HUN-REN Centre for Energy Research (HUN-REN EK-CER) is to carry out basic, applied and developmental scientific research of international standard in the fields of nuclear energy, functional materials and nanosystems, environmental protection, energy efficiency and energy security.

One of the 21 research groups is the Nuclear Security Department (NSD). Its activity covers research and practical application in the field of nuclear security and nuclear safeguards, as well as professional support for national and international organizations and companies. The research, method development and technical service tasks are carried out in several closely cooperating groups in the following areas: non-destructive (gamma spectrometry and neutron measurement) and destructive analysis (mass spectrometry, alpha spectrometry), dosimetry, instrument development, mobile expert support team and a detector testing laboratory.

Hungary provides regular and effective support to maintain and further develop the IAEA's nuclear safeguards system, mainly in three areas: IAEA training activities, testing of new instruments and equipment, and development of equipment and technologies. The Centre for Energy Research, as a Technical Support Organisation of the Hungarian Atomic Energy Authority, participates in these activities too.

Among others e.g., the NSD and its legal predecessor, the Institute of Isotopes, developed the PSFAT device to help safeguards inspectors in cases when Cherenkov viewing devices were not usable and a list-mode pulse-train recorder, PTR-32HV which has been authorized by the IAEA for safeguards applications. A measurement method was developed to determine the Pu content of disused Pu-Be neutron generators to measure their real Pu content (Pu content could only be calculated on the basis of the neutron-yield data provided by the supplier) before their shipment to a storage place. Based on the results of the measurements, the original Pu content of the sources – as described in the official documents – had to be significantly modified.

The NSD takes part also in different EU and IAEA training activities like the IAEA Traineeship Programme for nuclear professionals from developing countries and Additional Protocol Exercise (APEX) for IAEA inspectors.



# technical articles

Technical articles covering the latest findings of our community of experts on fundamental issues

# PROLIFERATION RESISTANCE OF A PEBBLE BED FUELS IN GEN IV REACTORS

by Hamidreza Yousefi

(Nuclear Research Group of San Piero a Grado (GRNSPG), University of Pisa (UNIPI), Italy)

(ESARDA Course Student Paper)

## Abstract

*Nowadays within the urge for safe and reliable sources for electricity production, there are various designs with respect to the type of the reactor and corresponding fuel that can be used. Each one of the designs has a unique characteristic and that's one of the reasons which makes the nuclear industry face many challenges. One of the most vital needs of every design, based on the regulation set by the International Atomic Energy Agency (IAEA) is the proof of Nuclear Non-Proliferation which indicates that the use of reactors and fuels, in general, the energy system is only limited to peaceful purposes. Therefore, the IAEA will impose some limitations and restrictions in terms of the use of energy systems, also, IAEA encourages the imposition of safeguards (rules) by design concept rather than the procedure for simplifying the safeguard applications on any nuclear facilities That is why Proliferation Resistance (PR) is defined as one of the characteristics of the nuclear energy system and can be subjected to either design or procedure. PR means impeding the diversion, undeclared production of nuclear material, and misuse of the technology, by the host state seeking to use nuclear technology for un-humanitarian and non-peaceful purposes.*

*One of the milestones in considering the is development of a special safeguard called Non-Proliferation Treaty (NPT). This treaty was opened for signature in 1968 and entered into force on 5th of March 1970. Under NPT, non-nuclear-weapon states that are described as countries which are not equipped with nuclear weapons, have committed themselves to impede any misuse of nuclear material such that can have adverse effect on peaceful purposes. Based on the meaning of PR and with keeping in mind that this world is going toward cutting-edge technology and growth in terms of design, the PR must comply with this pace of advancement, this is fundamental for the insurance of the safe use of nuclear energy system.*

*Nowadays, one of the most popular designs for nuclear fuel these days is pebble bed type fuel which its superior characteristics that make it a good choice for HTGR (High Temperature Gas cooled Reactors). The fuel of a nuclear reactor must have certain features, because of the environment in which the nuclear reactor operates that can be categorized as the following: 1-high neutron flux ($10^{14}$ n/cm$^2$.s for GenIV reactors HTGR), 2-Stress (thermal and mechanical stress for steady-state and transient operation), 3-Corrosion, 4-Intense gamma heating (due to prompt fission radiation, radiation-induced radioactivity of core materials, inelastic scattering of neutrons with material, etc.) and 5- very high operating temperature. These conditions are always present and will affect the materials of the nuclear reactor especially nuclear fuel cladding that will be subjected to those harsh conditions up to considered refueling time, indeed refueling is also done to maintain the rigidity of the cladding.*

*Additionally, the safe and economical operation of any nuclear power system relies highly on the fuel and materials of the construction. In this article, the aim is to study more about the features of the pebble bed fuels with methods for analysis of PR of these types of fuels.*

**keywords:** Nuclear Non-Proliferation, Nuclear safeguards, NPT, GenIV Reactors, HTGR, Pebble Bed Reactor Fuel

## 1. Introduction

The history of pebble bed fuels starts with the idea of High Temperature Gas cooled Reactors that are graphite moderated and cooled by helium which is part of Gen IV reactor types with enhanced safety features compared to

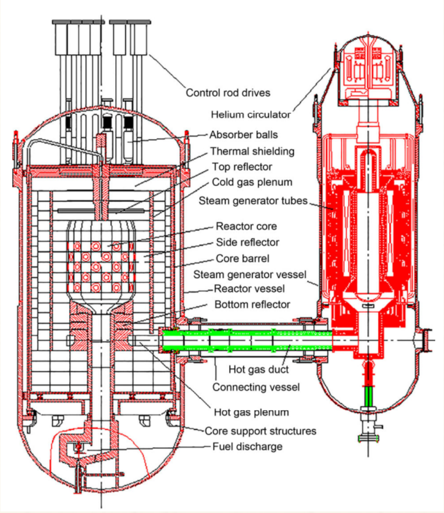



Fig. 1: HTGR Gen IV Reactor with Pebble Bed fuel [6].

previous reactors. The high temperature in these reactors can have the benefit of having high thermal-energy conversion efficiency that has a vital role in the cost-effectiveness of the design. Also, in these types of reactors, the co-production of hydrogen makes them an asset among other types. The key characteristic of this design is the use of graphite as a moderator of neutrons, Helium as coolant which is transparent to the neutrons and ceramic-coated particles as fuel [1]. Moreover, this type of reactor, due to unique operational conditions, uses a special kind of fuel with ceramic coating. The concept of ceramic coatings started a long time ago, but it is accelerated after the Fukushima Daiichi accident.

In each nuclear power plant, the propagation of accidents depends on the available energy which can be referred to as 1. Chemical energy 2. External events 3. Stored energy 4. Decay heat 5. Nuclear Transients [2]. The concept of ceramic coating has the aim to reduce the available chemical energy released in accidents which in the right situations, can exceed the decay heat of the core and can cause much more complicated accident scenarios to deal with. For the current types of fuels in nuclear reactors, metallic cladding is used, and the main reason is to retain the fission products for example in LWR's (Light Water Reactors) due to neutron economy, Zircaloy 4 & 2 (for PWR & BWR) alloys are used for cladding, however, the problem in these types of claddings arises when in the case of

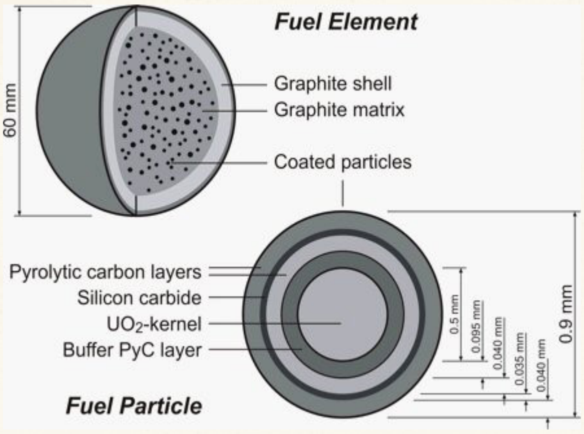



Fig. 2: Pebble bed Fuel [6].

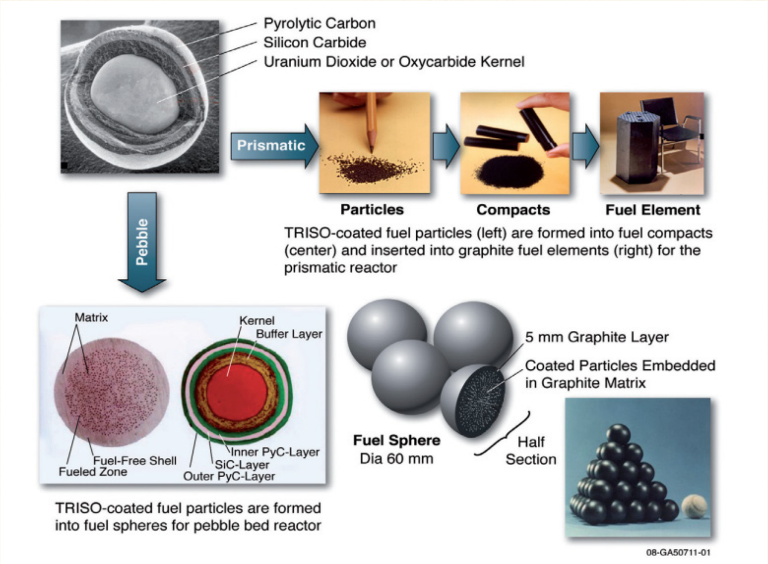



Fig. 3: High temperature gas reactor fuel system, showing TRISO fuel particles consolidated into compacts to be inserted into prismatic graphite blocks (upper right) or pebbles (lower) [4].

an increase in temperature, the energy stored in the cladding due to cold working will be released . Moreover, the chemical reaction of the cladding and coolant not only will produce an amount of energy greater than the decay heat but also lead to hydrogen production that can have a significant effect on the behavior of the system because of the introduction of Non-Condensable Gas [3] and possible creation of flammable or explosive gas mixtures.

$$Zr+2H_2O \rightarrow ZrO_2+2H_2+Q \qquad \text{Equation 1}$$

Q=Energy (140 kcal/g. mol)

Although in Gen IV reactors, Zircaloy is not used and in some like Sodium Fast Reactors(SFR), stainless steel takes its place, that in terms can increase the tolerance of the fuel facing stress and corrosion, but still the problem of hydrogen production remains in these types of fuels.

For these reasons, the use of fuel with ceramic coating is one way to simplify the design .This concept is popular among the researchers due to its significant feature of having very small chemical potential meaning less tendency to participate in chemical reaction, consequently lower release of energy, however, due to importance of insurance of safety of the plant, continues research must be done to demonstrate the safety of these fuels. Pebble bed fuels are also called TRISO-coated (Tri structural- ISO tropic) particle fuels. This kind of fuel has been extensively studied over the past four decades around the world such as the United Kingdom, Germany, Japan, the United States, Russia, China, and more recently in South Africa [4]. Last but not least, TRISO-coated particles are designed to maintain the fission products inside even when facing very high temperatures during accidents, thus making them unique in the nuclear industry[5].

As shown in Figure 3, a TRISO-coated particle is a spherical-layered composite, about 1 mm in diameter. It consists of a kernel of Uranium oxide (UO2), or Uranium oxy carbide (UCO) surrounded by a porous graphite buffer layer that absorbs radiation damage and allows space for fission gases produced during irradiation. Surrounding the buffer layer is a layer of dense pyrolytic carbon called the Inner Pyrolytic Carbon layer (IPyC), a silicon carbide (SiC)layer, and a dense outer pyrolytic carbon layer (OPyC)[1].

Pyrolytic carbon is a material similar to graphite, but with some covalent bonding between its graphene (is an allotrope of carbon consisting of a single layer of atoms arranged in a hexagonal lattice nanostructure) sheets as a result of imperfections in its production. Pyrolytic carbon is an artificial material; therefore it cannot be found in nature.

The use of pyrolytic carbon layers also has the advantage that this layer shrinks under irradiation and creates compressive forces that act to protect the SiC layer. This layer is the primary pressure boundary for the microsphere meaning that it is the first physical barrier against the release of radioactive material in the coolant as is described in IAEA as the main safety features of the fuel. This three-layer system is also used to provide thermo-mechanical strength to the fuel. In the HTGR reactor, there are billions of TRISO-coated particles in a graphite matrix in the form of either small cylinders, called compacts, or tennis ball-sized spheres, called pebbles[1].

## Proliferation Resistance (PR) analysis of Pebble Bed fuels:

### General Information about PR

To begin with, in order to analyze the Proliferation Resistance (PR), certain physical quantities of the energy system need to be considered. These include the initial enrichment of Uranium, the burn up (which in HTGR-10 case can be up to 90 GW-day per metric ton of Uranium) neutron flux, the initial mass of fissile, fertile material inside the core, and other quantities associated to neutronics are needed.[5, 10, 11].

The PR of the fuel can be categorized into two sections: intrinsic and extrinsic. Intrinsic

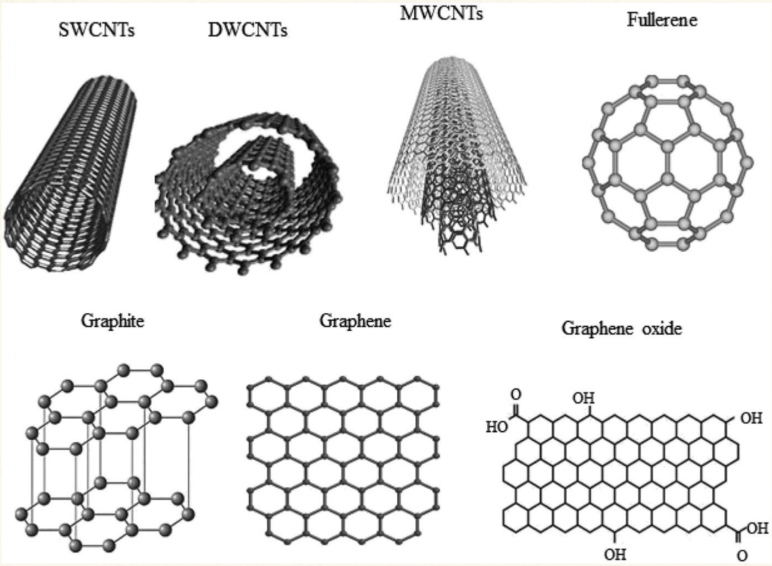



Fig. 4: Graphene is an atomic-scale hexagonal lattice made of carbon atoms [8].

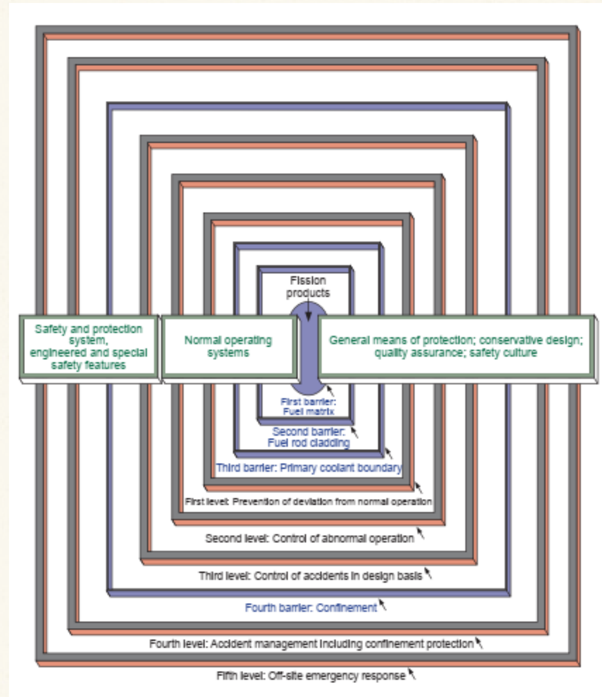



Fig. 5: Physical Barriers against release of radioactive material[9]. Permission is granted by IAEA.

means that the system itself has some characteristics that impose the PR, while the extrinsic resistance means that there are some external bodies (Auxiliary systems) which impose this resistance [12].

The PR laws need to be updated over time. The reason is that the analysis of PR is currently based on experience gained from operating LWRs. However, with the specific and new features of GenIV reactors, there is a need for a new approach. Additionally, there is a wealth of data available for Light Water Reactors (LWRs) from both commercial and research reactors in various countries. However, there is a limited database for Generation IV reactors, which is still being developed over time. One of the major challenges faced by analysts is the lack of data on realistic modeling and fuel burnup simulations of PBRs. This makes it difficult to evaluate the Special Nuclear Material (SNM) content of the core fuel and spent fuel. Care must be taken to ensure the accuracy of PR analysis due to the potential impact of uncertainties on calculations, such as reactor flux and other related factors. The assessment of SNM content is a fundamental pillar of a comprehensive safeguard system. Special Nuclear Material (SNM) is defined by Title I of the Atomic Energy Act of 1954 as Plutonium, Uranium-233, or Uranium enriched in isotopes Uranium-233 or Uranium-235. Additionally, the Nuclear Regulatory Commission (NRC) has the authority to determine any other material that falls under the SNM category. This definition maybe used in all countries or may be subjected on some changes, yet the important key is to consider the importance of SNM in Gen IV reactors that have different production and consumption rate.

## Specific Analysis of PR in PBR

Two different methods can be used to assess the PR of PBR fuels. The first method is the Proliferation Resistance and Evaluation Tool for Observed Risk (PRAETOR) code [13], a computer code developed to accurately analyze the proliferation resistance of nuclear installations. PR must be applied to all potential radioactive sources, particularly fissionable sources that can be physical, installations, or procedures. This includes the Nuclear Power Plant itself, with a focus on fuel assemblies. This code has the advantage of having an excellent decision analysis methodology called Multi Attribute Utility Analysis (MAUA), which is the main structure of the code. The code as other nuclear codes is established in Fortran 90 programming language [13].

PRAETOR uses 68 attributes both intrinsic and extrinsic as input (attributes) to evaluate the overall PR. One of the major disadvantages of these method is that the code is not able to differentiate between Uranium and Plutonium -based fuels. This lack of distinguishing ability can cause a severe problem since, the fission products of uranium and plutonium fuel, along with their energy and range are totally different, that means that their radioactivity of the fission product is also different. This distinction is important for us in PR analysis[14]. A separate method for PR analysis needs to be developed specifically for plutonium-based spheres, this method will alter the uranium-based fuel with Pu-based fuel according to physical quantities such as: 1-Spontaneous fission (SF), 2-Heat load, 3-Radiation load, 4- Rossi- α. The analysis of plutonium fuels in PR must be conducted meticulously. The presence of Pu can complicate the analysis of fuel in PR due to its higher probability of spontaneous fission. For instance, Pu-239 has a very high SF probability (100 SF/s) at critical mass. In general, presence of fissile material with capability of SF will make the PR analysis complicated. SF is very important when spent fuel is analyzed.

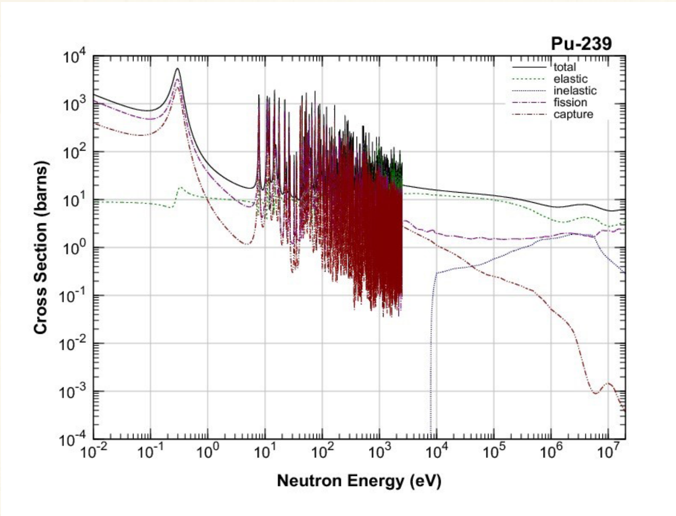



Fig. 6: Pu-239 Cross section [15].

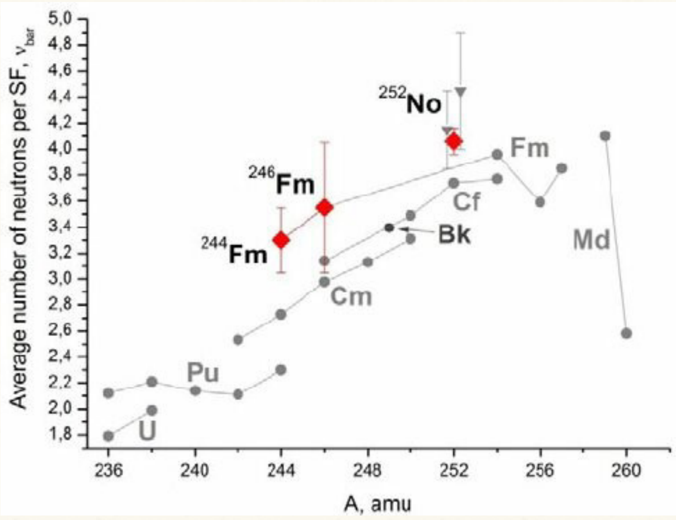



Fig. 7: Average number of neutrons per fission as a function of the atomic number A[16].

### Method 1
### Proliferation Resistance Analysis and Evaluation Tool for Observed Risk (PRAETOR)

In PRAETOR the PR is done using three tiers relying on the MAUA methodology. The MAUA (Multi Attribute Utility Analysis) methodology is a well-established decision-analysis technique, wherein a utility value is used to represent the attractiveness of a particular route for SNM diversion or theft[17].

The Tier 1 structure of the code is consistent with 68 attributes that define the characteristics of SNM in a nuclear system. These attributes represent utility values ranging from 0 to 1 for 11 subgroups. In Tier 2, the eleven subgroups are combined into utility values (ranging from 0 to 1) for four stages of nuclear proliferation, with the three most significant stages are:

1. SNM diversion
2. Transportation
3. Transformation

After preparing Tiers 1 and 2 using 68 attributes, Tier 3 will calculate the overall PR metric value on a scale of 0 to 1. The final metric in Tier 3, known as the "Overall PR value," will also range from 0 to 1. The closer this value is to unity, the higher the PR of the nuclear system being studied. By conducting a thorough analysis of Tiers 1 and 2, designers and decision-makers can identify factors that can either weaken or strengthen the PR of the current system. This is one of the advantages of using the code. Additionally, the code has the capability to predict the PR of a new reactor design (not built yet) by analyzing the output of the PRAETOR code after completing Tiers 1, 2, and 3. This feature allows for the identification of scenarios with minimum PR or maximum fuel diversion, making it useful for licensing of new nuclear power plants.

### PRAETOR Code Usage Principal

In the PREATOR code, possible classification of the attributes of the code in intrinsic and extrinsic groups can be done. Furthermore, the code uses two functional formats (Linear Multiplicative) of MAUA function.

$$U(x_1,x_2,\ldots,x_n) = \Sigma_i^n\, k_i u_i(x_i)$$

Equation 2 (Linear)

$$1+KU(x_1,x_2,\ldots,x_n)=\Pi\,^n_{i=1}(1+K\,k_i u_i(x_i))$$

Equation 3 (Multiplicative)

Where U is overall utility value for a certain tier of all attributes (features) values xi, ui is utility functions that map the input attributes between 0 and 1. ki is a weighting factors for the each attribute , while K is a scaling parameter[13].

These two equations have unique characteristics and using them can yield varying outcomes. For example, Equation 2 is an additive functional form that is particularly useful if the analyst's goal is to identify a system with the best results against PR. However, this method heavily relies on the weighting factors (ki).

In the second method, known as the multiplicative form, extreme values of the utility function can be implied to make the result more noticeable, especially when a high proliferation resistance is provided by single attributes. The method has the disadvantage of being less sensitive to changes in intermediate values. However, it can still function satisfactorily when comparing the proliferation resistance (PR) of special nuclear material (SNM) diversions from two nuclear systems.

### Use of other Codes in PRAETOR and Challenges

As mentioned previously, the PRAETOR code requires certain inputs (attributes) to initiate, and some of these inputs are derived from other codes, such as MCNP, to obtain physical quantities related to neutron physics. It is important to note that validation plays a crucial role in utilizing the results obtained from these codes. MCNP simulations provide a variety of intrinsic attributes of the PRAETOR code, including radiation dose rates, heating rates,

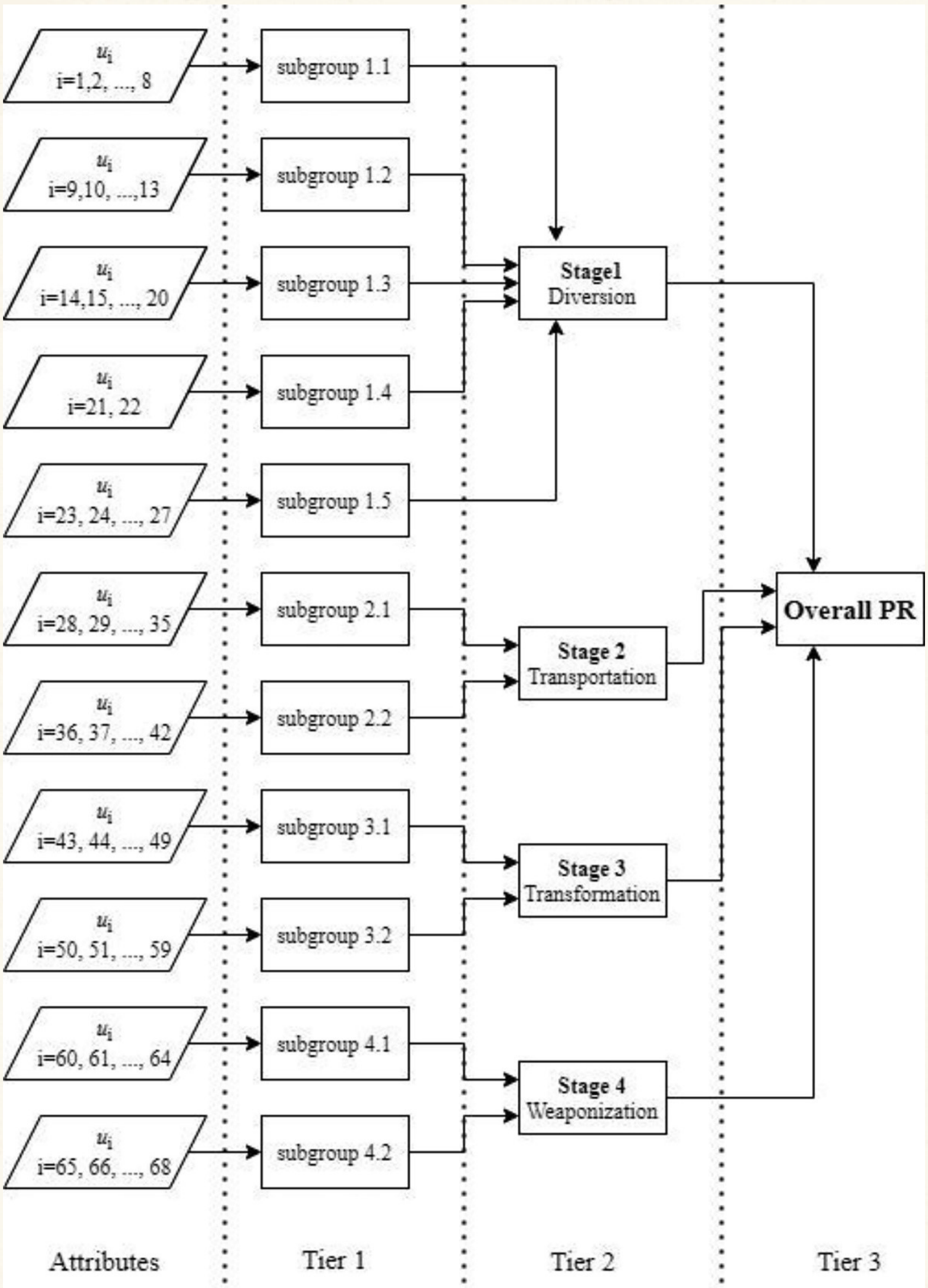



Fig. 8: Proliferation resistance evaluation scheme of PRAETOR with four stages of SNM diversion, transportation, transformation[12].

and shielding thickness. Additionally, MCNP is used to assess fuel burnup. For this evaluation, a body-centered cubic (BCC) structure with reflective boundaries has been used, which contains two identical fuel pebbles. Also, in burnup calculations, various factors are important. Among these factors, the initial enrichment of the fuel has a high sensitivity in PR analysis. As shown in Figure 9, the enrichment of U-235 will affect the $k_{eff}$, which is the neutron multiplication factor.

For extrinsic attributes, some will be determined by the state's proliferation characteristics, such as the availability of space for modifications, the number of people available for modifications, the number of export-controlled equipment, the number of workers, the size of the host country, the number of declared nuclear facilities, the presence of an additional protocol in force, and the facility size. Additionally, there are some extrinsic attributes that can be influenced by conservatism, meaning that these values can be set from the lowest to the highest possible in order to achieve the lowest PR. For example, uncertainties in accounting measurements, frequency of measurements, probability of detection, probability of detection by process monitoring, containment and surveillance of nuclear material, and many others [12].

### Uncertainties Associated in PRAETOR

There are two types of equations: linear and multiplicative. In the Linear method, the outcome strongly depends on the weighting factor ki. This can affect the analysis in such a way that the importance of utility can differ based on ki when the utility is a unit (1). This effect can be classified as user preference, which is one of the key and salient factors in every system code, regardless of the type. Therefore, the knowledge level and intentions of the person using the code are very important. It is suggested to always seek advice from an expert to ensure that the results are rational. In general, since nuclear technology is quite sophisticated, especially in the quantities related to the design and safety of nuclear power plants (NPP) which PR is one of the factors, therefore errors must be quantified and bounded. Based on this fact, it is suggested to investigate methodologies for addressing uncertainty in order to achieve this goal [18].

### Conservative Approximation in PRAETOR code

In both extrinsic and intrinsic attributes, conservatism can be employed to achieve the minimum PR. However, it is important to note that the use of conservatism in the input of the code does not always result in conservatism as an output. This fact is also considered in other aspects of nuclear system design. For instance, the decay heat calculation base of Appendix K of 10 CFR 50 states that a 20% increase in decay heat must be applied for the evaluation of the Emergency Core Cooling System (ECCS) (1.2 of the ANSI standard curve). This assumption will, of course, affect the calculation, leading to a more robust design of ECCS. However, in the case of Natural

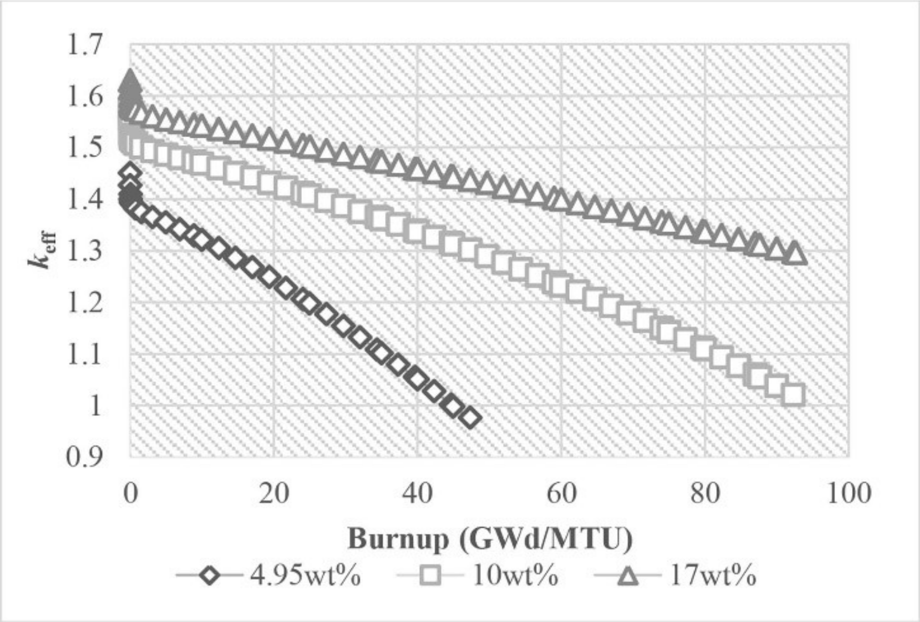



Fig. 9: Neutron multiplication factor vs fuel burnup for three initial U-235 enrichments [12].

Circulation, it can mislead the analyst. This means that in two equations, the weighting factor ki can play a role in determining the minimum or maximum PR. However, other aspects of this choice must be studied to ensure that it does not have unintended effects on the system. Furthermore, some of the PRAETOR extrinsic attributes have been selected using a conservative approach to minimize the potential risk. These factors are discussed in the extrinsic attributes section.

## Conclusion

In the PR assessment of each nuclear energy system, with a focus on fuel, it is important to acknowledge that the results may contain errors. One of the objectives should be to minimize these errors to an acceptable level. Also, since the PR of fuels is based on LWR fuels, there is a pressing need to update the analysis method. The first reason is that the new designs for the fuels can have different characteristics, making the LWR-based analysis inadequate. The second reason is the lack of data for new fuel types. It is worth mentioning that in order to obtain a more accurate evaluation of PR, it is necessary to acquire realistic physical quantities that reflect the need for more realistic tests in order to obtain the required measurements.

In the new design, attributes such as intrinsic and extrinsic factors can have varying effects on PR. PR can also be conducted on spent fuel, which is an important aspect of the PR analysis. In spent fuel especially the presence of materials capable of spontaneous fission must be taken seriously. These materials can introduce significant uncertainty and complexity into the analysis.

One of the famous methods that can be applied in PR is the PRAETOR code, which is based on the MAUA methodology. In this code, the user can select two equations based on their desired study goals and objectives. Each one of these equations has its own unique characteristics, making it vital to use both of them for comprehensive PR analysis.

## Acknowledgement

This paper is dedicated to my mother.

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