Proliferation resistances of Generation IV recycling facilities for nuclear fuel

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Abstract

The effects of global warming raise demands for reduced CO2 emissions, whereas at the same time the world's need for energy increases. With the aim to resolve some of the difficulties facing today's nuclear power, striving for safety, sustainability and waste minimization, a new generation of nuclear energy systems is being pursued: Generation IV.

New reactor concepts and new nuclear facilities should be at least as resistant to diversion of nuclear material for weapons production, as were the previous ones. However, the emerging generation of nuclear power will give rise to new challenges to the international safeguards community, due to new and increased flows of nuclear material in the nuclear fuel cycle. Before a wide implementation of Generation IV nuclear power facilities takes place, there lies still an opportunity to formulate safeguards requirements for the next generation of nuclear energy systems. In this context, this thesis constitutes one contribution to the global efforts to make future nuclear energy systems increasingly resistant to nuclear material diversion attempts.

This thesis comprises three papers, all of which concern safeguards and proliferation resistance in Generation IV nuclear energy systems and especially recycling facilities:

In Paper I, proliferation resistances of three fuel cycles, comprising different reprocessing techniques, are investigated. The results highlight the importance of making group actinide extraction techniques commercial, due to the inherently less vulnerable isotopic and radiological properties of the materials in such processes.

Paper II covers the schematic design and safeguards instrumentation of a Generation IV recycling facility. The identification of the safeguards needs of planned facilities can act as a guide towards the development of new instrumentation suitable for Generation IV nuclear energy systems.

Finally, Paper III describes a mode of procedure for assessing proliferation resistance of a recycling facility for fast reactor fuel. The assessments may be used, as in this case, as an aid to maintain or increase the inherent proliferation resistance when performing facility design changes and upgrades.

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I) Åberg Lindell, M., Grape, S., Håkansson, A., Jacobsson Svärd, S. (2013)
Assessment of proliferation resistances of aqueous reprocessing techniques using the TOPS methodology.
Annals of Nuclear Energy, **62**, 390-397.

My contribution: I specified the facility under study, chose and modified the assessment methodology, and performed the analysis. I was the main author of the paper.

II) Åberg Lindell, M., Grape, S., Håkansson, A., Jacobsson Svärd, S. (2013)
Schematic design and safeguards instrumentation of a Gen IV fuel recycling facility.
35th ESARDA Annual Meeting, 27-30 May 2013, Bruges, Belgium.

My contribution: I specified the facility under study, identified safeguards needs, and suggested measurement techniques. I was the main author of the paper.

III) Åberg Lindell, M., Grape, S., Håkansson, A., Jacobsson Svärd, S. (2013)
Proliferation resistance assessments during the design phase of a fuel recycling facility as a means of reducing proliferation risks.
GLOBAL 2013: International Nuclear Fuel Cycle Conference, 29 September - 3 October 2013, Salt Lake City, USA. (Peer-reviewed conference paper.)

My contribution: I specified the facility under study, chose and modified the combination of assessment methodologies, and provided illustrative examples of analyses. I was the main author of the paper.

Contents

1 Introduction

One of the most important global responsibilities of our time is to accommodate the need for a secure and sustainable supply of energy. The effects of global warming raise demands for reduced carbon dioxide emissions, whereas at the same time the energy demands increase. Especially the demand for electricity will grow substantially, underpinned by rising living standards in China, India and the Middle East [1].

Nuclear power is often viewed upon as an important part of the future energy mix, much due to its low emissions of carbon dioxide and the very high energy density of the nuclear fuel. However, nuclear power faces challenges of its own. In a long perspective, nuclear power is not sustainable if conducted as today, due to the finite uranium resources [2]. Furthermore, the management of nuclear waste remains in most countries today an unresolved issue. Another concern is the possibility to produce nuclear weapons from uranium or plutonium, which are elements occurring in the nuclear fuel cycle. It must therefore be assured to the international community, via the international control system known as nuclear safeguards, that all fissile material in nuclear power programs remains in peaceful use. With the aim to resolve some of the difficulties facing today's nuclear power, striving for sustainability, waste minimization and proliferation resistance, a new generation of nuclear energy systems is being pursued: Generation IV, which is also the context of this thesis.

In order to promote efficient use of the world's uranium resources, the development of advanced fuel recycling techniques is a crucial part of Generation IV. Deployment of advanced fuel cycles, where the fuel is repeatedly recycled in fast reactors, could significantly extend the long-term availability of nuclear power from hundreds to thousands of years [2]. Thus, a future sustainable implementation of nuclear power will, with little doubt, involve extensive recycling. Facilities for advanced recycling of nuclear fuel are the main focus of this thesis.

The degree of safety at a nuclear facility improves more or less continuously with the introduction of new technologies and stricter safety regulations. The same should ideally go for nuclear safeguards. New reactor concepts and new nuclear facilities should be at least as resistant to diversion of nuclear material, as were the previous ones, and accordingly, the emerging generation of nuclear power systems will give rise to new challenges to the international safeguards community, due to new and increased flows of nuclear material in the nuclear fuel cycle. Before a wide implementation of Generation IV nuclear power systems takes place, there lies still an opportunity to formulate safeguards requirements for their application. In this context, this thesis constitutes one contribution to the global efforts to make future nuclear energy systems increasingly resistant to nuclear material diversion attempts.

This thesis comprises three papers, all of which concern proliferation resistance in Generation IV nuclear energy systems. In Paper I, proliferation resistances of three fuel cycles, comprising different reprocessing techniques, are investigated. Paper II covers the schematic design and instrumentation of a Generation IV recycling facility. Finally, Paper III describes a mode of procedure for assessing proliferation resistance of a recycling facility for fast reactor fuel.

The nuclear material considered in all three papers is envisioned to be irradiated in lead-cooled fast reactors and recycled. In Paper I, a hypothetical 100 MW_e lead-cooled fast reactor was examined, whereas the small-scale, 0.5 MW_{th} Swedish lead-cooled fast reactor design Electra [3] was used as a reference in Papers II and III. Various types of fuel are possible to use in a lead-cooled fast reactor, including oxide fuels, which are the most viable option for implementation in the near future, and nitrides, which is the fuel type intended for the Electra reactor. Oxide and nitride fuels, with and without inclusion of minor actinides in the fuel, are discussed in Papers I-III.

The research presented in this thesis has been performed in the framework of the Swedish R&D program GENIUS, funded by the Swedish Research Council, which addresses generic aspects of Generation IV, of which safeguards is one. The choice of investigating lead-cooled reactor systems with aqueous reprocessing has been made for the research to align with the goals set by a proposed Swedish national program, in part based on the GENIUS program.

The outline of this thesis is the following: Chapter 2 provides some background information on Generation IV systems and nuclear fuel cycle options. In chapter 3, a general overview of the international safeguards regime is provided. Chapter 4.1 presents some possible challenges associated with safeguarding future nuclear energy systems, and in chapter 4.2 the work in Paper II, covering the design and safeguards instrumentation of an envisioned Generation IV recycling facility, is summarized. Chapter 5 introduces the concept of proliferation resistance and some of the methodologies used to evaluate it, with chapter 5.2 comprising summaries of the proliferation resistance analyses performed in Papers I and III. Chapters 6-7 contain conclusions drawn from Papers I-III, and an outlook on future research, respectively.

2 Generation IV nuclear energy systems

2.1 Reactor technologies and goals

As described above, this thesis focuses on the non-proliferation properties of so-called Generation IV (Gen IV) systems, which cover an emerging set of nuclear power technologies. The system aspect of Gen IV is strong and comprises reactors, recycling of used nuclear fuel and final waste storage. There are currently a number of promising reactor concepts under development to address various issues of concern of the current fleet of reactors. An international collaboration known as the Generation IV International Forum (GIF) has selected the following six reactor concepts to represent Generation IV, see table 1.

The Gen IV technology is issued with eight common goals to strive for. The goals are divided into four categories, and are listed in table 2. The scope of the research presented in this thesis is connected to the proliferation resistance

Generation IV System	Acronym
Gas-Cooled Fast Reactor System	GFR
Lead-Cooled Fast Reactor System	LFR
Molten Salt Reactor System	MSR
Sodium-Cooled Fast Reactor System	SFR
Supercritical-Water-Cooled Reactor System	SCWR
Very-High-Temperature Reactor System	VHTR

Table 1: The six selected Generation IV reactor systems. From [4].

goal, which will be discussed further in chapter 5. However, all goals should be fulfilled in order to ensure that nuclear power will pose a safe, reliable and sustainable energy source for the future.

As a model for the analysis in the work summarized in this thesis, the lead-cooled fast reactor (LFR) was chosen for reasons outlined in chapter 1. An LFR utilizes either pure lead or a lead-bismuth eutectic (Pb-Bi) as coolant medium. Since lead does not moderate neutrons considerably, the neutron spectrum in an LFR is fast, thus enabling fissions of actinides not fissionable in a thermal reactor, e.g. the minor actinides (mainly Np, Am and Cm), which may otherwise be problematic from a long-term storage point of view. Accordingly, fast reactors can form the basis of an advanced fuel cycle, as discussed in chapter 2.2. Furthermore, lead has a number of properties that contribute to the inherent safety of an LFR e.g. the high boiling point (1745 °C) and the high capability of convective cooling. In the case of a severe accident, advantages associated with using lead coolant include the capability to act as an efficient radiation shield, and the tendency to mix with molten fuel which reduces the risk of re-criticality.

2.2 Nuclear fuel cycles

Today's Generation II nuclear fuel cycle options govern the fate of spent nuclear fuel after it has been discharged from a reactor. In fact, 96% of the original uranium remains intact in the fuel, albeit with a lower share of the fissile isotope ^{235}U than in the fresh fuel. Furthermore, Pu is created during reactor operation, and will constitute about 1% of spent light-water reactor (LWR) fuel. The remaining 3% of the initial uranium has now been converted to fission products and minor actinides [5], which is the only fraction that cannot be reused in fuel for LWRs. Thus, with 97% of the material in discharged fuel reusable in LWRs, 'spent fuel' is a misleading term. Therefore, in this text, the term 'used fuel' is instead adopted to describe fuel that has been removed from a reactor.

There are three main options for the back-end of a nuclear fuel cycle; the *open*, *closed*, and *advanced closed* fuel cycles. The advanced closed fuel cycle, which forms the basis of the work presented here, will be discussed in some detail below.

Sustainability	1. Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production. 2. Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment.
Economics	1. Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources. 2. Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.
Safety and Reliability	1. Generation IV nuclear energy systems operations will excel in safety and reliability. 2. Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage. 3. Generation IV nuclear energy systems will eliminate the need for offsite emergency response.
Proliferation Resistance and Physical Protection	1. Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

Table 2: The eight goals set for Generation IV systems by GIF. From [4].

The open, or once-through, fuel cycle implies the following: Uranium is mined, enriched to 3-5% in ^{235}U, and manufactured into fuel assemblies, which are loaded into a reactor. In the most dominant type of reactors of today; LWRs, the fuel is irradiated in the reactor for about five years. After that, the fissile content has decreased due to fissioning of U and Pu, and the fuel is treated as waste and sent to storage before being sent to a permanent disposal in e.g. a geological repository. However, as mentioned above, there is still a significant amount of extractable energy in terms of heavy nuclei in the discarded fuel assembly.

Some countries have chosen to recycle the used fuel in order to recover U and Pu for repeated use in light-water reactors, with the main fabrication capacities for recycled fuel located in France, India and the UK [6]. In the separation process, Pu and U are separated from the fission products using a solvent extraction technique called Purex. For more information on the chemical processing, see [7]. The new fuel, which encompasses the recycled material, is called Mixed OXide fuel (MOX). Currently, about 30 LWRs worldwide use MOX fuel, and new MOX fabrication plants are currently being constructed in Japan, Russia, UK and USA [6].

With fast reactor technologies, a new fuel cycle option emerges; the advanced closed fuel cycle. One of the advantages of fast reactors is their ability to burn all long-lived actinides, such as Pu from used nuclear fuel. The long-lived minor actinides can also be incinerated in fast reactors, which is an advantage from a waste management perspective. Thus, by launching fast reactors, one may adopt a closed fuel cycle, where actinides are separated and reused multiple times, see figure 1. This option requires less uranium mining and gives

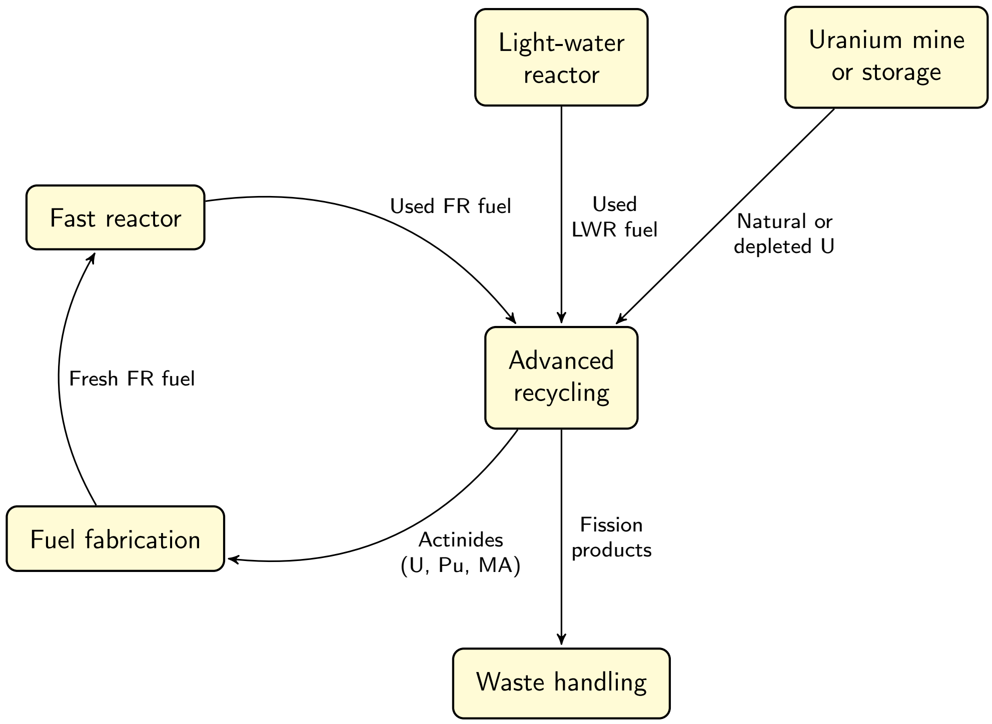

Figure 1: Some advanced recycling techniques allow for repeated recycling of fuel for fast reactors, with all actinides extracted as a group.

rise to smaller amounts of long-lived waste than the classical closed fuel cycle. There will still be highly radioactive waste, mainly consisting of relatively short-lived fission products, which must be put in a final repository, however, for a shorter period of time than waste from the other fuel cycle options; in approximately 1000 years instead of in the order of 100,000 years. In addition, the required repository space can be minimized. The resulting waste will also be less radiotoxic after the removal of actinides and it cannot be used for nuclear weapons production.

Several advanced recycling techniques are under development, one of which is called Ganex (Group actinide extraction). In the Ganex process, uranium, plutonium and minor actinides are extracted together to become fuel in Generation IV fast neutron reactors. Since there is no intermediate step containing pure Pu, which would be weapons useable, and since the radiation hazard associated with minor actinides may deter a diverter, Ganex has the potential to enhance proliferation resistance [8]. The Ganex process is a long-term goal which has, so far, proven to be efficient at the laboratory scale on kilograms of spent nuclear fuel [9].

In the papers presented in this thesis, different options for closed fuel cycles have been examined: Paper I discusses three different recycling options; Purex (for U and Pu recycling only), Ganex (where all actinides are extracted as a group), and combination of Purex, Diamex and Sanex (Purex with subsequent separation of minor actinides and lanthanides, which enables actinide recycling). Paper II describes two facility operation phases, where different recycling techniques would be implemented. It is assumed that one may need to use Purex initially, to obtain enough Pu for starting a new fast reactor. Thereafter the reactor would be self-sufficient in Pu production, and Ganex may instead be used. In Paper III, Purex is the assumed recycling process. Paper I accounts for a system with reactor, reprocessing and fuel fabrication facilities, whereas Papers II and III only deal with the recycling part of the fuel cycle.

3 Nuclear safeguards

Obviously, the concept of non-proliferation of nuclear materials has a particular significance in this thesis. To fight proliferation, the use of nuclear safeguards, together with physical protection and technologies that obstruct diversion of nuclear materials, is central. Below, a brief presentation of nuclear safeguards is made while physical protection is omitted because it lies outside the scope of this work. The notion of proliferation resistance is, however, covered in some length in chapter 5.

3.1 Legal framework

A vast majority of the states in the world have pledged not to misuse their nuclear energy programs for the purpose of producing nuclear weapons. In this context, nuclear safeguards is the notation for framework of all activities performed by the International Atomic Energy Agency (IAEA), which is directly subordinated the Security Council of the United Nations, to verify that a State lives up to its commitments according to international treaties.

In 1968, the most important and successful treaty for nuclear safeguards, the

Non-Proliferation Treaty (NPT) was introduced, with the aim to:

1. prevent the spread of nuclear weapons and weapons technology,
2. foster the peaceful uses of nuclear energy, and
3. further the goal of disarmament.

The treaty forbids nuclear-weapon states to transfer nuclear weapons, directly or indirectly, to non-nuclear-weapon states and/or to supply help in acquiring them. The latter part in turn undertake not to receive any nuclear explosives nor assistance in the manufacturing of nuclear weapons. Each non-nuclear-weapon state that signs the NPT undertakes also to accept nuclear safeguards under the IAEA safeguards system, with control and supervision of the signatory parties as a result. The NPT is, nonetheless, a voluntary agreement based on every State's will to meet its obligations. Currently, 190 States have signed the treaty, making it the most ratified arms control agreement in history. The only non-signatory states of NPT are India, Pakistan and Israel, and in addition North Korea withdrew from the treaty in 2003 [10]. Additional voluntary agreements that give the IAEA extended access and inspection rights, are widely implemented, such as the Additional Protocol (AP). There are also voluntary agreements for nuclear weapon states, enabling the application of safeguards, although not on a comprehensive scale [11].

For more information about the IAEA safeguards legal framework, and texts of the legal treaties and agreements, the reader is referred to the resources posted on the IAEA website [12].

3.2 Materials accountancy and inspections

Accountancy of nuclear materials is the foundation for the IAEA's control of signatory States' compliance with the NPT agreement. All quantities of nuclear material present in the State's fuel cycle must be established and book-kept on a regular basis. The IAEA performs inspections to verify that the records are correct, so that nuclear material is not diverted to weapons production.

A Significant Quantity (SQ) is "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded" [11]. SQ is a central concept in IAEA safeguards. The mass of 1 SQ varies depending on the type of material, see table 3.

The IAEA must be able to draw the conclusion that there has been no diversion of 1 SQ or more of nuclear material with a certain frequency that fulfills the IAEA's timeliness detection goals, see table 4, which have been set up depending on the specific expected time spans required for conversion of various nuclear materials to weapons-usable materials. The timeliness goal decides the frequency of the periodic activities necessary to perform, for the IAEA to be able to draw the conclusion that there has been no diversion of 1 SQ or more within the time span required to make a weapon of that particular material.

Material	Significant Quantity
Pu	8 kg
High-enriched U (^{235}U $\geq$ 20%)	25 kg ^{235}U
Low-enriched U (^{235}U $<$ 20%)	75 kg ^{235}U

Table 3: Significant quantities of the most important weapons-usable nuclear materials [11].

Nuclear material that can be used for the manufacture of weapons without transmutation or further enrichment, e.g. Pu in fuel assemblies, is called direct use material. It is associated with relatively short timeliness goals, in the order of months. Indirect use material, e.g. low-enriched uranium, must be further processed before weapons production is possible, and therefore has longer timeliness goals [11].

Material	Timeliness goal
Unirradiated direct use material	1 month
Irradiated direct use material	3 months
Indirect use material	1 year

Table 4: Timeliness goals as stated by the IAEA [11].

Different Pu isotopes have different properties, whereof the most attractive, fissile, isotopes are ^{239}Pu and ^{241}Pu. High levels of neutron emission and decay heat make ^{238}Pu, ^{240}Pu and ^{242}Pu difficult to use for weapons production. It is worth noting that, according to IAEA's conservative definitions, all plutonium isotopes are considered equal in terms of significant quantities and timeliness detection goals. Thus, Pu with isotopic compositions of poor quality does not generally reduce the need for safeguards, even though the actual material attractiveness may be reduced.

As an aid in the accountancy structure, a nuclear facility may be divided into several different Material Balance Areas (MBAs). Within each MBA, records of the quantities of nuclear material are maintained and updated to account for inventory changes. Changes of the chemical or physical form of nuclear material is also recorded, as are transfers of material into and out of MBAs. The size of an MBA should be related to the accuracy with which the material balance can be established. Flows and inventories of material are measured at Key Measurement Points (KMP), located at least at the inputs, outputs and storages in an MBA [11].

Paper II of this thesis presents a small-scale recycling facility divided into MBAs, with proposed KMPs. The assessment methodology presented in Paper III is partly based on the division of a recycling facility into the MBAs suggested in Paper II.

3.3 Techniques and equipment

A wide range of measuring techniques and equipment is available to the safeguards inspectors, to help them verify the completeness and correctness of a State's accountancy reports. A comprehensive overview of the techniques and equipment is provided in the IAEA document "Safeguards Techniques and Equipment" [13].

The detection of missing items (gross defects) can be reached through counting of items, and measurements of their attributes using non-destructive analysis (NDA) techniques. More than 100 NDA systems are used by the IAEA, out of which the most widely used are based on the detection of radiation such as neutrons or gamma rays [13].

For detection of the absence of fractions of nuclear material from an item (partial defects), the use of weighing of items and NDA measurements such as neutron counting or gamma ray spectrometry may be involved [13].

Very small material diversions (bias defects), which may be conducted over a protracted time, require sample taking and subsequent destructive analysis (DA) for detection [13]. Elemental and isotopic analyses of many kinds are performed at qualified laboratories located in 20 IAEA Member States [14].

Furthermore, containment and surveillance (C/S) techniques are applied to complement measurements, by monitoring access to the material and assuring that it follows predetermined routes, thus maintaining continuity of knowledge of the whereabouts of the nuclear material. Seals and optical surveillance are the most commonly used C/S measures [13].

The techniques used by the IAEA should ideally be cost-efficient as well as non-intrusive to the regular operations of the nuclear facility. Unattended and remote monitoring techniques, where data from safeguards systems is transmitted off-site to the IAEA headquarters, permit reduced inspection efforts. The usage of remote monitoring increases continuously, and it is expected to double within the next five years [13].

Paper II in this thesis points towards difficulties in safeguarding an envisioned recycling facility and discusses some prerequisites for suitable instrumentation.

4 Safeguards in Generation IV systems

4.1 Safeguards challenges for emerging nuclear power systems

Realization of new groundbreaking Gen IV technologies in the nuclear power systems will inevitably require reassessment of the existing safeguards requirements. Some of the safeguards challenges facing the emerging nuclear power systems are discussed below.

As an increasing number of countries launch nuclear power programs, larger quantities of nuclear material will be present in the system over all. Furthermore, the knowledge and experience of nuclear technology will spread. According to the World Nuclear Association, more than 45 countries are currently actively considering embarking upon nuclear power programs [15]. Accordingly, an increased need for safeguards inspections can be expected, in order to cover for the possible expansion in nuclear power. Assuming the resources to be fairly constant, the safeguards regime may also need to become more efficient and cost-effective in order to cope with the increased work load, e.g. by extending the use of short-notice random inspections and unattended monitoring.

With a comprehensive employment of Gen IV and closed nuclear fuel cycles, transports and handling of nuclear material will increase, as will the needs for recycling, which is considered to be a sensitive technology in nuclear safeguards. As a part of the start-up phase of fast reactors, pure Pu may likely be used initially for fuelling the new reactors. This poses new challenges to the international safeguards regime. On the other hand, disarmament will be supported by the extended recycling capabilities, since Pu from the existing stockpile of nuclear weapons can be used to manufacture new fuel for power-producing reactors [6].

Classical aqueous reprocessing, where streams of pure Pu occur, is controversial, since the separated Pu may be used as a basis for weapons production. Additionally, bulk handling facilities, such as reprocessing or fuel fabrication facilities, are in general more demanding to safeguard than item handling facilities where ID numbering of the material may be applied.

Finally, one may note that isotopic compositions and types of fast reactor fuel generally differ from the traditionally used oxide fuels for light-water reactors. The same measuring equipment may not automatically be applicable to the new types of fuel, higher burn-up levels etc. It must therefore be ensured that there is safeguards equipment suited for measurements of all new fuel types, at all fuel cycle stages. Safeguarding Gen IV related activities may accordingly require extended efforts in the development and evaluations of safeguards instrumentation.

4.2 Safeguarding a small Generation IV recycling facility

The Electra Fuel Cycle Center (Electra FCC), which is the envisioned recycling facility presented in Paper II, is aimed to

1. provide the 0.5 MW_{th} Electra reactor with fuel by separating Pu from used LWR fuel using Purex (Phase I) and,
2. in due time, recycle the nitride fuel used in Electra using the Ganex process (Phase II).

In the paper, Phase I is emphasized, since it is considered to pose the largest risk to diversion of nuclear material, based on the comparison of different reprocessing techniques performed in Paper I.

The Electra FCC was divided into five material balance areas, such that detailed records of the material accounts could be kept in each part of the recycling process, see figure 2. It is likely that the IAEA would perceive Electra FCC as one

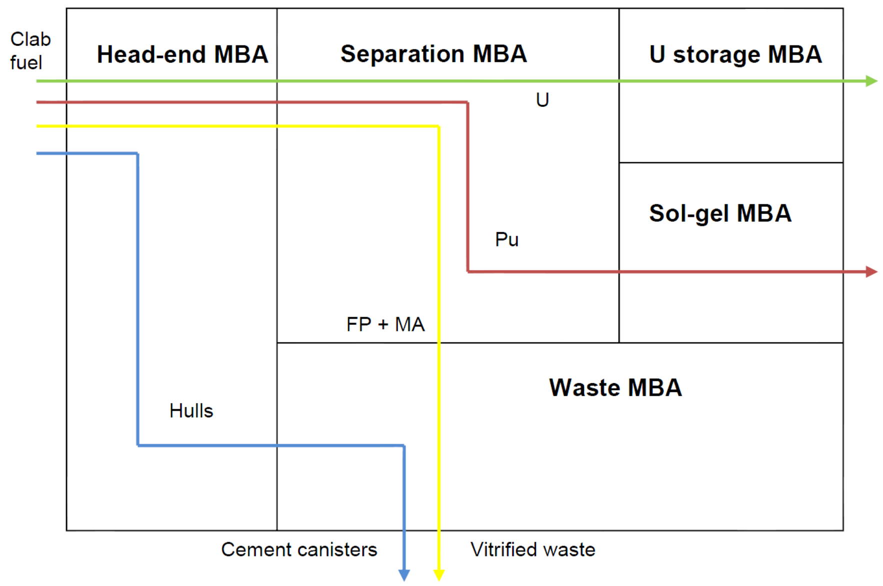

Figure 2: Schematic design of the recycling in Electra CC, Phase I. In the Head-end MBA, used fuel is received and dissolved as a preparation for the separation process. In the Sol-gel MBA, the solution containing separated Pu is manufactured into microspheres in a sol-gel microsphere pelletization process.

single MBA, due to its small size and throughput (approximately 7 kg of Pu per year of operation). However, the MBA distribution presented in Paper II also serves to resemble the approach for a large scale reprocessing plant which, due to its complexity, often requires several MBAs.

Key measurement points should be located within each MBA and at transfer points between different MBAs. Suggested KMPs for the sensitive ‘Head-end’ and ‘Separation’ MBAs are provided in Paper II, whereas the rest of the MBAs are investigated in less detail. The very small throughput assumed in the Electra FCC facility somewhat mitigates the difficulties that arise with undesirable properties of pure Pu. However, it is considered in the paper that, for a small recycling facility such as Electra FCC, some redundancy in the key measurement points is beneficial. Thus, the facility can be seen as a template for larger facilities with higher throughputs.

The KMPs required in Phase II of the facility’s operation are expected to remain in essentially the same locations as in Phase I. However, since the types of materials to measure will differ, the instrumentation for the KMPs should be revised to suit the materials in Phase II.

Today’s instrumentation standards will be sufficient to make Electra FCC fulfill the IAEA’s timeliness goals, and existing techniques such as gamma ray spectrometry, neutron coincidence counting and K-edge densitometry can readily be used in the facility. However, in a larger recycling facility which cannot rely on a small throughput to make it proliferation resistant, possible development of the instrumentation might be crucial.

A small scale facility such as Electra FCC will benefit not only research on Gen IV recycling techniques, but may also act as an aid in developing a safeguards approach for future large scale facilities, by adding novel measurement equipment and evaluating the system’s performance in detecting nuclear material. The low-throughput facility provides a unique environment for testing performances of new and existing safeguards equipment and data acquisition. This way, Safeguards By Design can be more easily implemented in full-size recycling facilities.

5 Proliferation resistance

A State in possession of nuclear facilities may be able to divert nuclear material such as U or Pu, or misuse a facility such that nuclear materials are produced, for subsequent weapons production. However, proliferation attempts can be obstructed if the nuclear facilities are designed to inherently withstand them. According to the IAEA, proliferation resistance is defined as “that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by States in order to acquire nuclear weapons or other nuclear explosive devices” [16]. Security threats posed by non-host-State actors, e.g. terrorist groups, are not included in this definition, and the means applied to impede such threats are commonly denoted as ‘physical protection’.

While one should not be led to believe that there is such a thing as a ‘proliferation proof’ facility, it is however possible to make diversion more difficult by increasing the time and cost needed for a State to complete a diversion attempt. For Gen IV systems to comply with the proliferation resistance goal set by the Generation IV International Forum, i.e. "Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials", proliferation resistance needs to be addressed when designing the new systems.

5.1 Assessment methodologies

To determine whether GIF's proliferation resistance goal is fulfilled or not, and to compare the viability of different fuel cycle options, one must assess proliferation resistances of different nuclear energy systems. There is a multitude of different methodologies developed for this purpose. Two of the established methodologies, TOPS and PR&PP, are briefly described in chapters 5.1.1 and 5.1.2 below. For the reader interested in other existing methodologies, papers on e.g. the INPRO [17] and SAPRA [18] methodologies are recommended.

5.1.1 TOPS

A task force established by the U.S. Department of Energy in 1999 developed the so-called TOPS methodology (Technological Opportunities To Increase The Proliferation Resistance Of Global Civilian Nuclear Power Systems) [19]. They identified a set of barriers impeding proliferation. An overview of the barriers, divided into three barrier categories, is provided in figure 3. Material and technical barriers are intrinsic, meaning that they concern inherent properties of a fuel cycle, its facilities and equipment. Material barriers represent inherent material qualities that describe to which extent the material is attractive to a proliferator, whereas the technical barriers relate to the intrinsic technical features of facilities, equipment and processes, which obstruct proliferators' access to materials and facilities. Institutional, or extrinsic, barriers, including safeguards and access control, form compensation for weaknesses in the former categories.

Effectiveness of the barriers can be assessed for different stages of the examined nuclear facility or nuclear fuel cycle, in this thesis denoted 'segments'. Higher, more effective, barriers require greater efforts to be overcome than lower, less effective, barriers. Classification of the effectiveness of the barriers can be semantic, ranging e.g. from 'insignificant' to 'very high', or numeric, with values ranging from e.g. 1 to 5. Barriers are not absolute, and do not always act independently, and the semantic alternative for classification may have an advantage in reflecting this. Numerical values may however be better suited for aggregation of values and comparison of results, as long as it is stressed by the analysts that the barrier strengths should not be seen as absolute values.

Various scenarios or proliferation threats can be evaluated using the TOPS methodology. A threat can e.g. include overt or covert diversion posed either by a State, or by a subnational group. For comprehensive comparison between the different nuclear facilities or nuclear fuel cycles, several threat contexts should be chosen for the TOPS analysis.

The TOPS methodology is described in more detail in Papers I and III, together with examples of performed analyses showing its application in practice.

5.1.2 PR&PP

The PR&PP methodology (Proliferation Resistance and Physical Protection) is a methodology developed for Gen IV systems by the Generation IV International Forum. It is based, much like TOPS, on the definition of a specific proliferation threat. The analysts assess the response of the examined facility or nuclear fuel cycle to the evaluated threat, by identifying potential targets such as materials that can be diverted and processes that can be misused, and all possible diversion paths, i.e. sequences of events leading to weapons production. After systematically defining targets and diversion paths, measures (somewhat similar in nature to the TOPS barriers) are estimated for each one of the different pathways, using the qualitative descriptors 'Very low', 'Low', 'Medium', 'High' and 'Very high' resistance.

The work flow of the methodology is illustrated in figure 4, and the proliferation resistance measures are listed in table 5. The level of detail of a PR&PP analysis may vary depending on the level of progress of the system design, and continuous assessments during the design phase of a new facility is encouraged. More information on the methodology can be found in ref. [20] as well as in Paper III of this thesis.

5.2 Practical application of assessment methodologies

In Paper I, the TOPS methodology was used to study inherent proliferation resistances of three different fuel recycling options, comprising different reprocessing technologies. TOPS was chosen since it is a readily available, well-established methodology with good documentation, and it is also straightforward to use. It does however rely on subjective assessments made by the analysts. The analysis in the paper covers proliferation threats where a technically advanced State performs covert diversion, of either abrupt or protracted kind. In order to be compatible with the threat investigated and the assumed facility design information, some of the barriers defined by the methodology were not applicable and therefore excluded from the analysis, as described more comprehensively in the paper.

The barriers were not considered equally significant to the proliferation resistance of the fuel cycle, and they were therefore weighted in proportion to their estimated importances. The barrier strengths were thereafter assessed for each facility segment, representing different forms of nuclear fuel, such as irradiated fuel assemblies and fresh fuel pellets. The metrics used were numerical

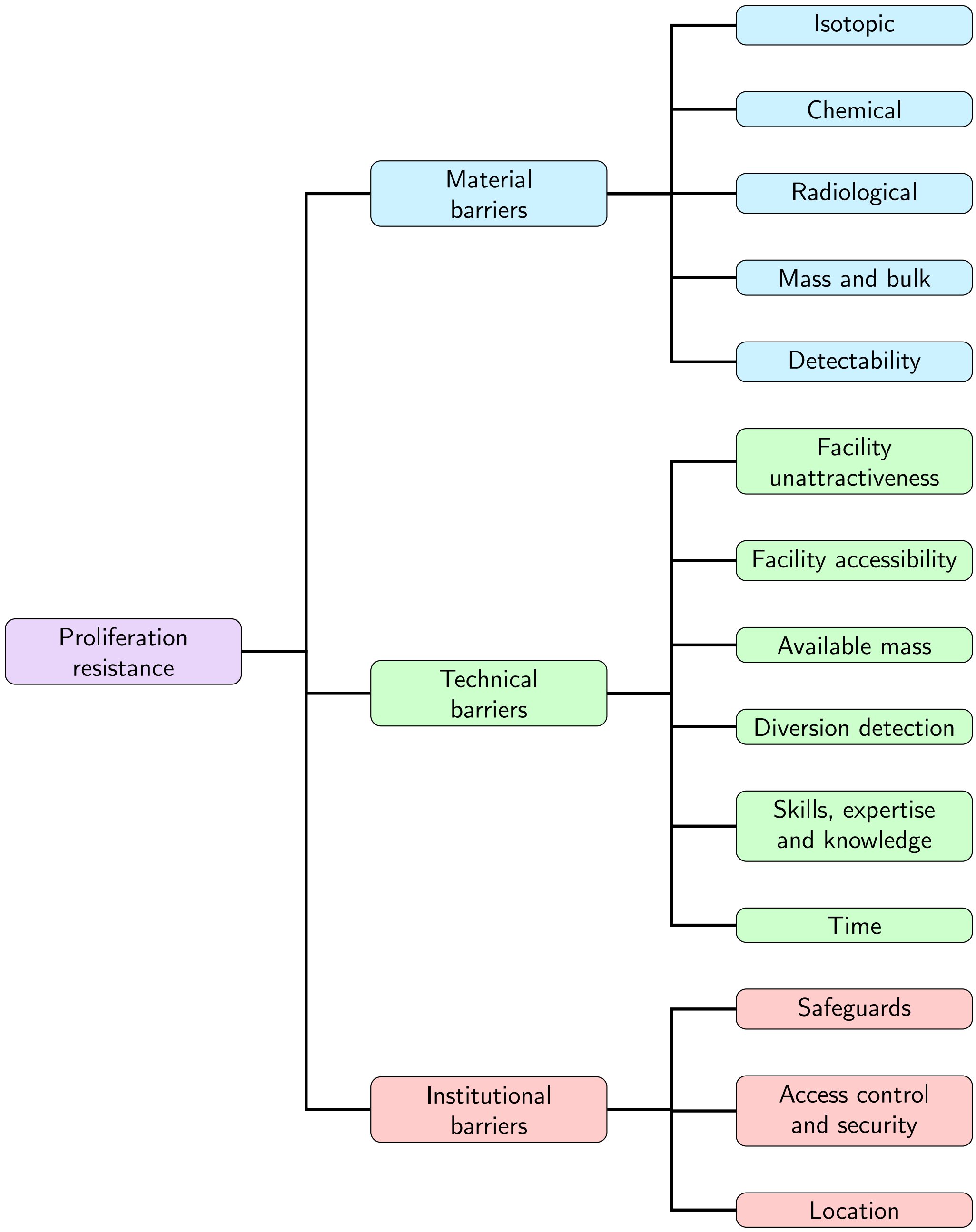

Figure 3: Graphical overview of the TOPS methodology illustrating how the total resistance (left) is estimated based on the barrier categories (center) and barriers (right).

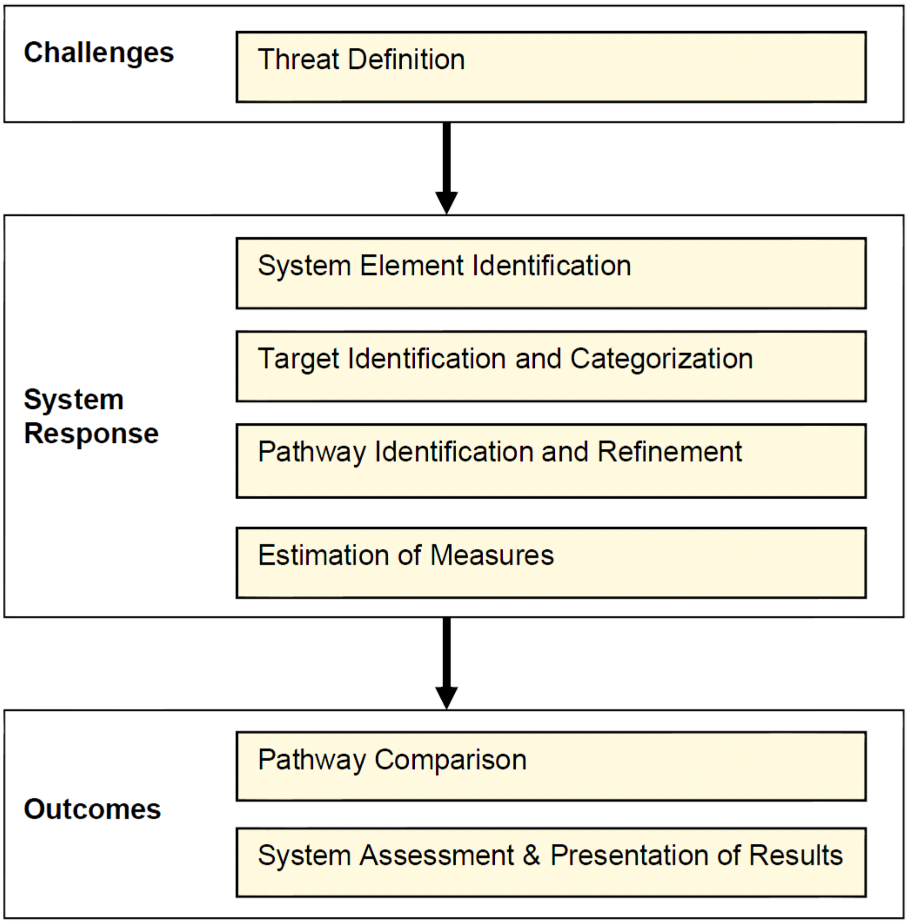

Figure 4: Framework for the PR&PP evaluation methodology. From [20].

values ranging from 1 (representing 'Very low resistance'), to 5 ('Very high resistance'). The results were aggregated such that the most vulnerable segment of each facility (reactor, reprocessing facility and fuel fabrication facility), considering material and technical barriers separately, was singled out to represent the weakest link of that facility. One of the conclusions drawn in the study, is that group actinide extraction is preferred to classical reprocessing due to less attractive material compositions in the system.

Paper III proposes a combination of the TOPS and PR&PP methodologies for iterative assessment of proliferation resistance throughout the lifetime of a recycling facility, as depicted in figure 5. The assessments may be used, as in this case, as an aid to maintain or increase the inherent proliferation resistance when performing facility design changes and upgrades. This way, Safeguards By Design can be supported from the initial planning stages of the facility to the end of its operation.

Proliferation Technical Difficulty	The inherent difficulty, arising from the need for technical sophistication and materials handling capabilities, required to overcome the multiple barriers to proliferation.
Proliferation Cost	The economic and staffing investment required to overcome the multiple technical barriers to proliferation, including the use of existing or new facilities.
Proliferation Time	The minimum time required to overcome the multiple barriers to proliferation (i.e., the total time planned by the Host State for the project).
Fissile Material Type	A categorization of material based on the degree to which its characteristics affect its utility for use in nuclear explosives.
Detection Probability	The cumulative probability of detecting a proliferation segment or pathway.
Detection Resource Efficiency	The efficiency in the use of staffing, equipment, and funding to apply international safeguards to the nuclear energy system.

Table 5: The proliferation measures used in the PR&PP methodology. From [20].

In the paper, a partial analysis was performed, where a limited number of diversion paths were identified and studied. This should be seen as an exemplification of what the first iteration step of an analysis might look like when performed using the combined methodology. Again, the chosen threat was a host State attempting to covertly divert nuclear material. Thus, the physical protection branch of the PR&PP methodology was not considered.

The role of TOPS in the combined methodology is to, as in Paper I, identify the parts of the facility most vulnerable to diversion. The obtained results may be used by the analysts as an indication of the areas where efforts to identify diversion pathways are the most crucial. TOPS also appears straightforward to use even when the facility design is primitive. Next, PR&PP is used to obtain more qualitative assessments of proliferation resistances of several identified pathways. PR&PP was chosen to be part of the iterative procedure in Paper III because it is extensive, well established and believed to complement TOPS well with its slightly different approach. The two analyses together are in Paper III suggested to be used as a guide towards a refined facility design, which in turn can be subject to analysis in the following iteration. As the number of iterations increases, the facility design will become better defined, and the proliferation resistance assessments increasingly detailed.

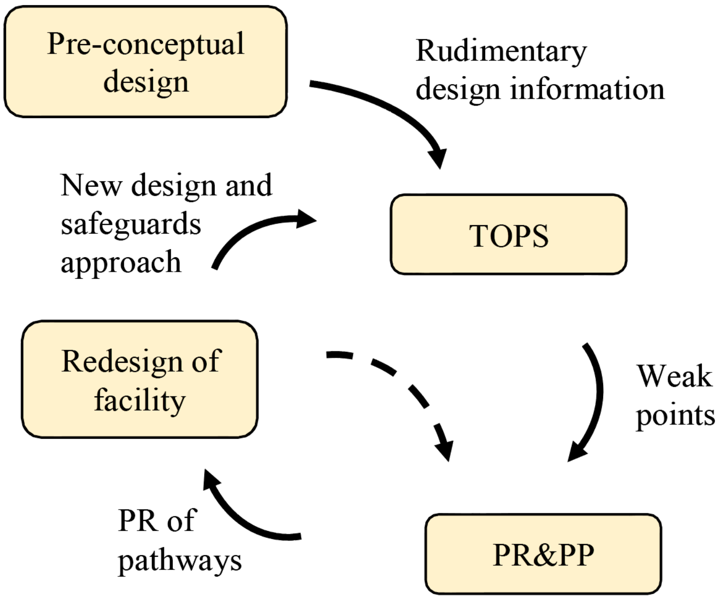

Figure 5: The facility design process suggested in Paper III, including the two proliferation resistance assessment methodologies and their outcomes. There is no given ending to the iterative process, which reflects the fact that assessments may be performed throughout the entire lifetime of the facility.

6 Conclusions and discussion

If Gen IV nuclear energy systems are to be the least desirable route for diversion, efforts should be made to include as much inherent proliferation resistance as reasonably achievable into new facility and system designs. As an example, in Paper I, it is suggested that the Ganex process should be used instead of Purex, not only due to its actinide separation capabilities, but also due to inherently less vulnerable isotopic and radiological properties of the materials resulting in superior performance in a proliferation resistance assessment. The increased proliferation resistance in the recycling facility propagates also to the reactor and fuel fabrication facilities, according to the analysis results of Paper I, making the choice of reprocessing technique even more important.

Results from Paper I more specifically show that, in the reactor, fresh fuel is more vulnerable than used fuel regardless of the chosen fuel cycle, due to its chemical and radiological properties and easier access. Material wise, Purex offers the lowest proliferation resistance, whereas from a technical perspective all three fuel cycles are equally resistant. In the reprocessing plant, the pure Pu streams are the weakest links of the Purex and Purex-Diamex/Sanex reprocessing, regarding both the material and technical barrier categories, since the isotopic and chemical barriers of pure Pu offer low proliferation resistance. In the Ganex case, the pure U stream and used fuel with minor actinides included in it, are instead the most vulnerable segments regarding material and technical barriers, respectively. Regarding technical barriers, used fuel elements are more vulnerable than all dissolved and separated materials, since they are considered to be more accessible. From both the material and technical perspectives, Ganex offers the highest proliferation resistance. In the fuel factory, powders and fuel pellets are more vulnerable than fuel elements, since they are easier to conceal and transport, and more difficult to account for. The Purex fuel cycle is the most vulnerable material wise. The lowest technical resistance values in the fuel fabrication segment collection are the same, regardless of the chosen reprocessing technique.

Furthermore, differences between the fuel cycle options discussed in Paper I, regarding weakest links of the TOPS technical barrier group, are seen only in the reprocessing plant. In order to increase the technical proliferation resistance values also in the reactor and fuel fabrication facilities of Gen IV systems, the facilities should be made difficult to modify and access, and safeguards equipment should be developed to improve precision and reliability. In this way, not only the new material compositions will improve the proliferation resistance of future nuclear power systems, but also new technical solutions will contribute.

Efforts to make Ganex and other group actinide separation techniques commercial are important, considering the expected increase in recycling activities that follow along an implementation of Gen IV nuclear energy systems.

The dedicated design of safeguards for new facilities, starting from the early design stages, will help ensure that the subsequent implementation of safeguards in the facility will be as smooth, cost efficient and non-intrusive as possible. Thus, Safeguards By Design lies not only in the interest of safeguards regulation authorities, but also in that of the operators. Discussions on proliferation resistance should take place between operators, safeguards authorities and other stakeholders, during all stages of planning a new facility design and throughout the facility's lifetime. Proliferation resistance assessments could be used as a base for such discussions, and as a guide for refining an unfinished facility design. Authorities performing licensing procedures may as well benefit from the support of a proliferation resistance evaluation.

There are multiple tools available for evaluating proliferation resistance and diversion risks of a nuclear installation. Which one of them is the best to use may depend on e.g. which stakeholder performs the analysis and what the results will be used for. TOPS may lend itself best to quick assessments and comparisons of facility alternatives, whereas PR&PP is a more extensive and demanding methodology. A combination of the two, as presented in Paper III, is an attempt to reap the benefits of both methodologies. No matter which methodology or combination of methodologies that is chosen, proliferation resistance assessments should be made before constructing a new nuclear facility, to compare different material flows, operation processes etc., and evaluate the resulting potential resistances to diversion.

One of the experienced difficulties of performing the proliferation resistance assessments of Papers I and III, was the lack of detailed design and process information of the envisioned facilities. The results of the evaluations could have been more detailed if the facility designs were developed further. However, when adopting an iterative evaluation process, the facilities will be increasingly refined, with less uncertainties in the proliferation resistance assessments as a result. Moreover, the results could have been improved if several experts were consulted to bring their points of view to the assessments.

Biased judgment in the group of analysts is a possible weakness in the proliferation resistance assessments, which can partly be mitigated by employing several experts for the task. Nonetheless, it is valuable to early in the design stage emphasize the need for Safeguards By Design and to have a structured way of identifying weak links in a system.

When designing new safeguards equipment and routines for future facilities, the operators' needs for measured data should be acknowledged. Not only the IAEA requires accurate data for their verification purposes, but operators may also need the same data for process quality control. Provided that the IAEA can still independently reach safeguards conclusions, joint use of safeguards equipment could be a way to make the use of resources more efficient, and make the safeguards measurements less intrusive to regular facility operations.

For improved sustainability in nuclear power, the price to be paid includes increased fuel handling activities and transports. In order to cope with this change, it is important to keep developing safeguards instrumentation and methods, to fit the new types of materials and the increased material flows that may arise. Appropriate safeguards instrumentation should be in place and readily available for the implementation of Gen IV systems. An identification of the needs for safeguards measurements in a facility, as performed to some extent in Paper II, is a good starting point for the development such instrumentation.

Small throughput facilities are inherently more resistant to diversion than larger ones, as a direct consequence of the smaller quantities of nuclear materials present. As discussed in Paper II, the use of small demonstration facilities functioning as templates for safeguards implementation is advisable since they may provide a unique performance testing environment for new and existing instruments. Various safeguards instrumentation setups could be implemented and evaluated at such a facility.

Future nuclear power systems, whether they include Gen IV or not, will require effective and efficient safeguards. Now is the time to work out the safeguards requirements and instruments tailored to fit the future nuclear power technology. The papers of this thesis highlight the importance, and suggests practical applications, of proliferation resistance assessments and Safeguards By Design, for the successful implementation of Gen IV safeguards.

7 Outlook

As mentioned in Paper III, evaluation of proliferation resistance may act as an aid in the technical development of safeguards instrumentation, in that it may guide the development towards the areas where nuclear facilities and fuel cycle systems are the most inherently vulnerable.

An area of future research is the investigation of requirements for a safeguards instrument in one of the most vulnerable facility segments of a reprocessing facility, thus working to strengthen the weakest link. It would be considered an advantage if the instrument is suited for joint use by the IAEA and the operator, such that both parts can benefit from the measurement results. Computer based simulations and experimental validation of the performance of such an instrument would follow naturally. Thus, the research presented in this thesis could form the basis for developing instrumentation for the nuclear facilities of Generation IV systems.

Furthermore, studies involving simulations of the individual and aggregated performances, in terms of measurement accuracy and availability, of the safeguards instruments in a facility would enable comparisons of various possible safeguards setups. It is also advisable to perform studies aimed to find the desired level of redundancy in safeguards measurements.

While performing safeguards research within the topics mentioned above, parallel discussions with licensing authorities may be beneficial, since their views upon the research may act as a guide towards further investigations and developments.

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