Alma Mater Studiorum – Università di Bologna

DOTTORATO DI RICERCA IN

INGEGNERIA ENERGETICA, NUCLEARE

E DEL CONTROLLO AMBIENTALE

Ciclo XXVII

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SAFETY, SECURITY AND SAFEGUARDS
IN GEN IV SODIUM FAST REACTOR

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Esame finale anno 2015

Nothing in life is to be feared,

it is only to be understood.

Now is the time to understand more,

so that we may fear less.

[Marie Curie]

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MEDAGLIONE

Il lavoro del candidato presenta uno studio analitico e critico della normativa nazionale ed internazionale in campo di safety, security e safeguards. Vi vengono analizzati i trattati internazionali e le raccomandazioni emanate dalla IAEA nonché le normative nazionali in vigore in Francia, Stati Uniti e Italia; a seguito di ciò viene presentato un confronto secondo i seguenti aspetti:

- Organizzazione dello stato e dei ministeri per confrontarne i diversi ruoli;
- Organizzazione dell'agenzia per la sicurezza;
- Sistemi di protezione fisica dei materiali e delle applicazioni nucleari;
- Piani di emergenza e di contingenza con confronto tra i relativi limiti di dose applicabili;
- Sanzioni monetarie e penali in caso di attentato o non rispetto delle normative vigenti.

Dato l'interesse della Japan Atomic Energy Agency per gli aspetti delle sanzioni penali e monetarie, è stato analizzato altresì il caso giapponese.

Questo confronto è stato presentato alla conferenza "34th annual meeting of the Institute of Nuclear Materials Management (INMM-J, 24 – 25 October 2013, Tokyo, Giappone)".

A seguito è stato svolto presso la Japan Atomic Energy Agency in Giappone, ove la candidata ha trascorso un anno, uno studio nel campo della resistenza alla proliferazione (PR) e della protezione fisica (PP) di un sistema nucleare di quarta generazione al sodio. A tale scopo è stato prima portato a termine il progetto del sistema nel suo insieme e successivamente è stata applicata la metodologia PR&PP per valutare la risposta del sistema e ottenere dati utilizzabili dai progettisti per il miglioramento del sistema. A causa della presenza di dati sensibili, non tutti i dettagli possono essere divulgati e alcuni non sono pertanto presenti nella tesi, né lo saranno nella presentazione.

L'attività ha comportato la definizione delle possibili minacce (diversion, misuse, breakout, furto e sabotaggio); l'identificazione dei possibili target e loro categorizzazione in termini di quantità, tipo di materiale, forma; identificazione di possibili scenari per ciascuna categoria di minaccia.

Per la valutazione della protezione fisica, i possibili percorsi per furto e sabotaggio sono stati analizzati con l'ausilio del software EASI (Estimate of Adversary Sequence Interruption) sviluppato dai Sandia National Laboratories. I risultati ottenuti per il sistema al sodio sono stati confrontati con possibili limiti di non proliferazione e con i risultati ottenuti dall'applicazione della metodologia ad un sistema nucleare ad acqua. Tale lavoro è stato presentato al "Workshop on the Proliferation Resistance and Physical Protection Evaluation (PR&PP) Methodology for Generation IV Nuclear Energy Systems", al "Symposium on International Safeguards: Linking Strategy, Implementation and People (20-24 ottobre 2014, Vienna)" e durante il "PRPP Working Group Meeting". Un articolo è in fase di revisione presso la rivista ESARDA Bullettin.

A latere, è stato anche svolto uno studio di Probabilistic Safety Assessment (PSA) di livello 3 sul TRIGA della Casaccia in collaborazione con l'ENEA. Tale studio, esulando dal filone conduttore della tesi, non è ivi riportato: tuttavia il lavoro è stato pubblicato sulla rivista Annals of Nuclear

Energy. Lo scenario ipotizzato è stato quello di una collisione di un aereo con conseguente completa distruzione del contenimento e del nocciolo e rilascio istantaneo di tutto il materiale radioattivo presente nell’atmosfera. Per stimare la propagazione della nube e la dispersione dei radionuclidi e la conseguente dose alla popolazione, sono stati utilizzati i codici di dispersione RASCAL, HotSpot e Genii. In particolare, il codice RASCAL è stato preventivamente modificato per trattare anche reattori di ricerca.

Section 1

The legislative framework

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1 NUCLEAR SAFETY AND SECURITY REGIME

The application of nuclear energy for electricity generation started with national programs in a few pioneering countries in the mid-1950s. Major worldwide expansion of nuclear power took place in the late 1960s and early 1970s, with a variety of reactor types and safety approaches. Since then, international cooperation has gradually increased, and has led to a substantial convergence of the design and operating principles for nuclear power plants [1].

The necessity to involve all countries as active partners in a single global nuclear safety regime became evident after the accident at the Chernobyl Nuclear Power Plant, while recent terrorist events have served as a catalyst for the development of the global nuclear security regime that is not as mature as the safety regime. Although concern about malicious acts involving nuclear installations is not new, recent terrorist events have demonstrated that an attack on a nuclear facility might be attempted and that terrorists have formidable capabilities and dedication. This has led to an increased focus on defenses against terrorists at nuclear facilities, as well as at other critical infrastructures [2].

Nowadays, several international conventions relevant to nuclear safety and security have been signed, and much progress has been achieved in the joint development of safety and security regulations and in the establishment of international networks among nuclear power plant operators and national regulators.

1.1 Global nuclear safety regime

The Global Nuclear Safety Regime is defined as the institutional, legal and technical framework for ensuring the safety of nuclear installations throughout the world. The objective of this regime is to lead to a world where all nuclear installations are operating safely. A schematic picture of the Global Nuclear Safety Regime is presented in Fig. 1.1.

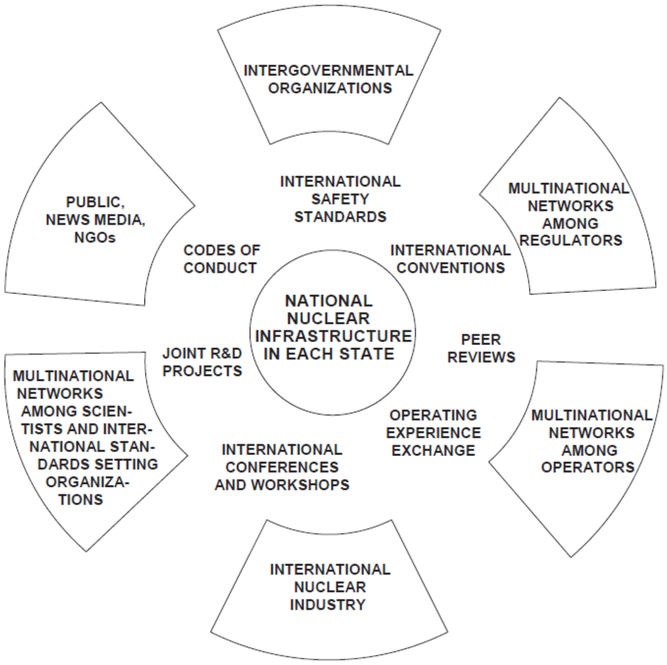


Fig. 1.1: Main elements of the global nuclear safety regime.

Its central and most important component continues to be a strong national nuclear infrastructure in each Member State. The active participants in each country's national infrastructure include:

- Operators of nuclear facilities;
- Nuclear safety regulators;
- Scientific and technical support organizations;
- Research organizations and universities;
- Suppliers of equipment and services;
- Other stakeholders with interests in securing nuclear safety.

International participants in the Global Nuclear Safety Regime are:

- Intergovernmental organizations dedicated to the nuclear field, such as the International Atomic Energy Agency (IAEA) and the Organization for Economic Co-operation and Development/Nuclear Energy Agency (OECD/NEA);
- Multinational networks among regulators, such as the International Nuclear Regulators Association (INRA), the Network of Regulators of Countries with Small Nuclear Programmers (NERS), the Western European Nuclear Regulators Association (WENRA) and the Forum of the State Nuclear Safety Authorities of the Countries Operating WWER Type Reactors.
- Multinational networks among operators, such as the World Association of Nuclear Operators (WANO), the "Owners groups" of different types of nuclear power plants vendors and the International Network for Safety Assurance of Fuel Manufacturers (INSAF).
- Stakeholders in the international nuclear industry, such as the Nuclear power plant vendors, The World Nuclear Association, the Suppliers of equipment and the Suppliers of services;
- Multinational networks among scientists;
- The public and the news media;
- Non-governmental organizations (NGOs);
- International standards setting organizations.

The assurance of nuclear safety is reinforced by a number of intergovernmental agreements. These include some Conventions that are legally binding on the participating States. Since 1986, some legally binding conventions that have the aim of increasing nuclear safety and security worldwide have been ratified in the areas of nuclear, radiation and waste safety. These are the (see Fig. 1.2 [3]):

- Convention on Early Notification of a Nuclear Accident – 1986 [4] (9 States are signatory, 3 are signatory with reservation; 63 States are party and 47 are party with reservation - data from the IAEA Office of Legal Affairs and are update at the July 03, 2012);
- Convention on Assistance in the Case of Nuclear Accident of Radiological Emergency – 1987

[4] (9 States are signatory, 1 are signatory with reservation; 49 States are party and 55 are party with reservation - data from the IAEA Office of Legal Affairs and are update at the July 03, 2012);

- Convention on Nuclear Safety (CNS) – 1994 [5] (10 States are signatory; 71 States are party and 3 are party with reservation - data from the IAEA Office of Legal Affairs and are update at the July 03, 2012);
- Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management – 2001 [6] (3 States are signatory; 59 States are party and 3 are party with reservation - data from the IAEA Office of Legal Affairs and are update at the July 03, 2012).

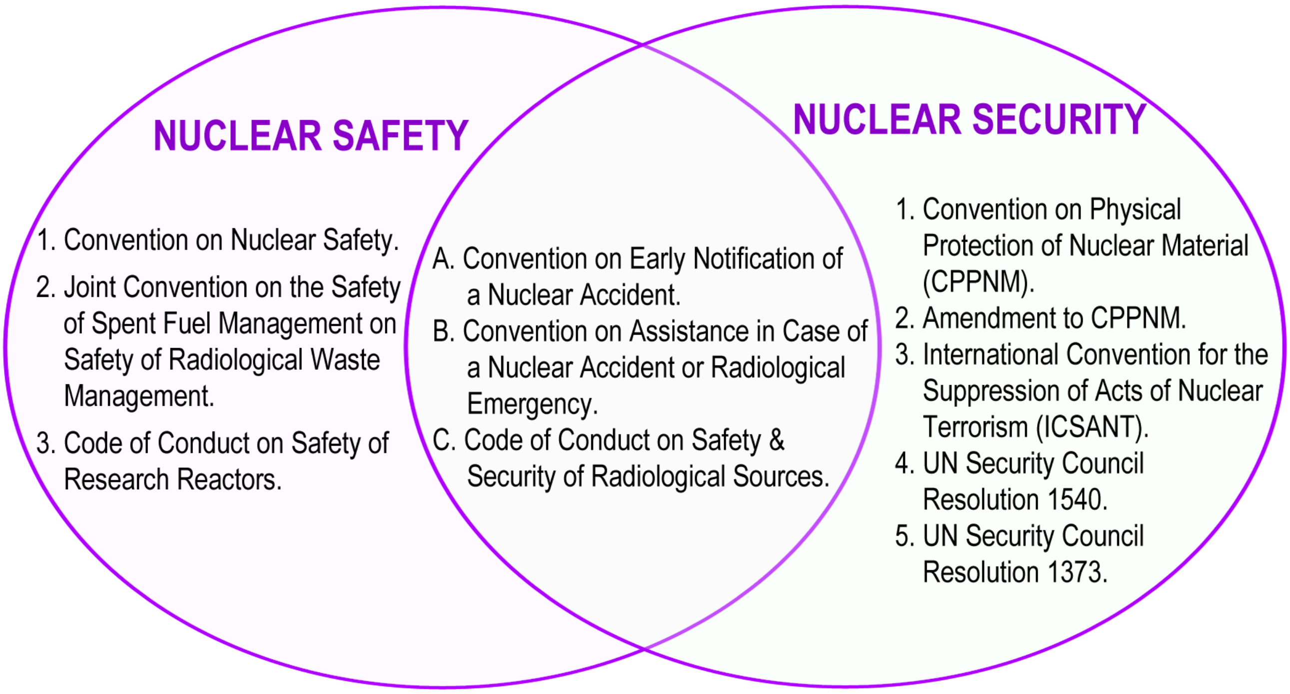


Fig. 1.2: Intersection of nuclear safety and nuclear security regime elements.

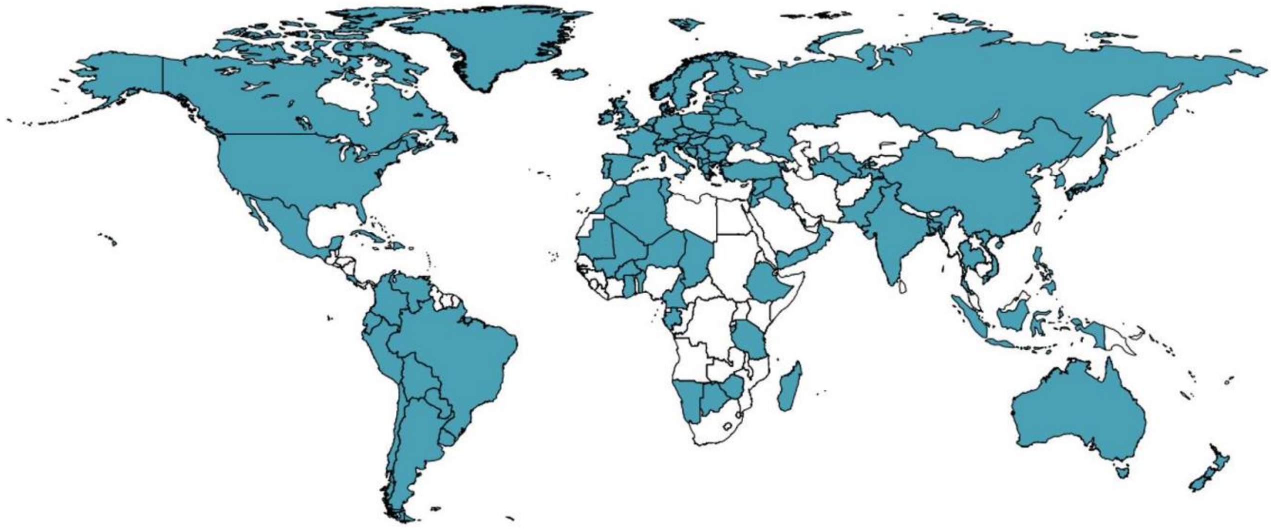


Fig. 1.3: International support for the CCSSRS (as of 06 May 2010).

In addition, there are Codes of Conduct that the IAEA General Conference has endorsed and that several Member States are politically committed to observe:

- Code of Conduct on the Safety and Security of Radioactive Sources – 2004 [7] (see Fig. 1.3);
- Code of Conduct on the Safety of Research Reactors – 2004 [8].

1.2 Global nuclear security regime

The overall objective of a State's Nuclear Security Regime is to protect persons, property, society, and the environment from malicious acts involving nuclear material and other radioactive material.

The Global Nuclear Security Regime comprises international legal instruments, including conventions and codes of conduct and the IAEA Nuclear Security Series publications, supplemented by IAEA security services. IAEA started publishing security related recommendations in 1972 in The Physical Protection of Nuclear Material and Nuclear Facilities [9], which has been revised several times [10]. Many bilateral nuclear cooperation agreements and the Convention for the Suppression of Acts of Nuclear Terrorism as the United Nations Security Council Resolutions require States to take these recommendations into account when adopting measures to protect nuclear material. After that, IAEA has established a Nuclear Security Programme and instituted a series of publications on nuclear security to provide recommendations and guidance that States can use in establishing, implementing and maintaining their national nuclear security regime. This Nuclear Security Series framework comprises four tiers of publications: Nuclear Security Fundamentals, Recommendations, Implementing Guides and Technical Guidance. The most important document in the protection of nuclear material and nuclear facilities is the Revision 5 of the INFCIRC/225 that is published in the IAEA Nuclear Security Series [11].

Some international instruments described in section 1.1 are relevant not only for the nuclear safety, but also for the nuclear security. These are the (see Fig. 1.2):

- Convention on Early Notification of a Nuclear Accident – 1986 [4];
- Convention on Assistance in the Case of Nuclear Accident of Radiological Emergency – 1987 [4];
- Code of Conduct on the Safety and Security of Radioactive Sources – 2004 [7].

Other international instruments, instead, are related only to nuclear security. These are:

- Convention on the Physical Protection of Nuclear Material (CPPNM) – 1987, scope extended 2005 [12] (94 States are party and 49 are party with reservation - data from the IAEA Office of Legal Affairs and are update at the July 03, 2012);
- Amendment to the Convention on the Physical Protection of Nuclear Material [13] (54 States are contracting and 2 are contracting with reservation - data from the IAEA Office of Legal Affairs and are update at the July 03, 2012);
- International Convention for the Suppression of Acts of Nuclear Terrorism [14] (139 States

participate - data from the United Nations Treaty Section and are update at the July 02, 2012);

- United Nations Security Council Resolution 1540 [15] (dealing with the weapon of mass destruction);
- United Nations Security Council Resolution 1373 [16] (requires member States to take measure tending to fight against the terrorism and to control their borders).

1.3 Responsibility for safety and security

The legal and regulatory framework on which safety and security are built, should define the responsibilities of several organizations: the State, the regulatory authority or authorities, and the operating organizations. These are summarized taking into account the INSAG-24 [2], the WINS document [17], the Handbook on Nuclear Law [18, 19] and the INFCIRC/225 Rev. 5 [20]. An example of organizations in nuclear security, as suggested by WINS, is given in Fig. 1.4.

Responsibility of the state

The State must set up an appropriate legislative and regulatory framework to ensure control of nuclear power plants, as well as of the transport and uses of nuclear material that present a radiological risk and thus require safety and security provisions. It must designate a regulatory authority or authorities in both the safety and security fields and provide the regulator(s) with the authority, competence and the financial and human resources necessary to accomplish their tasks. Moreover, they should be independent from nuclear operators and other government entities responsible for promoting nuclear power or the use of radioactive material. The State must verify that the responsibilities in safety and security are well defined and are satisfied and must also define rules for confidentiality and information protection in the security area and carry out checks to ensure the trustworthiness of personnel. The State plays also a critical role in ensuring adequate protection against terrorist threats. The State is directly involved in the assessment of the risk and nature of a potential terrorist attack. The risk of a terrorist event may vary over time, requiring the State to ensure that the security measures are suited to the threat situation. To address this, the State typically defines a design basis threat that must be met by the operator, with guidance as to how to adjust the defensive capability to account for the threat situation. In addition, the State must be prepared to augment the defensive capability of the operator in the event of an attack and, if necessary, to execute an operation to seize back control over the plant. If the threat is a theft of material, the State must participate in national and international programs to prevent the theft, or to recover stolen material.

Responsibility of the regulatory authorities

The regulator (or regulators) must define the requirements to be satisfied by the operator for both safety and security. The regulator must also set up and implement a licensing system and an inspection and enforcement system. The regulator must ensure that an adequate emergency response system is in place, including various off-site elements that are not the responsibility of the operator. In both the safety and security fields the regulator must also observe international commitments.

Because of the close relationship between safety and security, many countries see advantages in having a single regulator responsible for both. This authority may, in turn, be dependent on other government entities for assistance on security matters. That is, a regulator with responsibility for safety and security might be dependent on intelligence information from a specialized agency or 8 agencies. It may also turn to police or military entities for fighting capability to augment the operator's security forces. In the event that the security regulator is separate from the safety authority, it is essential to have a consultation and coordination mechanism between the two regulators to ensure that regulatory requirements are compatible and serve optimally to advance both safety and security.

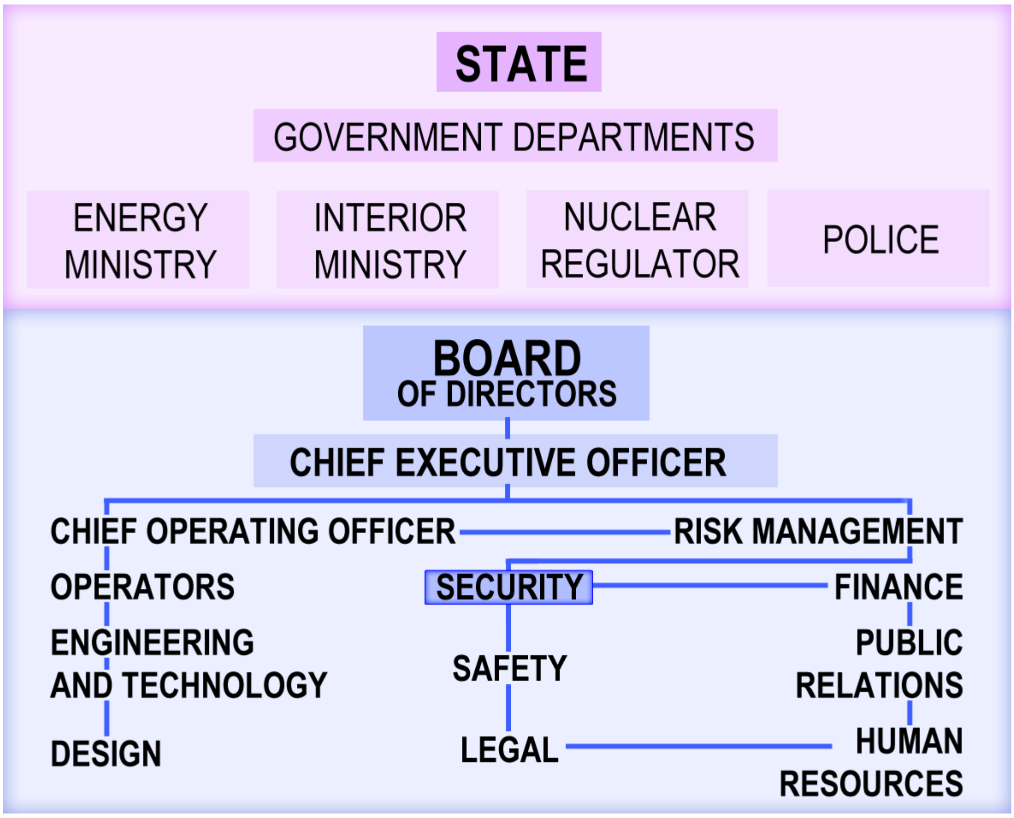


Fig. 1.4: Example of organisation in nuclear security.

Responsibility of operators

The operating organization has the prime responsibility for the safety and security of the nuclear power plant, although in the case of security, the operator's responsibility may be limited to defense against a design basis threat. This allocation of responsibility reflects the reality that operating staff are in the best position to identify the risks arising at the nuclear power plant and to ensure compliance with regulatory requirements. In this context, the operators must:

- Design, implement and maintain technical solutions and other arrangements to satisfy regulatory requirements related to both safety and security;
- Ensure first level control;
- Verify the skills and appropriate training of personnel;
- Inform the regulatory authorities of any event likely to affect the safety or security of the nuclear power plant and, as appropriate, request support;
- Maintain coordination with State organizations that are involved in safety or security; and
- Implement a quality assurance system in both the safety and security fields.

Operators should have a centralized information system and a centralized command center for directing operations during a safety or security event.

2 SAFETY AND SECURITY IN NUCLEAR FACILITIES

Nuclear safety and nuclear security have a common purpose: the protection of people, society and the environment. In both cases, such protection is achieved by preventing a large release of radioactive material.

For nuclear safety and security, in the IAEA glossary [21], the following definitions are found:

- Safety: "The achievement of proper operating conditions, prevention of accidents or mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation hazards."
- Security: "The prevention and detection of, and response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involving nuclear material, other radioactive substances or their associated facilities."

Safety evaluations focus on risks arising from unintended events initiated by natural occurrences (such as earthquakes, tornadoes, or flooding), hardware failures, other internal events or interruptions (such as fire, pipe breakage, or loss of electric power supply), or human mistakes (such as the incorrect application of procedures, or incorrect alignment of circuits). In the case of security, the risks, or events, feared arise from malicious acts carried out with the intent to steal material or to cause damage. Security events are therefore based on "intelligent" or "deliberate" actions carried out purposely for theft or sabotage and with the intention to circumvent protective measures.

2.1 Defense in depth

The acceptable risk is presumptively the same whether the initiating cause is a safety or a security event. The philosophy that is applied to achieve this fundamental objective is similar. Both safety and security typically follow the strategy of "Defense in Depth". The fundamental nature of the layers is similar. Priority is given to prevention. Second, abnormal situations need to be detected early and acted on promptly to avoid consequent damage. Mitigation is the third part of an effective strategy. Finally, extensive emergency planning should be in place in the event of the failure of prevention, protection and mitigation systems. Defense in depth for the safety of nuclear power plants is described in INSAG-10 [22]:

> *"All safety activities, whether organizational, behavioral or equipment related, are subject to layers of overlapping provisions so that if a failure should occur it would be compensated for or corrected without causing harm to individuals or the public at large."*

Defense in depth for security, instead, is discussed in the Amendment to the CPPNM [13], and outlined in INFCIRC/225 [10]. Defense in depth involves the establishment of a series of protection layers around potential targets for sabotage or theft. This approach takes into account the robustness of systems, structures and components (SSCs) by designing protection systems against adversary capabilities, considers accident management measures and containment systems, and endeavors to protect the function of these SSCs through physical protection measures. Systems for continuous monitoring and early alerts of a possible attempt to circumvent or cause the failure of a protection layer are an integrated part of prevention. The first line of defense for security consists of deterrence steps that serve to discourage an aggressor from attempting an attack. The second line of defense is to implement a security plan that prevents an aggressor from succeeding in an attack or, at the least, delays the aggressor for a sufficient period as to allow external support from police forces to arrive. These security plans typically entail a comprehensive strategy for the defense of the facility from an attack at the level of the design basis threat. Defense against threats beyond the design basis involve extensive coordination between the facility personnel and off-site reinforcements. Security plans for a nuclear power plant should encompass not only the prevention of malicious acts, but also the specification of effective response measures (so-called contingency plans), including, for example, securing a site. There is a need to ensure that the security plan is compatible with and complementary to the safety plan and it is necessary to ensure that coordination is organized among both safety and security responders as part of overall emergency planning. According to the CPPNM and the INFCIRC/225, contingency plans should be prepared at three levels: on-site; off-site at the local level; and at the national level both by operator and State to effectively respond to the assumed threat and must be tested via exercises comprising scenarios including safety and security issues.

The on-site contingency plan should be prepared and implemented by site operators and should include the guard force under its responsibility. It should ideally focus on the prevention of any actions leading to radiological consequences. On-site plans should be approved by the Member States competent authority. At the local level, off-site, the contingency plan should be prepared and implemented by local State representatives in liaison with local responders. Contingency and emergency plans must cover, as appropriate, communication with the public, counter-measures off-site, treatment of casualties, and the policing response and investigation [23].

Many of the principles to ensure protection are common, although their implementation may differ. Moreover, many elements or actions serve to enhance both safety and security simultaneously. For example, the containment structure at a nuclear power plant serves to prevent a significant release of radioactive material to the environment in the event of an accident, while simultaneously providing a robust structure that protects the reactor from a terrorist assault. Similarly, controls to limit access to vital areas not only serve a safety function by preventing or limiting exposures of workers and controlling access for maintenance to qualified personnel, but also serve a security purpose by inhibiting unauthorized access by intruders. Such controls may be of particular importance in the security context because the high radiation doses that might be encountered in a vital area may not be a significant deterrent given the apparent willingness of terrorists to forfeit their lives to achieve their objectives.

Nonetheless, there are also circumstances in which actions to serve one objective can be antagonistic to the achievement of the other. For example, the introduction of delay barriers for security reasons can limit rapid access to respond to a safety event or can limit emergency egress by plant personnel. Indeed, security considerations might serve to bar plant personnel from certain areas of the facility in the event of an attack that might need to be accessed for safety reasons. The establishment of fighting positions could adversely affect safety if the field of fire affects critical safety equipment or access to that equipment [2].

2.2 Plant’s lifetime phases

There are different challenges that arise in the various phases of a plant’s lifetime.

Siting

The site should be assessed for safety purposes by considering the frequency and severity of various external natural and human induced events that could affect the safety of the nuclear power plant; for security purposes by considering the vulnerability to assault of the site. For certain types of threat, the location and layout of the plant site may limit the likelihood that particular on-site areas will be affected, but some site conditions may benefit adversaries, such as the proximity of nuclear power plants to public transport infrastructure (roads, railways and airports) or to industry and populated areas. Other factors might include consideration of whether some areas within a country are more prone to terrorist activities or unrest than others or whether a given site is near the border with an unfriendly country or a country where terrorist activities are frequent.

The final selection of a site for a nuclear power plant should take into accounts both safety and security assessments.

Design

Nuclear power plants are designed by applying the defense in depth principle for both safety and security (as described in section 2.1).

Construction

Careful oversight must be exercised during initial construction. Such scrutiny serves to ensure that the plant is constructed as designed, thereby serving both safety and security purposes. This scrutiny should prevent the inadvertent or intentional introduction of weaknesses that could result in a radiological release during operation. Such oversight can present a major challenge because of the large number and diversity of workers entering the site during a construction period.

Operation and decommissioning

Operation must be conducted in a fashion that ensures that both safety and security functions are accomplished. The obligation to ensure safety and security extends over the lifetime of the facility, moreover, the safety obligation continues until all radiological hazards have been addressed. Special obligations may arise during periods in which extensive plant modifications are under way. During such activities, many contractors may need to enter the vital area of the plant, resulting in the need for appropriate access controls for both safety and security purposes. Care must be taken to prevent the inadvertent or intentional introduction of vulnerabilities. At a time when many operating plants are moving from analog to digital instrumentation and control, protection of the facility from bugs in the software or from hackers and malicious intruders requires special attention.

Maintenance, surveillance and inspections

The availability of safety and security systems must be permanently ensured. Maintenance operations as well as surveillance and inspections should be carried out on a regular basis and compensatory measures put in place whenever a safety or security capability is rendered unavailable. Again, coordination of safety and security capabilities is necessary so that compensatory measures do not undermine the necessary balance between safety and security. For example, the shutting off of electric power to an area in order to conduct maintenance should be undertaken with full awareness of the possible compromising of surveillance systems that serve security purposes and the need to introduce compensatory security measures.

It is common at many plants to undertake many maintenance and surveillance activities during refueling. This inevitably leads to large peaks in demand for supplementary human resources, which are in general provided by external organizations. This leads to the need for additional access and control measures to ensure security.

Feedback from operating experience

Events concerning equipment failures, identified anomalies, human errors and sabotage attempts must be recorded and evaluated appropriately. The information gained from identified incidents in the nuclear power plant or in others of similar design or operation makes it possible to improve its safety or its security. It is customary and appropriate for the operator’s safety personnel to share safety information widely. Such exchange of information is much more limited in the security domain and usually only involves to individuals on a need to know basis. At times a safety event may reveal security vulnerability and, in such a case, controls on the sharing of information may be necessary.

3 THE CPPNM AND THE INFCIRC/225 REVISION 5

Physical protection against unauthorized removal of nuclear material and against the sabotage of nuclear facilities or transports has long been a matter of national and international concern and cooperation. The international community has agreed to strengthen the Convention on the Physical Protection of Nuclear Material [12], and it has cooperated with the IAEA in establishing nuclear security guidance. The document Recommendations for the Physical Protection of Nuclear Material was first published in 1972 [9] and the revised version of these recommendations was published in 1975 in the INFCIRC series as INFCIRC/225.

3.1 The CPPNM

The CPPNM was signed at Vienna and at New York on 3 March 1980. In July 2005, a Diplomatic Conference was convened to amend the Convention and strengthen its provisions. [13] The purposes of this Convention are to achieve and maintain worldwide effective physical protection of nuclear material used for peaceful purposes and of nuclear facilities used for peaceful purposes; to prevent and combat offences relating to such material and facilities worldwide; as well as to facilitate co-operation among States Parties to those ends. The amendments will take effect once they have been ratified by two-thirds of the States Parties of the Convention (in Fig. 3.1 the current status of the CPPNM and its Amendment is presented). [24]

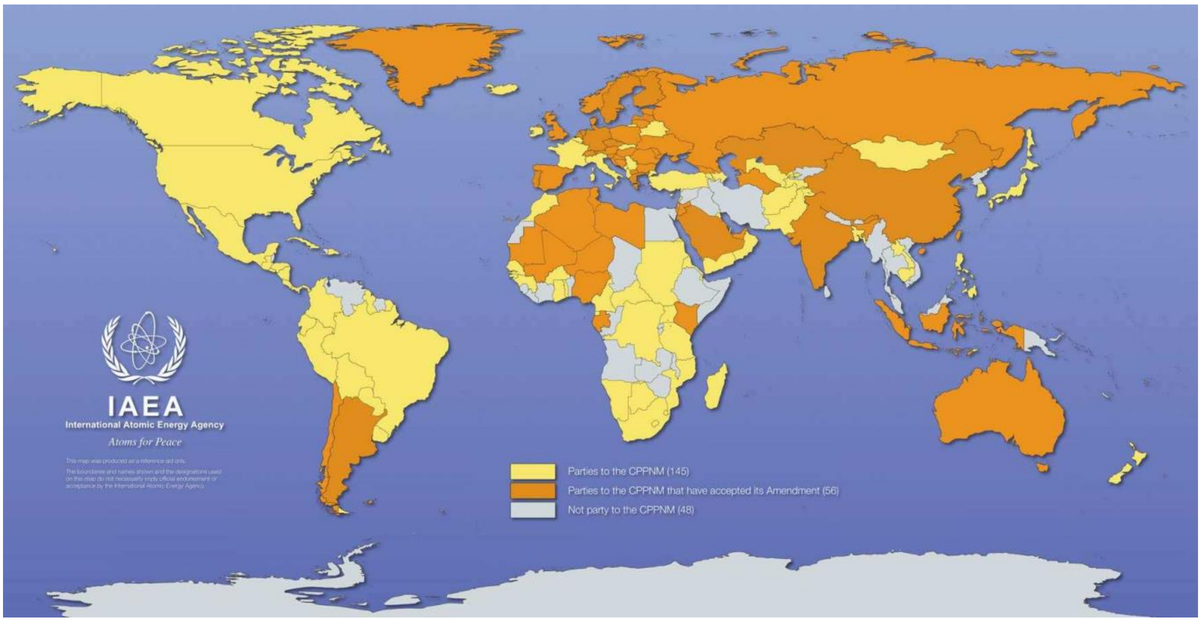


Fig. 3.1: Status of the CPPNM and its Amendment (as of 8 May 2012).

Convention and its amendment shall apply to nuclear material used for peaceful purposes in use, storage and transport and to nuclear facilities used for peaceful purposes. Moreover, it is ratified that each State Party shall establish, implement and maintain an appropriate physical protection regime applicable to nuclear material and nuclear facilities under its jurisdiction, with the aims of:

- Protecting against theft and other unlawful taking of nuclear material in use, storage and transport;
- Ensuring the implementation of rapid and comprehensive measures to locate and, where appropriate, recover missing or stolen nuclear material;
- Protecting nuclear material and nuclear facilities against sabotage;
- Mitigating or minimizing the radiological consequences of sabotage.

In detail, both the categorization of nuclear material (see Tab. 3.1) and levels of physical protection to be applied in international transport of nuclear materials are provided. [12]
This categorization and, more in detail, the requirements for physical protection to be applied for each different material can be found in the IAEA recommendations on physical protection. [20]
Another important factor is that each State shall establish or designate a competent authority or authorities responsible for the implementation of the legislative and regulatory framework. A particular attention is given to the list of intentional acts that must be punished. In particular, these are:

- Act without lawful authority which constitutes the receipt, possession, use, transfer, alteration, disposal or dispersal of nuclear material and which causes or is likely to cause death or serious injury to any person or substantial damage to property or to the environment;
- A theft or robbery of nuclear material;
- A misappropriation or fraudulent obtaining of nuclear material;
- An act which constitutes the carrying, sending, or moving of nuclear material into or out of a State without lawful authority;
- An act directed against a nuclear facility, or an act interfering with the operation of a nuclear facility, where the offender intentionally causes, or where he knows that the act is likely to cause, death or serious injury to any person or substantial damage to property or to the environment by exposure to radiation or release of radioactive substances, unless the act is undertaken in conformity with the national law of the State Party in the territory of which the nuclear facility is situated;
- An act constituting a demand for nuclear material by threat or use of force or by any other form of intimidation;
- An act constituting a demand for nuclear material by threat or use of force or by any other form of intimidation.

Tab. 3.1: Categorization of nuclear material.

Material	Form	Category I	Category II	Category III [e]
Pu [a]	Un-irradiated [b]	2 kg or more	Less than 2 kg but more than 500 g	500 g or less but more than 15 g
^{235}U	Un-irradiated [b]			
	U enriched to 20% 235U or more	5 kg or more	Less than 5 kg but more than 1 kg	1 kg or less but more than 15 g
	U enriched to 10% 235U, but less than 20%		10 kg or more	Less than 10 kg but more than 1 kg
	U enriched above natural, but less than 10%			10 kg or more
^{233}U	Un-irradiated [b]	2 kg or more	Less than 2 kg but more than 500 g	500 g or less but more than 15 g
Irradiated fuel			Depleted or natural U, Th or low-enriched fuel (less than 10% fissile content) [d,e]	

[a] All plutonium except that with isotopic concentration exceeding 80% in 238 Pu.

[b] Material not irradiated in a reactor or material irradiated in a reactor but with a radiation level equal to or less than 1 Gy/h at one meter unshielded.

[c] Quantities not falling in Category III and natural uranium should be protected in accordance with prudent management practice.

[d] Although this level of protection is recommended, it would be open to States, upon evaluation of the specific circumstances, to assign a different category of physical protection.

[e] Other fuel which by virtue of its original fissile material content is classified as Category I and II before irradiation may be reduced one category level while the radiation level from the fuel exceeds 1 Gy/h at one meter unshielded.

3.2 The INFCIRC/225 Rev. 5

The INFCIRC/225 provides a set of recommended requirements to achieve the Physical Protection Objectives (see below) and to apply the Fundamental Principles (see below) that were endorsed by the IAEA Board of the Governors and General Conference in September 2001. [25] In particular, it gives recommendations on how to develop or enhance, implement and maintain a physical protection regime for nuclear material and nuclear facilities, through the establishment or improvement of their capabilities to implement legislative and regulatory programs to address the protection of nuclear material and nuclear facilities in order to reduce the risk of malicious acts involving that material or those facilities. Three types of risk are taken into consideration for the protection of nuclear material and nuclear facilities:

- Risk of unauthorized removal with the intent to construct a nuclear explosive device;
- Risk of unauthorized removal which could lead to subsequent dispersal;
- Risk of sabotage.

Moreover, it includes also actions undertaken to locate and recover nuclear material prior to the reporting of lost, missing or stolen nuclear material to a competent authority according to national regulations.

According to the categorization of nuclear material present in the CPPNM (see Tab. 3.1) the requirements for each category of nuclear material against unauthorized removal in use and storage are described in this document. The main concept can be summarized as in Fig. 3.2.

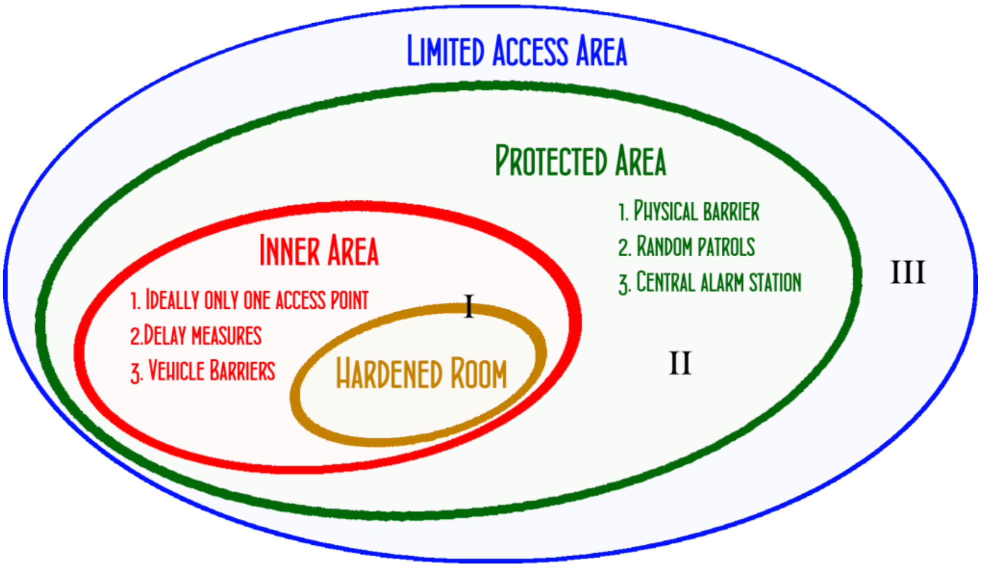


Fig. 3.2: Requirements for categories I, II and III nuclear material.

Objectives of a state's physical protection regime

The objectives of the State's physical protection regime, which is an essential component of the State's nuclear security regime, should be:

- To protect against unauthorized removal. Protecting against theft and other unlawful taking of nuclear material;
- To locate and recover missing nuclear material. Ensuring the implementation of rapid and comprehensive measures to locate and, where appropriate, recover missing or stolen nuclear material;
- To protect against sabotage. Protecting nuclear material and nuclear facilities against sabotage;
- To mitigate or minimize effects of sabotage. Mitigating or minimizing the radiological consequences of sabotage.

Fundamental principles for a state's physical protection regime

A. *Responsibility of the State*. The responsibility for the establishment, implementation and maintenance of a physical protection regime within a State rests entirely with that State.

B. *Responsibilities during International Transport*. The responsibility of a State for ensuring that nuclear material is adequately protected extends to the international transport thereof, until that responsibility is properly transferred to another State, as appropriate.

C. *Legislative and Regulatory Framework*. The State is responsible for establishing and maintaining a legislative and regulatory framework to govern physical protection. This framework should provide for the establishment of applicable physical protection requirements and include a system of evaluation and licensing or other procedures to grant authorization. This framework should include a system of inspection of nuclear facilities and transport to verify compliance with applicable requirements and conditions of the license or other authorizing document, and to establish a means to enforce applicable requirements and conditions, including effective sanctions.

D. *Competent Authority*. The State should establish or designate a competent authority which is responsible for the implementation of the legislative and regulatory framework, and is provided with adequate authority, competence and financial and human resources to fulfill its assigned responsibilities. The State should take steps to ensure an effective independence between the functions of the State's competent authority and those of any other body in charge of the promotion or utilization of nuclear energy.

E. *Responsibility of the Licensed Holders*. The responsibilities for implementing the various elements of physical protection within a State should be clearly identified. The State should ensure that the prime responsibility for the implementation of physical protection of nuclear material or of nuclear facilities rests with the holders of the relevant licenses or of other authorizing documents (e.g. operators or shippers).

F. *Security Culture*. All organizations involved in implementing physical protection should give due priority to the security culture, to its development and maintenance necessary to ensure its effective implementation in the entire organization.

G. *Threat*. The State's physical protection should be based on the State's current evaluation of the threat.

H. *Graded Approach*. Physical protection requirements should be based on a graded approach, taking into account the current evaluation of the threat, the relative attractiveness, the nature of the nuclear material and potential consequences associated with the unauthorized removal of nuclear material and with the sabotage against nuclear material or nuclear facilities.

I. *Defense in Depth*. The State's requirements for physical protection should reflect a concept of several layers and methods of protection (structural, other technical, personnel and organizational) that have to be overcome or circumvented by an adversary in order to achieve his objectives.

J. *Quality Assurance*. A quality assurance policy and quality assurance programs should be established and implemented with a view to providing confidence that specified requirements for all activities important to physical protection are satisfied.

K. *Contingency Plans*. Contingency (emergency) plans to respond to unauthorized removal of nuclear material or sabotage of nuclear facilities or nuclear material, or attempts thereof, should be prepared and appropriately exercised by all licensed holders and authorities concerned.

L. *Confidentiality*. The State should establish requirements for protecting the confidentiality of information, the unauthorized disclosure of which could compromise the physical protection of nuclear material and nuclear facilities.

4 THE LEGISLATION IN FRANCE

France has developed a large-scale nuclear program for more than 40 years. This program includes a complete nuclear fuel cycle, with most electricity produced by nuclear plants, as well as many test and research facilities. The common point between all these facilities is the use of fissile or fertile material. The integration of the risks associated with this program is part of the responsibilities of the French State with respect to its citizens, but also the international community.

This integration led France to develop a general protection policy against malevolent actions, which is part of the legal framework of the Defense code [26, 27, 28, 29] (see Fig. 4.1), for both legislative and regulatory purposes. This legal framework has been revised in recent years to reinforce the protection of nuclear material and associated facilities. This regulatory renovation was completed in 2011 and aims to:

- Meet international requirements (UN resolutions against nuclear terrorism, amendment to the convention on the physical protection of nuclear material and facilities [13], changing ideas and practices in the field of nuclear security inherent to the development of the security series texts of the IAEA);
- Bring closer and harmonize regulations, particularly regulations on the theft and diversion of nuclear material (nuclear proliferation) and the protection of nuclear facilities against malevolent actions (radiological consequences);
- Consider the complementary nature of nuclear security and safety policies in the field of protection against acts of malice (sabotage);
- Revise the Design Basis Threat (tougher threats to take into account the changing international context);
- Reinforce the legal framework, particularly in view of the emergence of a growing number of private operators holding of nuclear material.

4.1 State organization

Several entities within public authorities are involved in nuclear security provisions:

1. The General Secretariat of Defense and National Security (SGDSN) is a service of the Prime Minister and coordinates between the different ministers in terms of defense and security. The SGDSN is in charge of preparing and updating regulations on activities of vital importance, which includes defining the threats to be considered. The SGDSN is also responsible for defining confidentiality policy and preparing enforcement rules.
2. The Minister in charge of energy is responsible for control of nuclear material for civil use. It is backed up by a service consisting of personnel in charge of processing documents and preparing regulations. This service is subject to the responsibility of the senior defense and security official for the Minister of ecology, sustainable development, transport and

housing (HFDS), which acts as the nuclear security authority. In addition, the HFDS can use the services of a technical support body, the Institut de radioprotection et de sûreté nucléaire (IRSN).

3. The Minister of the interior, overseas, regional authorities and immigration holds authority over all local and national law enforcement agencies likely to be involved in the event of malevolent actions. Intelligence services reporting to this Minister play a key role in preventing malevolent actions and contributing to the assessment of the threat.
4. Departmental prefects manage the State activities in each department, so they are mainly responsible for the local organization of all crises which occur in the department and, in particular, those caused by an accident or a malevolent action, possibly affecting a nuclear facility. This key role of the departmental prefect in the event of a crisis led to a remit to approve the Specific Protection Plan (SPP) prepared by the operator and apply the External Protection Plan (EPP) provided for in regulations on activities of vital importance.
5. The Nuclear Safety Authority (NSA) analyses, in terms of impact and consequences, the risks and drawbacks that nuclear installations could cause in terms of public health, safety and security or for the protection of nature and the environment, whatever the origin of such risks (resulting or not from malevolent action). If necessary, the NSA defines the necessary provisions for the protection of these interests. In the event of an emergency radiological situation, of whatever origin, the NSA acts in a consultative role with regard to the French public authorities (in particular the Prefect, the Minister in charge of managing the crisis and the Prime Minister), especially with respect to protecting the population and the environment. The NSA also has the mission of ensuring that the operator takes the necessary measures to render its installation safe in the event of it being the victim of a malevolent action.

4.2 The Nuclear Safety Authority

The NSA is made up of a college of five members appointed by decree on account of their competence in the field of nuclear safety and radiation protection. In Fig. 4.2 a scheme of the NSA organization is presented. Three of the members, including the chairman, are appointed by the President of the Republic. The two other members are appointed respectively by the President of the National Assembly and the President of the Senate. The mandate of the members is for six years. Nobody can be appointed to the college after age sixty-five. The mandate of the members is not renewable. The duties of a member cannot be terminated except in the event of an impediment or resignation recorded by the NSA acting by a majority of the members of its college. However, the President of the Republic can also terminate the duties of a member of the college in the event of a serious failure to comply with his obligations.

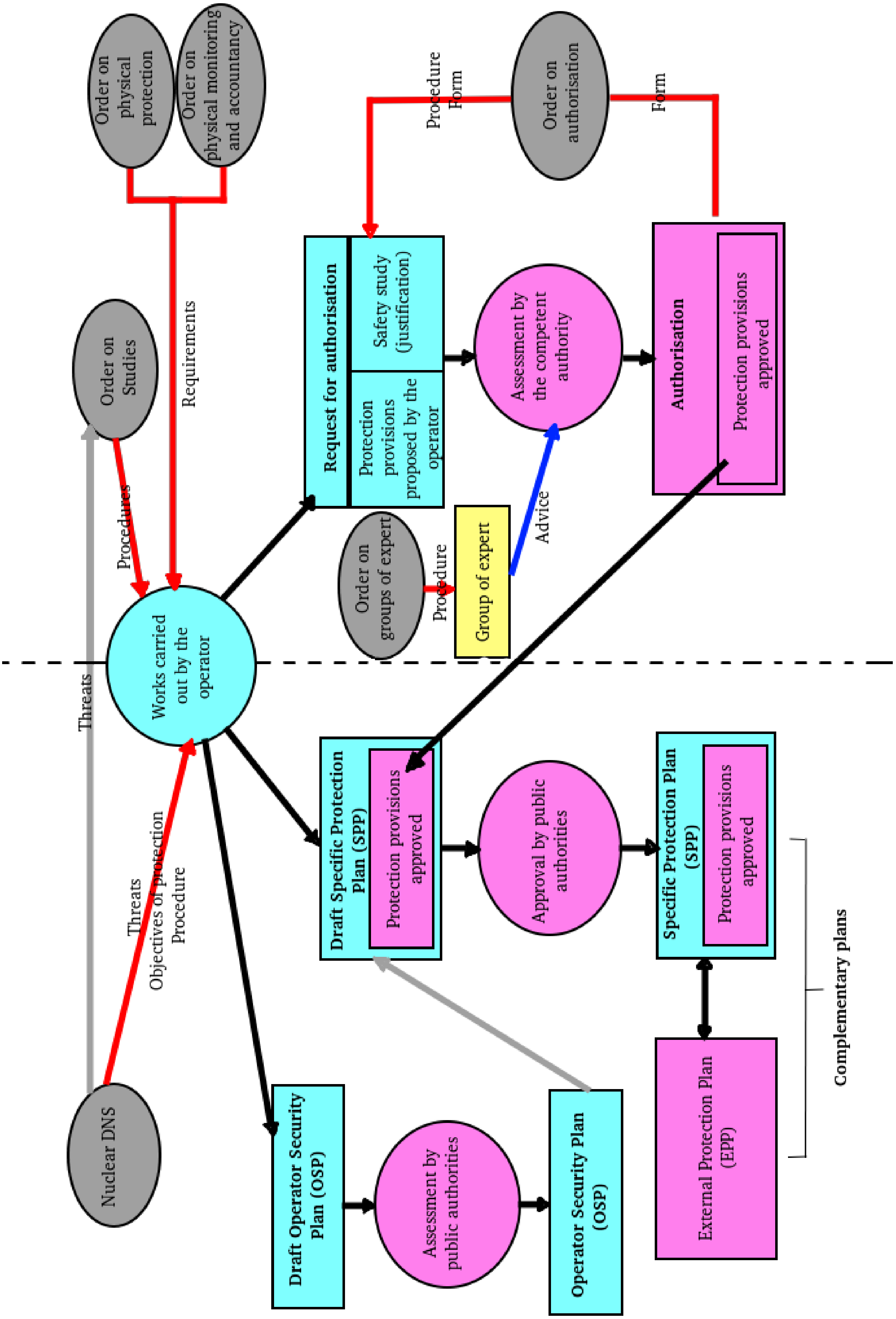


Fig. 4.1: Nuclear security regulations in France.

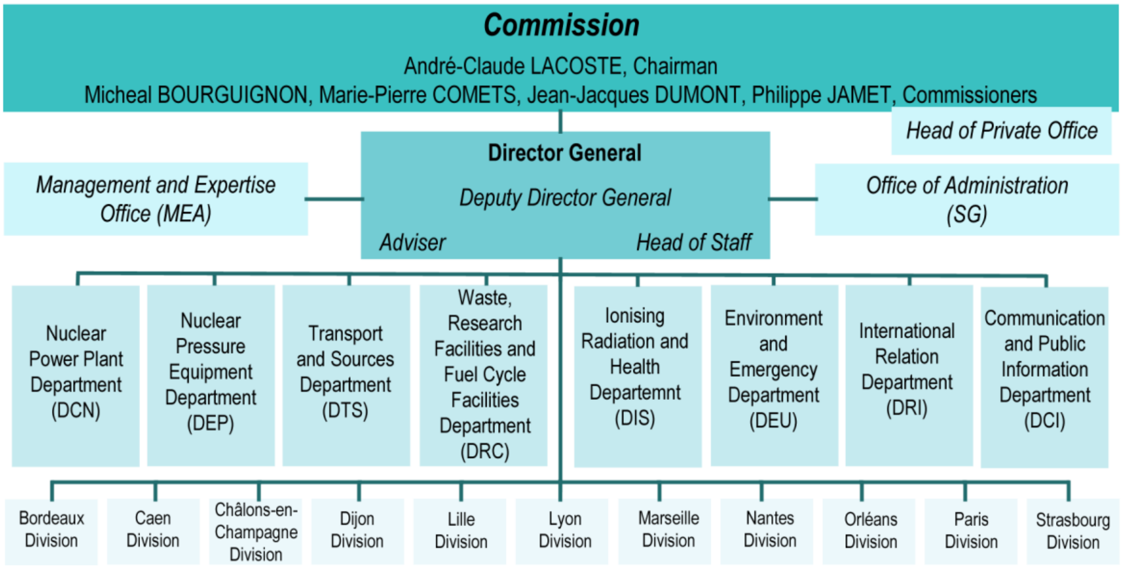


Fig. 4.2: French Nuclear Safety Authority organization.

The members of the college of the Nuclear Safety Authority exercise their duties full time. The chairman and members of the college receive respectively a salary equal to that paid to the first and second of the two higher categories of State employment classified outside the pay scale. The members of the college exercise their duties entirely impartially without receiving any instructions from the Government or from another other person or institution. The post of member of the college is incompatible with any professional activity, any elective mandate and any other public employment. The NSA records, by a majority of the members composing the college, the automatic resignation of any member who finds himself in one of these cases of incompatibility.

The NSA, as an independent administrative authority, participates in the surveillance of nuclear safety and radiation protection and in informing the public in these fields. In this respect, the NSA is consulted on draft decrees and draft ministerial orders of a regulatory nature relating to nuclear safety. It can take regulatory decisions of a technical nature to complete the implementing procedures for decrees and orders adopted in the nuclear safety or radiation protection field, except for those relating to occupational medicine. These decisions are subject to the approval of the ministers. Besides these activities, the NSA takes part in the management of radiological emergency situations resulting from events likely to endanger personal health and the environment by exposure to ionizing radiations and occurring in France or likely to affect the French territory. Not only it contributes with its technical assistance to the competent authorities in elaborating, as part of the emergency response plans, arrangements but when such an emergency situation occurs, it assists the Government for all matters within its competence. It sends the competent authorities its recommendations on the measures to be taken at the medical and health levels or regarding civil security. It informs the public of the safety state of the installation that caused the emergency situation, when the latter is subject to its surveillance, and of the possible releases into the environment and their risks for personal health and the environment [30].

4.3 Physical protection of facilities

In France there are different legislations according to the protection of facilities of vital importance [26, 28] and the physical protection of facilities housing nuclear materials [31].
The first important thing is the definition of area of vital importance: an area of activity of vital importance is constituted of activities contributing to a same objective, which:

1. Concern the production and the distribution of indispensable goods or services:
   a) to satisfy needs essential for the life of populations;
   b) or to the exercise of the authority of the State;
   c) or to the running of the economy;
   d) or to maintaining the defense potential;
   e) or to national security;

   From the moment that these activities become difficult to substitute or replace;
2. Or may pose a serious danger for the population.

The Coordinating Minister for an area of activity of vital importance conducts the risk analysis of this sector, while taking into account the threat scenarios. The results of the risk analysis are subject to the opinion of the commission for the defense and security of areas of activity of vital importance, with the exception of results involving areas of activity of vital importance for which the Minister of Defense is the coordinator. The national security directive(s) are based on the risk analysis and they apply to an area of activity of vital importance and detail the objectives and the security policies of the area. They define planned and graduated measures for vigilance, prevention, protection and reaction against any threat, particularly of a terrorist nature. For the application of these measures, the Prime Minister, after opinion of the commission, sets out by orders:

1. The analysis and risk management method;
2. The method to follow so as to determine, by area of activity of vital importance, the threat scenarios and their classification by order of importance depending on the envisaged type or level of threat;
3. The model plans for the security plans of operators of vital importance (Operator Security Plan, OSP), specific protection plans (SPP) and external protection plans (EPP). They are notified to each operator of vital importance concerned and to all the administrative authorities that need to be informed thereof.

Regarding these security plans, the operator of vital importance which manages or uses more than one establishment, facility or installation drafts the OSP. The purpose of OSP is to define the general policy for protecting all of these establishments, facilities or installations, particularly those organized into networks. On the basis of this plans, the operator of vital importance must present the SPP of each point of vital importance to the prefect of the department under whose jurisdiction the point is located. The SPP comprises permanent protection measures and temporary and graduated measures. For each point of vital importance provided with the SPP, the Departmental Prefect draws up, in consultation with the delegate of the operator of vital importance for defense and security of this point, an EPP. The EPP, which details the planned measures of vigilance, prevention, protection and reaction provided by the public authorities, is protected under the conditions of national defense secrecy.

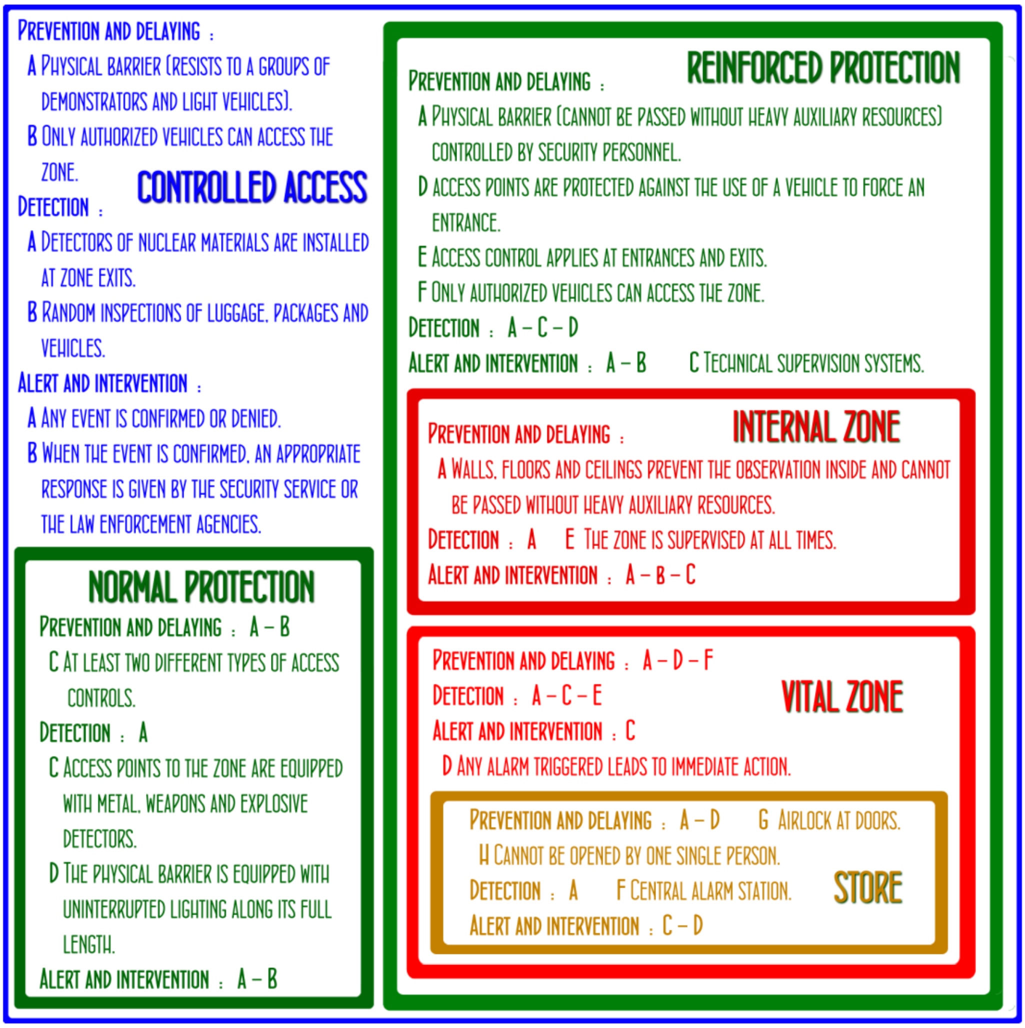
For the physical protection of facilities containing nuclear materials, it is considered as "physical protection system" (PPS) all devices and procedures deployed by the holder of the authorization to protect targets against malevolent action likely to lead to the theft or diversion of materials or to radiological consequences. This system includes active and passive means of prevention, delaying, detection, warning, follow-up of intruders and intervention.

In respect of the concept of defense-in-depth, several protection lines can be implemented:

- A zone with controlled access;
- A zone with normal protection;
- A zone with reinforced protection;
- An internal zone;
- A vital zone;
- A storage area known as a "store".

These different area request different PPS: a zone with normal protection or reinforced protection is included in a zone with controlled access; an internal or vital zone is located in a zone with reinforced protection; a store is contained in an internal zone. Each zone is marked out by a physical barrier separate to the barriers around the other zones, unless special provisions are mentioned in appendix to this order. This physical barrier has a limited number of openings and access points. Special penetration in a zone, particularly buried penetration, openings and, when closed, access points to a zone, are equipped with devices providing protection equivalent to the devices in the zone in question.

Access points are supervised directly and at all times when open. In addition, emergency exits are equipped with opening and presence detectors. All the PPS can be divided into measure for Prevention & Delaying, Detection and Alert & Intervention. In the Order of 10 June 2011 [31], a detail description of the measure applicable to each zone is presented, while a summary is represent in Fig. 4.3.


CONTROLLED ACCESS

PREVENTION AND DELAYING :

A PHYSICAL BARRIER (RESISTS TO A GROUPS OF DEMONSTRATORS AND LIGHT VEHICLES).

B ONLY AUTHORIZED VEHICLES CAN ACCESS THE ZONE.

DETECTION :

A DETECTORS OF NUCLEAR MATERIALS ARE INSTALLED AT ZONE EXITS.

B RANDOM INSPECTIONS OF LUGGAGE, PACKAGES AND VEHICLES.

ALERT AND INTERVENTION :

A ANY EVENT IS CONFIRMED OR DENIED.

B WHEN THE EVENT IS CONFIRMED, AN APPROPRIATE RESPONSE IS GIVEN BY THE SECURITY SERVICE OR THE LAW ENFORCEMENT AGENCIES.

NORMAL PROTECTION

PREVENTION AND DELAYING : A – B

C AT LEAST TWO DIFFERENT TYPES OF ACCESS CONTROLS.

DETECTION : A

C ACCESS POINTS TO THE ZONE ARE EQUIPPED WITH METAL, WEAPONS AND EXPLOSIVE DETECTORS.

D THE PHYSICAL BARRIER IS EQUIPPED WITH UNINTERRUPTED LIGHTING ALONG ITS FULL LENGTH.

ALERT AND INTERVENTION : A – B

REINFORCED PROTECTION

PREVENTION AND DELAYING :

A PHYSICAL BARRIER (CANNOT BE PASSED WITHOUT HEAVY AUXILIARY RESOURCES) CONTROLLED BY SECURITY PERSONNEL.

D ACCESS POINTS ARE PROTECTED AGAINST THE USE OF A VEHICLE TO FORCE AN ENTRANCE.

E ACCESS CONTROL APPLIES AT ENTRANCES AND EXITS.

F ONLY AUTHORIZED VEHICLES CAN ACCESS THE ZONE.

DETECTION : A – C – D

ALERT AND INTERVENTION : A – B C TECHNICAL SUPERVISION SYSTEMS.

INTERNAL ZONE

PREVENTION AND DELAYING :

A WALLS, FLOORS AND CEILINGS PREVENT THE OBSERVATION INSIDE AND CANNOT BE PASSED WITHOUT HEAVY AUXILIARY RESOURCES.

DETECTION : A E THE ZONE IS SUPERVISED AT ALL TIMES.

ALERT AND INTERVENTION : A – B – C

VITAL ZONE

PREVENTION AND DELAYING : A – D – F

DETECTION : A – C – E

ALERT AND INTERVENTION : C

D ANY ALARM TRIGGERED LEADS TO IMMEDIATE ACTION.

STORE

PREVENTION AND DELAYING : A – D G AIRLOCK AT DOORS.

H CANNOT BE OPENED BY ONE SINGLE PERSON.

DETECTION : A F CENTRAL ALARM STATION.

ALERT AND INTERVENTION : C – D

Fig. 4.3: Physical protection system in France.

4.4 Physical protection & Accountancy of nuclear material

For the purpose of their protection against loss, theft and diversion, nuclear materials are classified, according to their nature and quantity, into three categories (I, II and III) as defined in Tab. 3.1 for Pu, ^{235}U and ^{233}U and in Table 4.1 for other materials [27, 29].

The nuclear materials assigned to category I are used within an internal zone. They are stored in a store. However, the category I nuclear materials contained in power reactor fuel assemblies may be stored immerged in a pool in an internal zone. Category II nuclear materials are held inside a zone with normal protection. Category III nuclear materials are protected with a zone with controlled access. In addition, access to these nuclear materials is technically prohibited to unauthorized individuals and handling devices. The corresponding protective devices are described in the authorization. No nuclear material, regardless of its category, is stored in a transport vehicle beyond the duration necessary for loading and unloading operations. The authorization defines the conditions for the protection of these operations [31].

Tab. 4.1: Categorization of nuclear material.

Material	Form	Category I	Category II	Category III [e]
^{3}H	Un-irradiated [b]			More than 2 kg
Natural Uranium: uranium depleted in the isotope ^{235}U Th	Un-irradiated [b]			500 kg or more
Lithium enriched in ^{6}Li				1 kg or more of contained ^{6}Li
Irradiated fuels	Irradiated [d]		All fuels	
Dispersed and weakly concentrated materials	Objects with an average fissile matter content of less than or equal to 0.1% by mass [e]	-----	-----	3 g or more (Pu and ^{233}U) 15 or more (^{235}U)

[b] Nuclear materials not irradiated in a reactor or material irradiated in a reactor yielding an absorbed dose rate in air below or equal to but with a radiation level equal to or less than 1 Gy/h at one meter unshielded.

[d] Nuclear materials irradiated in a reactor yielding an absorbed dose rate in air in excess of 1 Gy/h at one meter unshielded

[e] Nuclear materials that are dispersed within objects (alloys, waste packages, etc.) and whose mass content is expressed as the total mass of nuclear materials over the net mass of the object.

In the case of a mixture of materials, the threshold T for affiliation with category I, II or III is determined by means of the formula $1/T = \sum f_i/T_i$ where fi represents the mass fraction of material i in the mixture and Ti represents the threshold associated with material i as defined in the above table.

The accountancy of nuclear material, consist of a system of tracking, measuring, and accounting for nuclear material to deter or detect theft or loss. The equipment and procedures for assuring physical monitoring, physical protection and accountancy are dissociated. Moreover, persons with the responsibility or missions relating to physical monitoring of nuclear materials are not authorized to be involved in the accountancy of nuclear materials or measures for physical protection [32]. Establishments and installations are divided into one or more accountancy zones: this division provides that a physical monitoring zone is not covered by several accountancy zones (for “accountancy zone” is mean a part of the establishment or installation subject to authorization that may contain nuclear materials and in which any operation affecting the inventory of materials held is registered in the operator’s accountancy). When a physical monitoring zone contains only nuclear materials in the form of identified articles, it is possible to derogate from this measure to take into account limitations from the application of international agreements on the verification of nuclear materials. In this case, the physical monitoring zone is entirely contained in the different accountancy zones that cover it and assignment of articles to these accountancy zones is registered in the physical monitoring system and subject to the traceability measures.

In France, the accountancy (in gram) is kept by accountancy zone for each of the following materials:

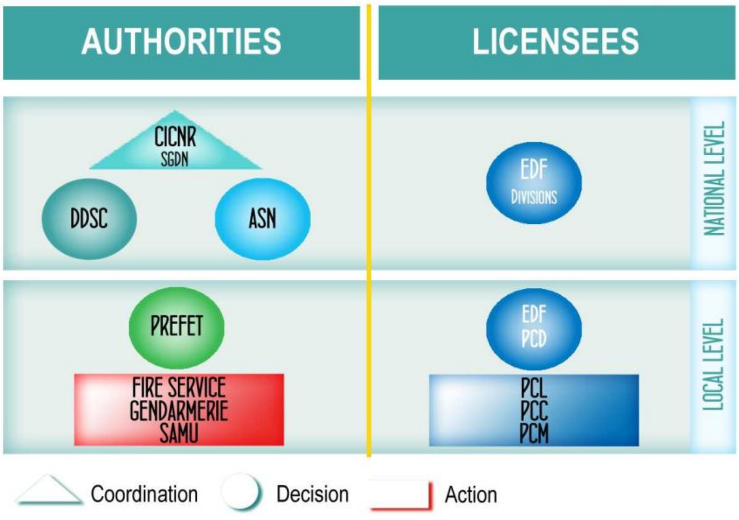
1. Thorium, except for alloys containing less than 5% thorium by mass;
2. Depleted uranium;
3. Natural uranium;

4. Uranium enriched to less than 10 percent in uranium-235;
5. Uranium enriched to 10% or more, but less than 20% in uranium-235;
6. Uranium enriched to 20 percent or more in uranium-235;
7. Uranium-233;
8. Plutonium;
9. Deuterium in the form of a gas, as hydride or heavy water;
10. Concentrated tritium;
11. Lithium enriched with lithium-6.

The accountancy distinguishes also nuclear materials intended for defense purposes and those intended for any other use. Every variation affecting the inventory are registered: chronological registration in a log book of each of the changes, as movements outside the accountancy zone, arrivals and departures or internal operations, affecting the quantity of the inventory of nuclear materials in an accountancy zone or its distribution. Variations in inventory are registered the same day they are observed using documents to ensure tracing and submitted by those in charge of physical monitoring. Accountancy will provide current accountancy inventory immediately upon request.

4.5 Emergency and contingency plans

Application of the principle of defense in depth entails the inclusion of severe accidents with a very low probability of occurrence when drafting the emergency plans, in order to determine the actions necessary to protect plant personnel and the population and to control the accident. The response organization of the authorities and that of the licensee are presented in Fig. 4.4.



CICNR: International committee on nuclear or radiological emergencies
SGDN: General secretariat for national defense
PCL: Local command post
DDSC: Directorate for defense and civil security
PCC: Supervision command post
PCD: Management command post
PCM: Resources command post

Fig. 4.4: French emergency organization in accident at an EDF nuclear reactor.

In France, two different emergency plans are present: the on-site and the off-site. These plans differ each other both in the managing and aims.
The on-site emergency plan (PUI), prepared by the licensee, is aimed at bringing the plant back to a safe condition and mitigating accident consequences. It defines the organizational arrangements and the resources to be implemented on the site. It also comprises arrangements for informing the public authorities rapidly. It means that the licensee of the affected nuclear installation, implements the organizational provisions and the means needed to bring the accident under control, to assess and mitigate its consequences, to protect persons on the site and alert and regularly inform the authorities.
The off-site emergency plan (PPI or ORSEC), instead, drafted by the préfet, is aimed to protect populations in the short term in the event of an accident and provide the licensee or the party in charge of transport with outside intervention assistance. It specifies the initial actions to take to protect the population, the roles of the various services concerned, the systems for giving the alert, and the human and material resources likely to be engaged. In this case, the préfet of the département in which the installation is located, takes the necessary decisions to protect the population, the environment and the property threatened by the accident. He is thus responsible for coordinating the resources, both public and private, human and material, deployed in the plan. He keeps the population and the mayors informed of events. Moreover, PPIs identify the population protection actions to limit the consequences of an accident [33, 34, 35, 36]. The action levels are defined by ASN decision 2009-DC-0153 of 18 August 2009 [37]:

- An effective dose of 10 mSv for sheltering;
- An effective dose of 50 mSv for evacuation;
- An equivalent dose to the thyroid of 50mSv for the administration of stable iodine.

For example, the PPIs defined for the vicinity of a PWR reactor stipulate sheltering of the population and the absorption of stable iodine within a 10km radius, plus evacuation of the population within a 5 km radius. In detail:

- Sheltering and listening: the individuals concerned, alerted by a siren, take shelter at home or in a building, with all openings carefully closed, and wait for instructions from the préfet broadcast by radio;
- Administration of stable iodine tablets: when ordered by the préfet, the individuals liable to be exposed to releases of radioactive iodine are urged take the prescribed dose of potassium iodide tablets;
- Evacuation: in the event of an imminent risk of large-scale radioactive releases, the préfet may order evacuation. The populations concerned are asked to prepare a bag of essential personal effects, secure and leave their homes and go to the nearest muster point.

In the event of effective release of radioactive substances into the environment, these three actions also include the first action that should be decided on exit from the emergency phase to prepare for management of the post-accident phase (see Fig. 4.5). The region would then be zoned with [36]:

- A Population Protection Zone (PPZ) within which contamination reduction actions will be rapidly undertaken;
- A Tightened Surveillance Zone (TSZ) within which the consumption and sale of foodstuffs produced will initially be prohibited, and subsequently subject to a conditional release inspection based on the maximum permissible radioactivity levels set by the European Commission;
- If necessary, a population clearing zone within the PPZ if external exposure levels due to deposits justify it.

Furthermore, since 1987, actions to control urban development around non-nuclear industrial facilities has been deployed, but these actions have been reinforced since the AZF accident[1] of 2001.

The broad principles of urban development control are:

- Preserve the operability of the off-site emergency plans;
- Favor urban development outside the risk zone;
- Allow controlled development that meets the needs of the resident population.

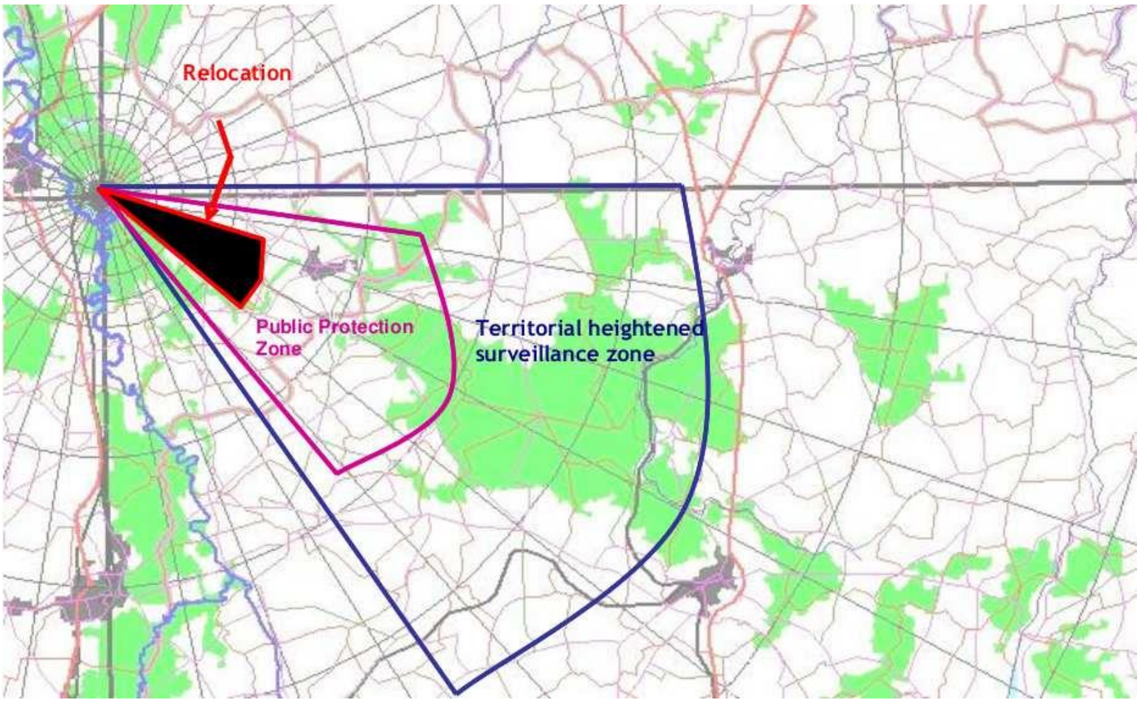


Fig. 4.5: Schematic representation of post-accident zoning.

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[1] On 21 September 2001 a fertiliser factory containing ammonium nitrate storage facilities exploded. The factory was located 3 km from the centre of Toulouse on an island of the Garonne River surrounded by an urban environment: 22 people were killed on the factory site and 8 persons outside; in total 2500 persons were injured.

From the security point of view, instead, the SGDSN analyses risks and plans prevention and operating provisions to counteract terrorist threats and monitors the application of these provisions. One key element of this approach is the "Vigipirate" plan, a government vigilance, prevention and protection plan. Designed in 1978, the plan was revised after the attacks of 11 September 2001, in order to improve the State's ability to manage potential threats to the population, activities of vital importance and the continuity of the life of the nation. The "Vigipirate" plan has two objectives: protect the population, infrastructures and institutions, and prepare responses in the event of an attack. The most recent version of the plan is based on the assumption that the terrorist threat must now be considered as permanent. It defines set of basic operational provisions applied in all circumstances, even in the absence of precise signs of threats.

4.6 Penalties

Inside the French Defense Code [26, 28, 30] and the Act No. 2006-686 of 13 June 2006 on Transparency and Security in the Nuclear Field [38], all the possibilities of offences and penalties are described. In particular, they are to apply to the fusible, fissile or fertile nuclear materials, as well as any material, other than ores, containing one or more fusible, fissile or fertile materials. In Tab. 4.2 a summary of these sanctions is shown. In addition to penalties show in Tab. 4.2, any individuals found guilty of any of these offences will be:

- Deprived of civic, civil and family rights;
- Forbidden to hold a public function or to exercise the professional or social activity in the context of which the offence has been committed;
- Liable to permanent closure or closure for 5 years at most of the establishments or of one or more establishments of the company that helped to commit the offences;
- Excluded from public procurement contracts for a maximum of five years;
- Liable to the confiscation of the nuclear materials as well as the equipment used to prepare, use or transport these materials;
- Banned from residing in France;
- Barred from the French territory, if the offenders are foreigners, either definitely or for a period of ten years maximum.

Tab. 4.2: Penalties in France.

Crime	Penalties
Carrying out without authorization imports and exports of nuclear materials or unduly obtaining this authorization by any fraudulent means; or improperly appropriating the nuclear materials; or abandoning or dispersing the nuclear materials; or altering or damaging the nuclear materials; or destroying structural elements in which the nuclear materials are conditioned. And any attempt to commit these offences. (Article L.1333-9)	Imprisonment of 10 years and fine of 7,500,000€ (about $10,250,000). (Article L.1333-9) If organized gang: Imprisonment of 15 years and fine of 7,500,000€. If committed to acquire a nuclear weapon: Imprisonment of 20 years and fine of 7,500,000€. (Article 1333-13-4)
Hindering the exercise of control pursuant imports and exports of nuclear materials or providing inaccurate information to the agents responsible for this control. (Article L.1333-12)	Imprisonment of 2 years and fine of 30,000€ (about $41,000). (Article L.1333-12) If organized gang: Imprisonment of 10 years and fine of 150,000€ (about $205,000). If committed to acquire a nuclear weapon: Imprisonment of 20 years and fine of 7,500,000€. (Article 1333-13-4)
Ascertain the loss, theft, disappearance or diversion of these materials and failed to inform the police or gendarmerie services within no more than twenty-four hours following such ascertainment. (Article L.1333-13)	Imprisonment of 2 years and fine of 37,500€ (about $51,000). (Article L.1333-13) If organized gang: Imprisonment of 10 years and fine of 150,000€.
Exporting without authorization related products to the nuclear materials contained in the list defined by a joint decree of the ministry of defense and ministry in charge of industry; or unduly obtaining by any fraudulent means the authorization to export these same products. (Article L.1333-13-1)	Imprisonment of 5 years and fine of 75,000€ (about $103,000). (Article L.1333-13-1) If committed with a view to enabling anyone acquire a nuclear weapon: Imprisonment of 15 years and fine of 7,500,000€. (Article L.1333-13-4)
Creating or operating a basic nuclear installation without the authorization. (Article 48 of Act n°. 2006-686)	Imprisonment of 3 years and fine of 150,000€. (Article 48 of Act n°. 2006-686)
Transporting radioactive substances without authorization. (Article 48 of Act n°. 2006-686)	Imprisonment of 1 year and fine of 30,000€. (Article 48 of Act n°. 2006-686)

The period of imprisonment applicable to the offender or accomplice in relation to the offences provided, shall be reduced by half if, after informing the administrative or judicial authority, he has helped to stop the illegal acts or to prevent the offence from resulting in loss of human life or permanent disability, and to identify, where applicable, other offenders or accomplices.

5 THE ITALIAN SITUATION: COMPARISON WITH FRENCH LEGISLATION

After signing of the CPPNM in 1980, Italy is endowed with its own system to meet the CPPNM obligations with the law of August 7th 1982 number 704 [39]. Due to the fact that this law only ratifies the CPPNM, the then-Ministry of Industry, Trade and Industry (now Ministry of Economic Development - MSE) took the initiative to establish, with the Decree of 10th 1979, an Interministerial Committee for the physical protection of nuclear materials during their use. It was composed by representatives of competent State departments, which had the task of guiding, inquiring and verifying the passive physical protection plans prepared by the operators. The supervisory actions on passive physical protection have been undertaken, over these years, by the nuclear department of ISPRA (actually acting as the Italian NSA - see Section 5.2). Nowadays, to ratify the Amendment to the CPPNM, the bill number 2942 [40, 41] is under discussion and approval of Italian Senate. It was first presented on October 5th 2011 and the last modification was put forth on May 8th 2012 (the list of activities can be consulted at the Italian Senate website) [42].

5.1 State organization

Following the last version of the bill number 2942, the proposed organization inside the Italian state consists of:

1. The Ministry of Foreign Affairs (MAE) for all matters referred to collaboration and cooperation with other states in case of sabotage or theft, and for communication of relevant contact points, through international channels provided.
2. The Ministry of Interior (MI), as the competent Authority for both the active physical protection of nuclear facilities and nuclear material also during transport and for the collaboration with the MAE. Moreover, the MI is the competent authority for the description of the Design Basis Threat (DBT).
3. The Ministry of Environment (MATTM), as competent authority for the physical protection of passive materials and nuclear facilities, with the Ministry of Economic Development (MSE).
4. ISPRA (acting now, temporary, as NSA) may provide technical support to all these authorities.

5.2 The Nuclear Safety Authority

The situation in Italy about the Italian NSA has changed during the last few years and, with the decree n. 201 of December 6th, NSA is now abolished. All the activities and responsibilities that must be covered by the NSA are actually performed by ISPRA, even if this is only a temporary duty, as it is expressly said in the decree, the original Italian text is following

> *13. Gli enti di cui all'allegato A sono soppressi a decorrere dalla data di entrata in vigore del presente decreto e i relativi organi decadono, fatti salvi gli adempimenti di cui al*

comma 15.

14. Le funzioni attribuite agli enti di cui al comma 13 dalla normativa vigente e le inerenti risorse finanziarie e strumentali compresi i relativi rapporti giuridici attivi e passivi, sono trasferiti, senza che sia esperita alcuna procedura di liquidazione, neppure giudiziale, alle amministrazioni corrispondentemente indicate nel medesimo allegato A.

ALLEGATO A

Ente soppresso	*Amministrazione interessata*	*Ente incorporante*
Agenzia per la sicurezza nucleare	*Ministero dello sviluppo economico*	*Ministero dello sviluppo economico, di concerto con il Ministero dell'ambiente e della tutela del territorio e del mare*

15. Con decreti non regolamentari del Ministro interessato, di concerto con il Ministro dell'economia e delle finanze e con il Ministro per la pubblica amministrazione e la semplificazione da adottare entro novanta giorni dalla data di entrata in vigore del presente decreto, sono trasferite le risorse strumentali e finanziarie degli enti soppressi. Fino all'adozione dei predetti decreti, per garantire la continuità dei rapporti già in capo all'ente soppresso, l'amministrazione incorporante può delegare uno o più dirigenti per lo svolgimento delle attività di ordinaria amministrazione, ivi comprese le operazioni di pagamento e riscossione a valere sui conti correnti già intestati all'ente soppresso che rimangono aperti fino alla data di emanazione dei decreti medesimi.

20-bis. Con riguardo all'Agenzia per la sicurezza nucleare, in via transitoria e fino all'adozione, di concerto anche con il Ministro dell'ambiente e della tutela del territorio e del mare, del decreto di cui al comma 15 e alla contestuale definizione di un assetto organizzativo rispettoso delle garanzie di indipendenza previste dall'Unione europea, le funzioni e i compiti facenti capo all'ente soppresso sono attribuiti all'Istituto superiore per la protezione e la ricerca ambientale (ISPRA).

According to law n. 99 of July 23th 2009 and following modification by decree n. 34 of March 31th 2011 [43, 44], the NSA should have been formed by four members and the president. Each member should be appointed by the Italian President following suggestions from the President of the Council of Ministers, while the NSA president should be denominated by the President of the Council of Ministers. They would be able to remain in charge for seven years. As in France, the members of the college of the Nuclear Safety Authority should exercise their duties full time and entirely impartially without receiving any instructions from the Government or from other persons or institutions. The position of member of the college should be incompatible with any professional activity, any elective mandate and any other public employment.

The NSA should be the national body for technical regulation, control and authorization for the safety of radioactive waste and nuclear materials originating from medical and industrial activities. Moreover, as the French NSA, it should participate in the surveillance of nuclear safety and radiation protection. The NSA should be consulted on draft decrees and draft ministerial orders of a regulatory nature relating to nuclear safety. It would be able to take regulatory decisions of a technical nature to complete the implementing procedures for decrees and orders adopted in the nuclear safety or radiation protection field.

5.3 Physical protection & Accountancy of nuclear material

For Italy, differently from France, even if the requisite for physical protection are not yet present, but they will be established by the MATTM and the MI within 6 months from the approval of the bill number 2942, some important definitions in this field are present. In particular, the distinction between active and passive physical protection is clarified: the active one represents all the police actions to prevent or counter both fraudulent obtaining of nuclear material and sabotage of nuclear facilities; the passive one, instead, hems in all the structures, systems and procedures to surveillance nuclear facilities and protect nuclear material from both misappropriation and sabotage.

For accountancy, instead, the legislation is present and it takes count not only of the nuclear material [45], but also of the radioactive materials [46, 47]. Regarding nuclear materials, each holder of fissile materials, raw and mineral, must send to the MSE and to the NSA a notification of detention, even if there are some exception (ex. metal or miner with less than 10 kg of natural uranium or thorium, finished products with thorium... [48]), but everybody must take accountancy of these materials. Moreover, in case of reactor with a production or a consumption of fissile materials more than 1 g/y a detailed report of these activities must be product. As for France, every variations, operations and movement affecting the inventory must be registered with all details.

5.4 Emergency and contingency plans

In Italy, the nuclear crisis refer to incidental events that give rise or may give rise to a release of radioactivity into the environment and are carried out in facilities outside the national territory, in the nuclear-powered ships inside port areas, during transport of radioactive materials or that have not previously been correlated with any specific area of the country. Two different plans are described in the law: the external emergency plan (PEE) and the national emergency plan (PNE).

The PEE [49], like the French PPI, is prepared by the prefect and is a civil protection plan that organizes, in accordance with other local governments public or private, the resources available to reduce or mitigate the effects of an industrial accident on areas outside the plant perimeter. The main task of the PEE is the identification of areas at risk. For each of these zones, the PEE sets the different response of civil protection. According to the different effects that may occur in these areas, they will be classified as follow:

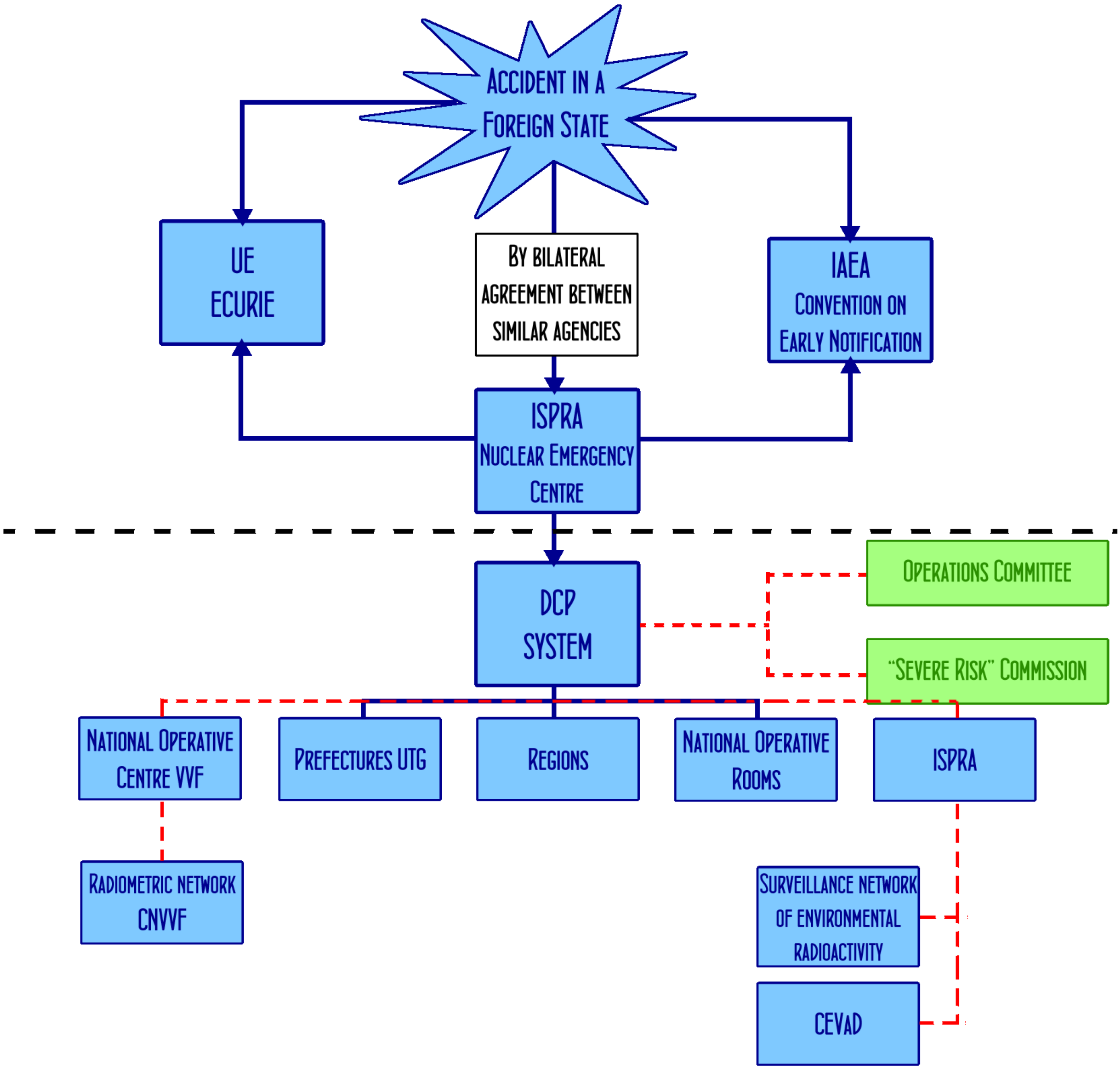
- Area of maximum exposure (or high impact) that represents the area immediately adjacent to the plant and is generally characterized by serious and irreversible healthy effects. In this area the protection actions to be planned consists, generally, in sheltering indoors, even if, in some special cases, the evacuation can be planned.

- Area of damage that represents an area where the consequences of the accident are still serious, especially for particular categories of people, as children, elderly, sick, pregnant women. In this area, due to the bigger extent and the low level of dangerous, the only protection action is the sheltering indoors.
- Area of attention that is the outermost zone to the accident and it is characterized by effects generally not serious.

Differently from the French case, the dose levels (in mSv) for the different actions are express in general term as [50]:

- From a few to a few tens, effective dose for sheltering indoors;
- From a few tens to a few hundreds, effective dose for evacuation;
- From some ten to some hundreds of equivalent dose for the administration of stable iodine.

The PNE [50, 51] identifies and control the measures to cope with the consequences of accidents that occur in nuclear power plants located outside the national territory (the NPP in Krško, Slovenia, and the NPP in St. Alban, France), which require response actions coordinated at national level. The plan defines the operational procedures for managing the flow of information between the various parties involved (see Fig. 5.1), the activation and coordination of key components of the National Service of Civil Protection. Moreover, the PNE describes the organizational model for emergency management with an indication of priority interventions to be placed at the national level for the purpose of minimizing the effects induced by the radiological emergency on the Italian population and environment. For the planning of the PNE, also the threshold values express in Tab. 5.1 are to take into account [50, 52].



Blue boxes are for both alert phase and alarm one, while the green boxes are only in case of alarm phase.

Fig. 5.1: Italian emergency organization in Alert and Alarm phase.

Tab. 5.1: Dose threshold levels for a period less than 2 days.

Organ or Tissue	Dose level [Gy]
Lung	6
Skin	3
Thyroid	5
Crystalline lens	2
Gonad	3
Fetus	0.1

5.5 Penalties

The bill number 2942 [40] and its modifications [41] will add, to the Italian penal code, all the sanctions and penalties coming not only from the non-conformity with the laws, but also from malevolent act against nuclear materials and facilities. In Tab. 5.2 a summary of these sanctions is shown.

Tab. 5.2: Penalties in Italy.

Crime	Penalties
Attempt on the safety of nuclear installations or facilities, sites or facilities used for the production, storage or transport of nuclear material, if it will be resulting in risk for public safety. (Art. 8 to modify the Art. 433 of the Penal Code)	Imprisonment from to 2 to 8 years. (Art. 8)
Purchase, receipt, possession, sale to third parties, use, transportation, importation, exportation, processing, disposal or dispersal of nuclear material capable of causing death or personal injury to one or more persons or significant damage to property or to environment. (Art. 9)	Imprisonment from to 2 to 6 years and fine from 5,000 to 20,000€ ($6,800 to 27,000). If there is the possibility that these acts will cause enduring damage: Imprisonment from to 3 to 7 years and fine from 50,000 to 250,000€ ($68,000 to 340,000). (Art. 9)
Holder of licensing that non respects prescription. (Art. 9)	Fine from 3,000 to 15,000€ ($4,000 to 20,500). (Art. 9)
Exporting without authorization related products to the nuclear materials; Unduly obtaining by any fraudulent means the authorization to export these same products. (Art. 29 law 1860)	Imprisonment from to 1 to 2 years and fine from 2,000,000 to 10,000,000 lire*. (Art. 29 law 1860)
Start up a NPP without authorization. (Art. 30 law 1860)	Imprisonment from to 2 to 3 years and fine from 5,000,000 to 10,000,000 lire*. (Art. 30 law 1860)
Transporting radioactive substances without authorization. (Art. 29 law 1860)	Fine of 500,000 – 1,000,000 lire*. (Art. 29 law 1860)

* For conversion consider that 1 € is 1936.27 ITL.

6 THE US CASE

The USA is the world's largest producer of nuclear power, accounting for more than 30% of worldwide nuclear generation of electricity. The country has 104 nuclear reactors produced 807 billion kWh in 2010, over 20% of total electrical output. There are 69 pressurized water reactors (PWRs) with combined capacity of about 67 GWe and 35 boiling water reactors (BWRs) with combined capacity of about 34 GWe – for a total capacity of 101 236MWe (see Fig. 6.1 for details [53]). Following a period of 30 years in which few new reactors were built, it is expected that 4 – 6 new units may come on line by 2020.

The USA nuclear policy is complex and a lot of department and agencies are present to regulate and organize nuclear activities. Before the Energy Reorganization Act of 1974 [54], nuclear regulation was responsibility of the Atomic Energy Commission (AEC), which Congress first established in the Atomic Energy Act of 1946 [55]. Eight years later, Congress replaced that law with the Atomic Energy Act of 1954 [56], which for the first time made the development of commercial nuclear power possible. The act assigned at the AEC functions of both encouraging the use of nuclear power and regulating its safety. The AEC's regulatory programs sought to ensure public health and safety from the hazards of nuclear power without imposing excessive requirements that would inhibit the growth of the industry. By 1974, the AEC's regulatory programs had come under such strong attack that Congress decided to abolish the agency and the NRC was instituted (see section 6.1) [57].

Moreover, the USA has a federal system of government with some powers and responsibilities carried out by states and municipalities, including the taxation and regulation of property and certain commercial activity within their boundaries. This means that, while the national government in Washington has primary jurisdiction with respect to most nuclear policy matters, states as well as local governments can have a significant impact on nuclear power use and capacity. For example, in 1976 the California state approved a law to prohibit the construction of new nuclear power plants until approval of a means to dispose of spent fuel.

Fig. 6.1: USA Operating Nuclear Power Reactors.

6.1 US Nuclear Regulatory Commission (NRC)

After the abolishment of the AEC, with the Energy Reorganization Act of 1974 [54], the NRC was instituted and its promotional activities were placed in the Energy Research and Development Administration (later the US Department of Energy – see section 6.2). The NRC began operations on January 19th 1975 [58]. It is an independent government agency that regulates all aspects of the nuclear industry in the USA, including reactors, fuel cycle facilities and the transportation, disposal and storage of spent fuel [59]. In particular, the NRC's regulatory activities are focused on reactor safety oversight and reactor license renewal of existing plants, materials safety oversight and materials licensing for a variety of purposes and waste management of both high-level waste and low-level waste (see Fig. 6.2 [60]). In addition, the NRC is preparing to evaluate new applications for nuclear plants. In this respect, the NRC continues to implement the Reactor Oversight Process (ROP), which is the agency's program for inspecting and assessing licensee performance at operating NPPs in a manner that is risk-informed, objective, predictable, and understandable. ROP instructions and inspection procedures help ensure that licensee actions and regulatory responses are commensurate with the safety or security significance of the particular event, deficiency, or weakness. Within each ROP cornerstone (see Fig. 6.3 [61]), NRC inspectors implement inspection procedures, and NPP licensees report performance indicator results to the NRC. The security cornerstone focuses on the following five key licensee performance attributes: access authorization, access control, physical protection systems, material control and accounting, and response to contingency events. The NRC is headed by a five-member Commission. The President designates one member to serve as Chairman and official spokesperson. The Executive Director for Operations (EDO) carries out the policies and decisions of the Commission and directs the activities of the program offices [62].

Fig. 6.2: NRC's regulatory process.

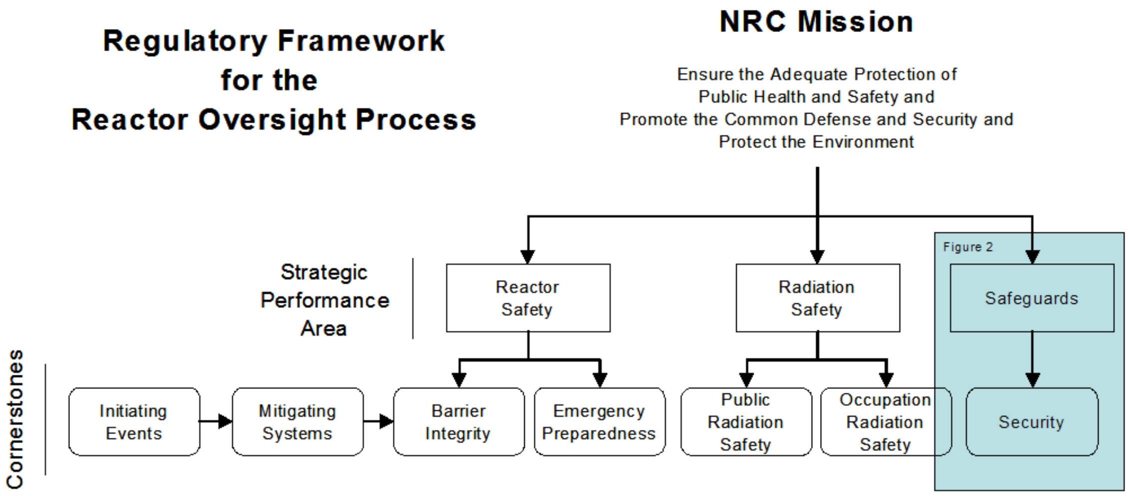


Fig. 6.3: Cornerstones of the Reactor Oversight Process.

6.2 US Department of Energy (DOE)

The US Department of Energy was formed in 1977 and it brought together activities under the AEC as the civil successor to the Manhattan Project, the Energy Research and Development Administration (ERDA) which succeeded it in 1974, and other bodies (see Fig. 6.4 [63]). The purpose was to achieve better coordination of policy by putting previously disparate agencies and programs together into a single Cabinet-level department. The Secretary of Energy reports to the President. The DOE's responsibilities include policy and funding for programs not only on nuclear energy, but also on fossil fuels, hydropower and alternative sources of energy. The DOE also manages the government's 21 national laboratories.

In addition to the DOE's responsibilities for civilian nuclear energy, its National Nuclear Security Administration (NNSA) oversees the military application of nuclear energy, maintaining the country's weapons stockpile and managing the design, production and testing of nuclear weapons [59].

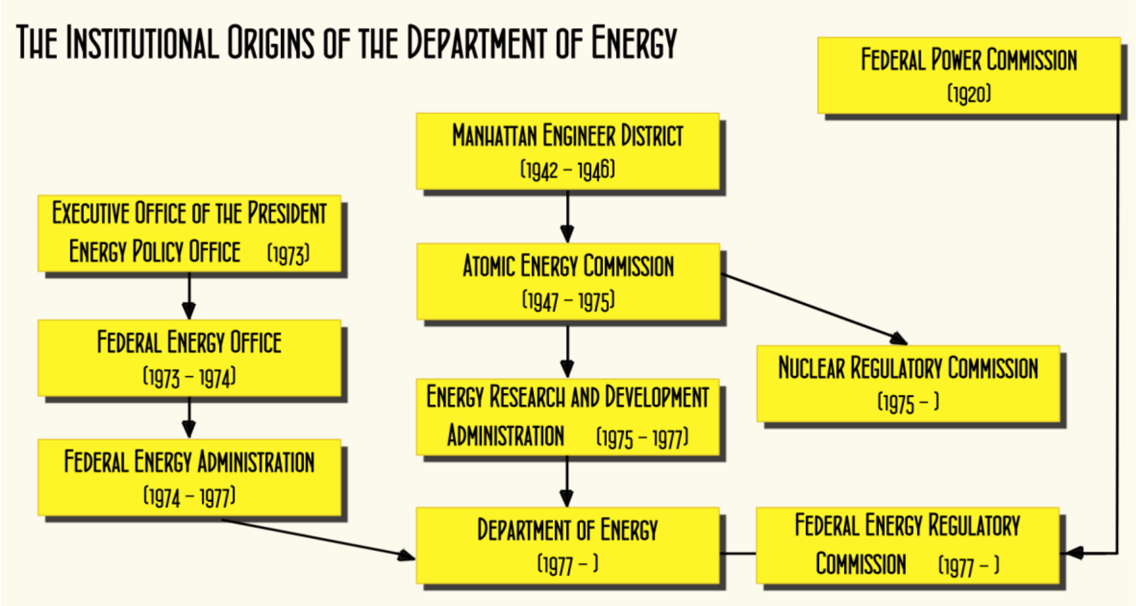


Fig. 6.4: The institutional origins of the Department of Energy.

6.3 Physical protection of facilities

For the regulation of physical protection of facilities in USA, the NRC regulation title 10 of “Code of Federal Regulations”, part 73 is to be considered [64]. Parts from 73.40 to 73.61 describe the requirements for physical protection against radiological sabotage, or against theft of special nuclear material, or against both at fixed sites, be they licensed activities, storage, NPPs or non-power reactors. Moreover, for NPPs, in part 73.58, the safety/security interface requirements are described. In this respect, in the regulation is written:

> *(b) The licensee shall assess and manage the potential for adverse effects on safety and security, including the site emergency plan, before implementing changes to plant configurations, facility conditions, or security.*
> *(c) The scope of changes to be assessed and managed must include planned and emergent activities (such as, but not limited to, physical modifications, procedural changes, changes to operator actions or security assignments, maintenance activities, system reconfiguration, access modification or restrictions, and changes to the security plan and its implementation).*
> *(d) Where potential conflicts are identified, the licensee shall communicate them to appropriate licensee personnel and take compensatory and/or mitigating actions to maintain safety and security under applicable Commission regulations, requirements, and license conditions.*

A licensee physical protection system, at fixed sites, shall include the following measures:

- Security organization: guards armed with a handgun and Tactical Response Team (each TRT member shall be armed with a 9 mm semiautomatic pistol; all but one member of the TRT shall be armed additionally with either a shotgun or semiautomatic rifle, the remaining member of the TRT shall carry a rifle of no less caliber than 7.62 mm). TRT members, armed response personnel, and guards shall qualify and requalify, at least every 12 months, for day and night firing with assigned weapons. In addition, in the part 73.46 of 10 CFR, all the technical and physical training requirements are specified.
- Physical barrier subsystems: for the structure of PPS see Fig. 6.5. Moreover these structures, a numbered picture badge identification subsystem shall be used for all individual. All points of personnel and vehicle access into a protected area shall be controlled for firearms, explosives, and incendiary devices except for Federal, State, and local law enforcement personnel on official duty and United States Department of Energy couriers engaged in the transport of special nuclear material. The individual responsible for the last access control function (controlling admission to the protected area) shall be isolated within a structure with bullet resisting walls, doors, ceiling, floor, and windows.

Physical protection system, at licensed activities (possesses, uses, or stores formula quantities of strategic special nuclear material that are not readily separable from other radioactive material and which have total external radiation dose rates in excess of 100 rems/h at a distance of 3 feet from any accessible surfaces without intervening shielding), shall include the following measures:

- Security organization including guards, to protect his facility against radiological sabotage and the special nuclear material in his possession against theft. At least one supervisor of the security organization shall be on site at all times.
- Physical barrier as described in Fig. 6.6. All alarms required shall annunciate in a continuously manned central alarm station located within the protected area and in at least one other continuously manned station such that a single act cannot remove the capability for calling for assistance or otherwise responding to an alarm. All alarms shall be self-checking and tamper indicating. The annunciation of an alarm at the onsite central station shall indicate the type of alarm (e.g., intrusion alarm, emergency exit alarm, etc.) and location.

Physical protection systems of licensee that stores spent nuclear fuel and high-level radioactive waste shall include the following measures:

- The security organization must include sufficient personnel per shift to provide for monitoring of detection systems and the conduct of surveillance, assessment access control, and communications to assure adequate response. Members of the security organization must be trained, equipped, qualified, and re-qualified to perform assigned job duties.
- Physical barrier as described in Fig. 6.7.

In the paragraph 73.55 of 10 CFR, the requirements for physical protection of licensed activities in nuclear power reactors against radiological sabotage are described. The main requirements are:

- The identification and description of the security plan that must describe how the licensee will implement requirements through the establishment and maintenance of a security organization, the use of security equipment and technology, the training and qualification of security personnel, the implementation of predetermined response plans and strategies, and the protection of digital computer and communication systems and networks.
- Security organization with at least one member, onsite and available at all times, who has the authority to direct the activities of the security organization.
- Physical barrier: the reactor control room, the central alarm station, and the location within which the last access control function for access to the protected area is performed, must be bullet-resisting. See Figure 6.8 for details.
- As a minimum the licensee shall review each element of the physical protection program at least every 24 months.

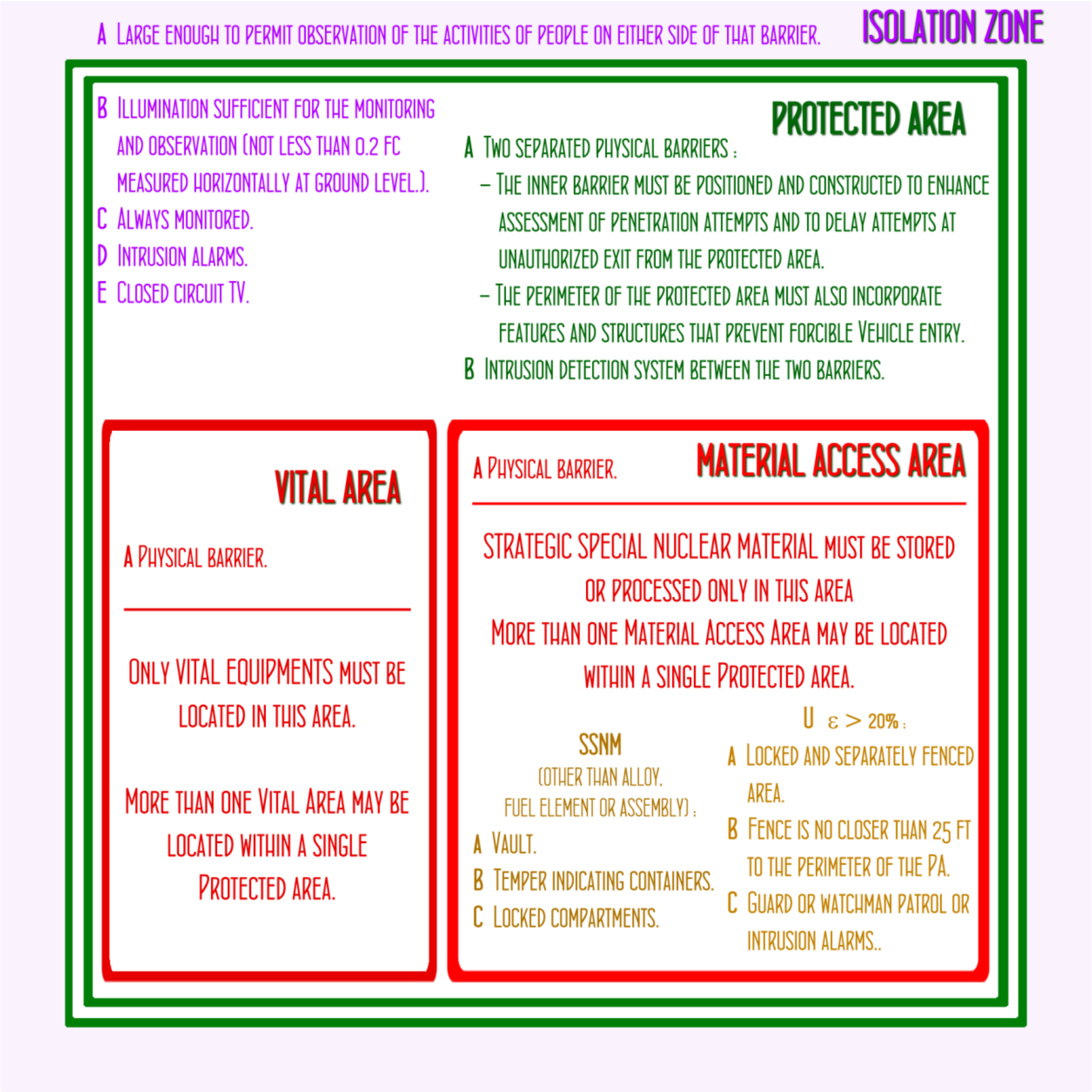


Fig. 6.5: Physical Protection System at fixed sites in USA.

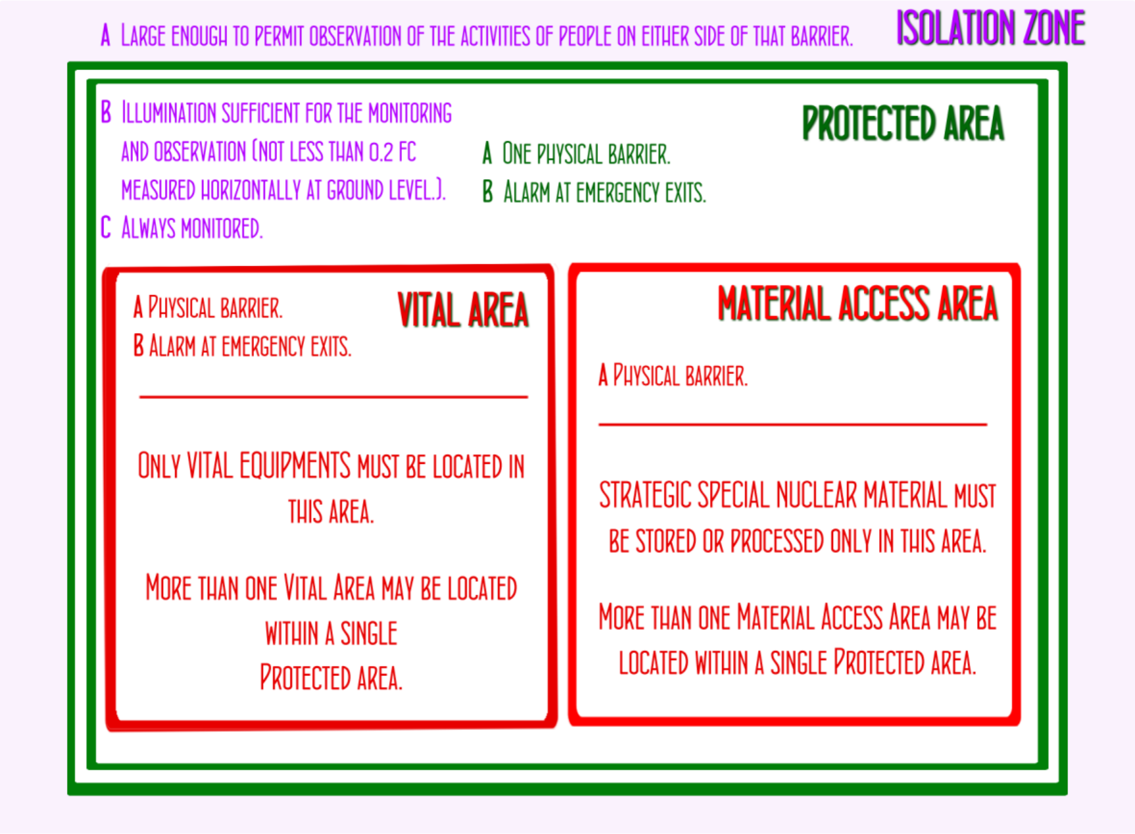


Fig. 6.6: Physical Protection System at licensed activities in USA.

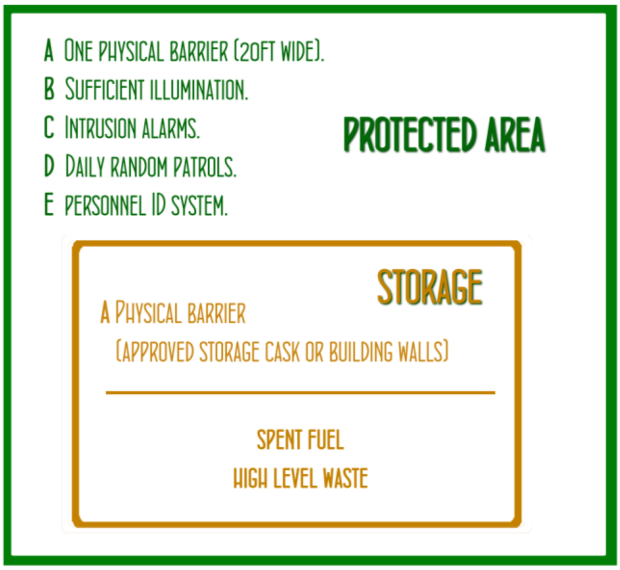


Fig. 6.7: Physical Protection System at storages in USA.

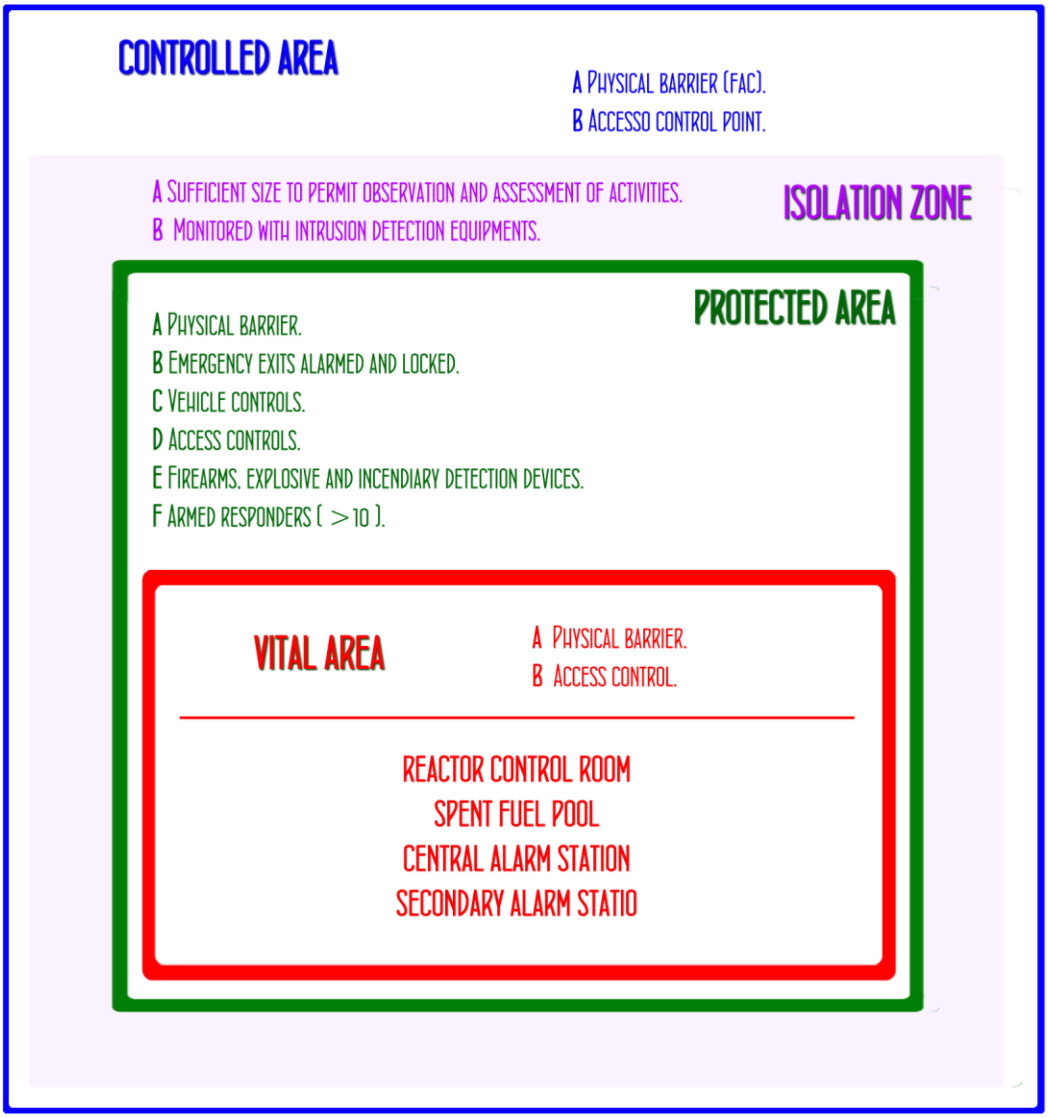


Fig. 6.8: Physical Protection System at nuclear power reactors in USA.

6.4 Physical protection & Accountancy of nuclear material

The classification of nuclear materials, has found in the 10 CFR part 73.2 [64], has some changes compared with the CPPNM classification. Details are presented in Tab. 6.1.

Tab. 6.1: Categorization of Nuclear Material in USA.

Material	**Form**	**Category I**	**Category II**	**Category III** [e]
Pu	Un-irradiated	Any combination more than 5 kg computed by the “formula quantity” [a]	Less than I but more than 500 g; Any combination more than 1 kg computed by the “formula quantity” [b]	Less than II but more than 15 g; Any combination more than 15 g computed by the “formula quantity” [c]
^{235}U	U enriched to 20% 235U or more	Any combination more than 5 kg computed by the “formula quantity” [a]	Less than I but more than 1 kg; Any combination more than 1 kg computed by the “formula quantity” [b]	Less than II but more than 15 g; Any combination more than 15 g computed by the “formula quantity” [c]
	U enriched to 10% 235U, but less than 20%		10 kg or more	Less than 10 kg but more than 1 kg
	U enriched above natural, but less than 10%			10 kg or more
^{233}U	Irradiated [d]	Any combination more than 5 kg computed by the “formula quantity” [a]	Less than I but more than 500 g; Any combination more than 1 kg computed by the “formula quantity” [b]	Less than II but more than 15 g; Any combination more than 15 g computed by the “formula quantity” [c]

[a] grams = (gramscontainedU^{235})+2.5(gramsU^{233} + gramsPu).
[b] grams = (gramscontainedU^{235})+2(gramsU^{233} + gramsPu).
[c] grams = (gramscontainedU^{235})+(gramsU^{233})+(gramsPu).

For the physical protection on these materials the regulation in law is the 10 CFR part 73.67, while for the control and accountancy is the 10 CFR part 74 [65].

The requisites for the physical protection are:

- For material of low strategic significance, the storage or use must be limited in a controlled access area with an intrusion alarm or other device or procedures.
- For material of moderate strategic significance, the use must be limited in controlled access area which is illuminated sufficiently to allow detection and surveillance of unauthorized penetration or activities; the storage, instead, must be performed using vault-type room or approved security cabinet. Materials must be monitored with intrusion alarm or other device or procedures to detect unauthorized penetration or activities. Moreover, a search on a random basis of vehicles and packages leaving the controlled access areas must be performed.

As regard the control of nuclear materials, in case of loss or theft or other unlawful diversion of special nuclear material which the licensee is licensed to possess, or any incident in which an attempt has been made to commit a theft or unlawful diversion of special nuclear material, each licensee who possesses one gram or more of contained U^{235}, U^{233} or Pu shall notify the NRC Operations Center within 1h.

Regarding the accountancy of nuclear materials, each licensee possessing, or who had possessed in the previous reporting period, at any one time and location, special nuclear material in a quantity totaling one gram or more of contained U^{235}, U^{233} or Pu shall complete and submit, in computer-readable format Material Balance Reports concerning special nuclear material that the licensee has received, produced, possessed, transferred, consumed, disposed, or lost. With each Material Balance Report, the Physical Inventory Listing Report must be submitted. Reports must be submitted for each Reporting Identification Symbol (RIS) account including all holding accounts. Moreover, in case of discrepancy identified during the report review and reconciliation process, each licensee shall resolve these discrepancies within 30 calendar days of notification of a discrepancy identified by NRC.

- For material of low strategic significance, in each inventory period, control total material control and accounting measurement uncertainty so that twice its standard error is less than the greater of 9000g of U^{235} or 0.25% of the active inventory. The physical inventory must be performed at least every 12 months and, within 60 days after the start of the inventory, reconcile and adjust the book inventory to the results of the physical inventory, and resolve, or report an inability to resolve, any inventory difference which is rejected by a statistical test which has a 90 % power of detecting a discrepancy of a quantity of U^{235} established by NRC on a site-specific basis.
- For material of moderate strategic significance, the physical inventories of all possessed SNM for each plant shall be conducted at intervals not to exceed 9 calendar months and within 60 calendar days after the start of each physical inventory the inventory difference (ID) and its associated standard error of inventory difference (SEID) for both element and isotope must be calculated, for the material balance period terminated by the physical inventory. Moreover, the material control and accountancy system must incorporate checks and balances that are sufficient to detect falsification of data and reports that could conceal diversion of SNM by a single individual (including an employee in any position) or collusion between two individuals (one or both of whom have authorized access to SNM).
- For material of strategic significance, other than the previously measure, a statistical test, that has at least a 95% power of detecting an abrupt loss of five formula kilograms within three working days of a loss of Category IA[2] material from any accessible process location

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[2] Category IA material means SSNM directly useable in the manufacture of a nuclear explosive device, except if:
  - The dimensions are large enough (at least 2 m in one dimension, greater than 1 m in each of two dimensions, or greater than 25 cm in each of three dimensions) to preclude hiding the item on an individual;
  - The total weight of an encapsulated item of SSNMis such that it cannot be carried inconspicuously by one person (i.e., at least 50 kg gross weight);
  - The quantity of SSNM (less than 0.05 formula kilograms) in each container requires protracted diversions to accumulate five formula kilograms.

and within seven calendar days of a loss of Category IB[3] material from any accessible process location, shall be present in the control program. The detection capability must be sufficient for laboratory samples containing less than 0.05 formula kilograms of SSNM and the licensee shall verify on a statistical sampling basis, the presence and integrity of SSNM items.

6.5 Emergency and contingency plans

As a condition of their license, operators of NPPs must develop and maintain Emergency Preparedness (EP) plans that meet comprehensive NRC EP requirements. The regulations for this case are the 10 CFR part 50.47 and appendix E, the NUREG-0800 part 13.3 and 14.3.10, the NUREG-0654/FEMA-REP-1, the NUREG-0696 and the NUREG- 0737 [66, 67, 68, 69, 70, 71, 72].

The NRC assesses the capabilities of the nuclear power plant operator to protect the public by requiring the performance of a full-scale exercise at least once every two years that includes the participation of government agencies. These exercises are performed in order to maintain the skills of the emergency responders and to identify and correct weaknesses. They are evaluated by NRC inspectors and FEMA (Federal Emergency Management Agency)[4] evaluators. Between these two-year exercises, additional drills are conducted by the nuclear power plant operators that are evaluated by NRC inspectors.

NRC is the Coordinating Agency for radiological events occurring at NRC-licensed facilities and for radioactive materials either licensed by NRC or under NRC's Agreement States Program. As Coordinating Agency, NRC has technical leadership for the Federal government's response to the event. If the severity of an event rises to the level of General Emergency (see Tab. 6.2 and Tab. 6.5 for detailed description of emergency levels [73]), or is terrorist-related [74], Department of Homeland Security will take on the role of coordinating the overall Federal response to the event, while NRC would retain a technical leadership role, other Federal agencies who may respond to an event at an NRC-licensed facility, or involving NRC-licensed material, include Federal Emergency Management Agency, the Department of Energy, the Environment Protection Agency, the Department of Agriculture, the Department of Health and Human Services, the National Oceanographic and Atmospheric Administration, and the Department of State (see Fig. 6.10 [73]).

Immediately upon becoming aware that an incident has occurred that may result in a radiation dose that exceeds federal government protective action guides, responsible nuclear power plant personnel evaluate plant conditions and then make EPA PAGs to the State and local government agencies on how to protect the population. Nuclear power plant personnel are required to report the PARs to the State or local government agencies (within 15 minutes). State and local officials make the final decision on what protective action is necessary to protect public health and safety, and then relay these decisions to the public in a timely manner (normally within approximately 15 minutes).

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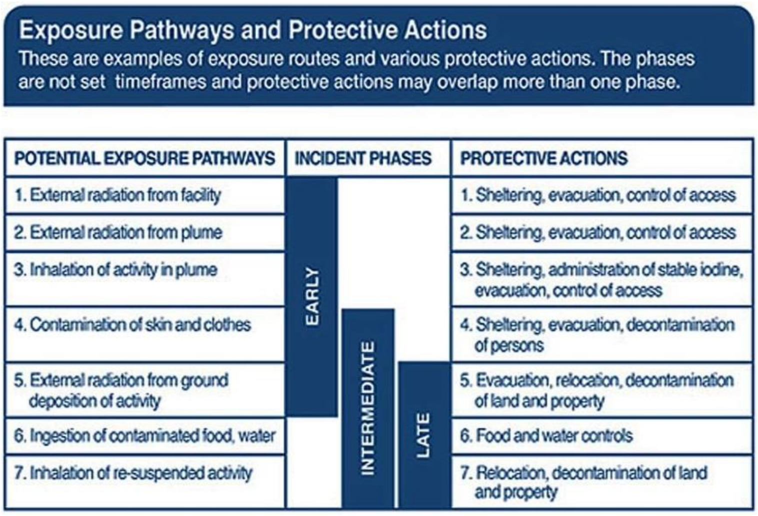
[3] Category IB material means all SSNM material other than Category IA.

[4] The FEMA coordinates the federal government's role in preparing for, preventing, mitigating the effects of, responding to, and recovering from all domestic disasters, whether natural or man-made, including acts of terror.

Tab. 6.2: Licensee Emergency Classes for NPPs.

Notification of Unusual Event	Alert	Site Area Emergency	General Emergency
Events are in process or have occurred which indicate potential degradation in the level of safety of the plant. No release of radioactive material requiring offsite response or monitoring is expected unless further degradation occurs.	Events are in process or have occurred which involve an actual or potential substantial degradation in the level of safety of the plant. Any releases of radioactive material from the plant are expected to be limited to a small fraction of the EPA Protective Action Guideline exposure levels (see Fig. 6.9, Tab. 6.3 and Tab. 6.4).	Events in process or have occurred which involve actual or likely major failures of plant functions needed for protection of the public. Any releases of radioactive material are not expected to exceed the EPA PAGs except near the site boundary.	Events in process or have occurred which involve actual or imminent substantial core damage or melting of reactor fuel with the potential for loss of containment integrity. Radioactive releases during a general emergency can reasonably be expected to exceed the EPA PAGs for more than the immediate site area.



Exposure Pathways and Protective Actions

These are examples of exposure routes and various protective actions. The phases are not set timeframes and protective actions may overlap more than one phase.

POTENTIAL EXPOSURE PATHWAYS	INCIDENT PHASES			PROTECTIVE ACTIONS
1. External radiation from facility	EARLY			1. Sheltering, evacuation, control of access
2. External radiation from plume				2. Sheltering, evacuation, control of access
3. Inhalation of activity in plume				3. Sheltering, administration of stable iodine, evacuation, control of access
4. Contamination of skin and clothes		INTERMEDIATE		4. Sheltering, evacuation, decontamination of persons
5. External radiation from ground deposition of activity			LATE	5. Evacuation, relocation, decontamination of land and property
6. Ingestion of contaminated food, water				6. Food and water controls
7. Inhalation of re-suspended activity				7. Relocation, decontamination of land and property

Fig. 6.9: EPA exposure pathways, incident phases, and protective actions.

Tab. 6.3: PAGs for the early phase of a nuclear incident.

Protective Action	PAG (projected dose)	Comments
Evacuation (or sheltering)	1 ÷ 5 rem	Evacuation (or, for some situations, she1tering) should normally be initiated at 1 rem.
Administration of stable iodine	25 rem	Requires approval of State medical officials

Tab. 6.4: PAGs for exposure to deposited radioactivity during the intermediate phase of a nuclear incident.

Protective Action	PAG (projected dose)	Comments
Relocate the general population	≥ 2 rem	Beta dose to skin may be up to 50 times higher.
Apply simple dose reduction techniques	< 2 rem	These protective actions should be taken to reduce doses to as low as practicable levels.

Tab. 6.5: Licensee Emergency Classes for nuclear materials and fuel cycle facility licensees.

Alert	Site Area Emergency
Events may occur, are in progress, or have occurred that could lead to a release of radioactive materials, but the release is not expected to require a response by an offsite response organization to protect people offsite.	Events may occur, are in progress, or have occurred that could lead to a significant release of radioactive materials, and the release could require a response by offsite response organizations to protect people offsite.

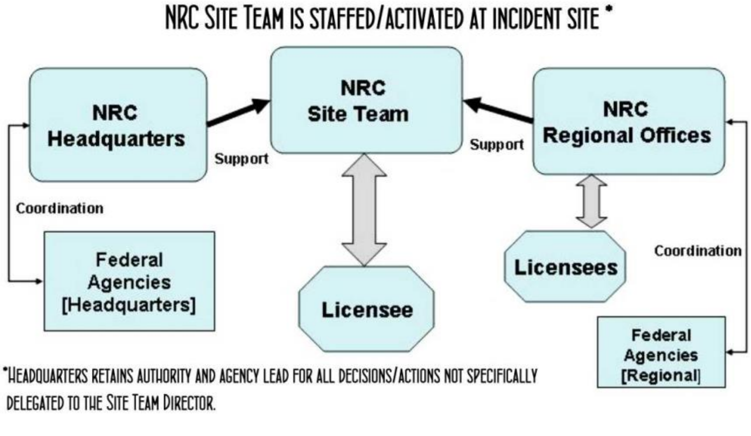


Fig. 6.10: NRC activation response mode.

The Preliminary Safety Analysis Report shall contain sufficient information to ensure the compatibility of proposed emergency plans for both onsite areas and the Emergency Planning Zones (EPZs), with facility design features, site layout, and site location with respect to such considerations as access routes, surrounding population distributions, land use, and local jurisdictional boundaries for the EPZs in the case of nuclear power reactors. EPZs for power reactors are discussed in NUREG–0396 and EPA 520/1–78–016. There are two EPZs around each nuclear power plant:

- The Plume Exposure Pathway EPZ has a radius of about 10miles from the reactor site. Predetermined protective action plans are in place for this EPZ and are designed to avoid or reduce dose from potential exposure of radioactive materials. These actions include sheltering, evacuation, and the use of potassium iodide (see Fig. 6.11 [75]).
- The ingestion exposure pathway EPZ has a radius of about 50 miles from the reactor site. Predetermined protective action plans are in place for this EPZ and are designed to avoid or reduce dose from potential ingestion of radioactive materials. These actions include a ban of contaminated food and water.

The size of the EPZs for a nuclear power plant shall be determined in relation to local emergency response needs and capabilities as they are affected by such conditions as demography, topography, land characteristics, access routes, and jurisdictional boundaries. The size of the EPZs also may be determined on a case-by-case basis for gas-cooled nuclear reactors and for reactors with an authorized power level less than 250MWt. Generally, the plume exposure pathway EPZ for nuclear power plants with an authorized power level greater than 250MWt shall consist of an area about 16 km in radius and the ingestion pathway EPZ shall consist of an area about 80 km in radius.

The center of the map is the location of the commercial nuclear power plant reactor building. Concentric circles of 2, 5, and 10 miles have been drawn and divided into triangular sectors identified by letters from A to R. Municipalities identified to be within the 10-mile EPZ have been assigned numbers from 1 to 24. The triangular sectors provide a method of identifying what municipalities are affected by the radioactive plume as it travels.

Fig. 6.11: Typical 10-Mile Plume Exposure Pathway EPZ Map.

6.6 Penalties

The Atomic Energy Act of 1954 [56], as amended, describes all the sanctions and penalties coming not only from the non-conformity with the laws, but also from malevolent act against nuclear materials and facilities. Moreover, in the United States Code [76] is possible to find some provision against the use of radiological dispersal device and weapons of mass destruction (including any weapon that is designed to release radiation or radioactivity at a level dangerous to human life).

In Tab. 6.6 a summary of these sanctions is shown.

Tab. 6.6: Penalties in USA.

Crime	Penalties
Willfully violates, attempts to violate, or conspires to violate: transfer or receive in interstate commerce, transfer, deliver, acquire, own, possess, receive possession of or title to, or import into or export from the US any SNM unless authorization (Sec. 57). transfer or receive in interstate commerce, manufacture, produce, transfer, acquire, possess, use, import, or export any utilization or production facility without a license (Sec. 101). Interferes, attempts to interfere, or conspires to interfere with the suspension of any licenses in case of state of war or national emergency (Sec. 108).	Imprisonment not more than 10 years or/and fine of not more than $10,000. With intent to injure the US or to secure an advantage to any foreign nation: Imprisonment for life, or by imprisonment for any term of years or a fine of not more than $20,000 or both. (Sec. 222)
A) Knowingly participate in the development of, manufacture, produce, transfer, acquire, receive, possess, import, export, or use, or possess and threaten to use, any atomic weapon (Sec. 92). B) Uses, attempts or conspires to use, or possesses and threatens to use, any atomic weapon, in the course of a violation of section 92. C) If the death of another result from a person's violation of section 92.	A) Imprisonment not less than 25 years or imprisonment for life and fine not more than $2,000,000. (Sec. 222) B) Imprisonment for not less than 30 years or imprisoned for life and fine not more than $2,000,000. (Sec. 222) C) Imprisonment for life and fine not more than $2,000,000. (Sec. 222)
Individual director, officer or employee of a person indemnified under an agreement of indemnification who, by act or omission, knowingly and willfully violates or causes to be violated any section of the Atomic Energy Act or any applicable nuclear safety-related rule, regulation or order issued thereunder by the Secretary of Energy, which violation results in or, if undetected, would have resulted in a nuclear incident. (Sec. 223 with reference to Sec. 170d)	Imprisonment not more than 2 years or/and fine of not more than $25,000 per day of violation. If the conviction is for a violation committed after a first conviction: Imprisonment not more than 5 years or/and fine of not more than $50,000 per day of violation. (Sec. 223)

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Tab. 6.6 (continued): Penalties in USA.

Crime	Penalties
Individual director, officer, or employee of a firm constructing, or supplying the components of any utilization facility who by act or omission, in connection with such construction or supply, knowingly and willfully violates or causes to be violated, any section of the Atomic Energy Act or any license condition, which violation results, or if undetected could have resulted, in a significant impairment of a basic component of such a facility. (Sec. 223)	Imprisonment not more than 2 years or/and fine of not more than $25,000 per day of violation. If the conviction is for a violation committed after a first conviction: Imprisonment not more than 2 years or/and fine of not more than $50,000 per day of violation. (Sec. 223)
Willfully violates, attempts to violate, or conspires to violate, any provision of the Atomic Energy Act for which no criminal penalty is specifically provided. (Sec. 223)	Imprisonment not more than 2 years or/and fine of not more than $5,000. With intent to injure the US or to secure an advantage to any foreign nation: Imprisonment not more than 20 years or/and fine of not more than $20,000. (Sec. 223)
Entry upon or carrying, transporting, or otherwise introducing or causing to be introduced any dangerous weapon, explosive, or other dangerous instrument or material likely to produce substantial injury or damage to persons or property, into or upon any facility, installation, or real property subject to the jurisdiction, administration, in the custody of the Commission. (Sec. 229)	Fine of not more than 1 000 $. If installation or other property is enclosed by a fence, wall, floor, roof, or other structural barrier shall be guilty of a misdemeanor and upon conviction thereof shall be punished by: Imprisonment not more than 1 year or/and fine of not more than $5,000. (Sec. 229)
Knowingly destroys or causes physical damage (or attempts or conspires to do such an act) to any production facility or utilization facility; any nuclear waste treatment, storage, or disposal facility; any nuclear fuel for a utilization facility or any spent nuclear fuel from such a facility; any uranium enrichment, uranium conversion, or nuclear fuel fabrication facility; any production, utilization, waste storage, waste treatment, waste disposal, uranium enrichment, uranium conversion, or nuclear fuel fabrication facility during construction of the facility, if the destruction or damage caused or attempted to be caused could adversely affect public health and safety during the operation of the facility; any primary facility or backup facility from which a radiological emergency preparedness alert and warning system is activated; or any radioactive material or other property. (Sec. 236)	Imprisonment not more than 20 years or/and fine of not more than $10,000. If the death results: Imprisoned for any term of years or for life. (Sec. 236)

Table continues on the next page

Tab. 6.6 (continued): Penalties in USA.

Crime	**Penalties**
Knowingly produce, construct, otherwise acquire, transfer directly or indirectly, receive, possess, import, export, or use, or possess and threaten to use any weapon that is designed or intended to release radiation or radioactivity at a level dangerous to human life; or any device or other object that is capable of and designed or intended to endanger human life through the release of radiation or radioactivity. (Title 18 Sec. 2332h of the United States Code)	Imprisonment not less than 25 years or to imprisonment for life and fine of not more than $2,000,000. If the death of another results: Imprisonment for life and fine not more than $2,000,000. (Title 18 Sec. 2332h of the United States Code)
Uses, threatens, or attempts or conspires to use, a weapon of mass destruction without lawful authority. (Title 18 Sec. 2332a of the United States Code)	Imprisonment for any term of years or for life. If the death results: Punished by death or imprisoned for any term of years or for life. (Title 18 Sec. 2332a of the United States Code)

Section 2

PR&PP methodology

CONTENT – SECTION 2

LIST OF FIGURES – SECTION 2

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1 INTRODUCTION

Although it had been known since 1938 that the chain reaction of nuclear fission would produce enormous amount of energy, the nuclear age began with the military application of nuclear science and technology in 1945, but immediately after the Second World War, the international non-proliferation campaign was launched. At first, the United States unilaterally pursued a so-called “denial policy” in prohibiting any sort of international transfer of nuclear technology. This began with the McMahon Bill, which was submitted to the Senate in September 1945. The Bill was enacted as the US Atomic Energy Act in August 1946. The denial policy unilaterally denied all other countries access to nuclear technology under the US Atomic Energy Commission (AEC). On the other hand, the United States multilaterally pursued an international non-proliferation agreement that was intended to place nuclear material and activities under the jurisdiction of the United Nations (UN). In June 1946, the United States presented the Acheson-Lilienthal Plan (known as the Baruch Plan) to the United Nations Atomic Energy Commission (UNAEC). It was central to the Baruch Plan that fissile materials should be placed in the “safekeeping” of this international agency. This plan involved for the first time, the concept of safeguards and export control. However, the Baruch Plan failed because of objections by the USSR. Moreover, despite strenuous US efforts to keep in place the denial policy, nuclear proliferation was rapid and the Atoms for Peace Policy was established. President Eisenhower emphasized the need to exploit atomic energy for peaceful purposes, rather than for warfare and he proposed that the international agency should manage fissile material safely, throughout worldwide inspections and control systems and devise methods to allocate the fissionable material for peaceful uses:

> *The Atomic Energy Agency could be made responsible for impounding, storage and protection of the contributed fissionable and other material. ... The more important responsibility of this atomic energy agency would be to devise methods whereby this fissionable material would be allocated to serve the peaceful pursuits of mankind.*

Following the Atoms for Peace speech, the International Atomic Energy Agency (IAEA) was created with multilateral agreement under the authority of the UN in New York in September 1957. Once the IAEA was launched, an international safeguards system was established, although the safeguards were initially applied on a bilateral basis. In 1961, the IAEA safeguards began to replace the bilateral safeguards that suppliers had imposed, and the IAEA safeguards document, INFCIRC/26, which was to be applied to research reactors with less than 100 MWt was prepared [77, 78].

However, IAEA safeguards were insufficient to prevent nuclear proliferation, so in July 1968, the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) was opened for signature. Although the NPT was not universally accepted, especially by China and France, the NPT came into force in March 1970 with 97 signatory states. With the NPT becoming effective, the international non-proliferation regime was formed to prevent horizontal proliferation between nuclear weapon states (NWS) and non-nuclear weapon states (NNWS) under Articles I–III and to prevent vertical proliferation under Article VI. By the NPT, NNWS parties were required to place all of their fissile material under permanent IAEA safeguards, the scope and implementation of which were laid down in the model document INFCIRC/153. The comprehensive safeguards were developed and introduced under the NPT. The NPT prohibited the export of nuclear material and equipment without the recipient's acceptance of the IAEA safeguards.

However, the Indian nuclear explosion of 1974, which involved material and facilities supplied for peaceful purposes, brought a reappraisal of the United States nonproliferation policy. Following the Kissinger initiative, seven major nuclear suppliers (the United States, Canada, the UK, France, West Germany, Japan and the USSR) held a meeting of the Nuclear Suppliers Group (NSG) in London in June 1975 to seek agreement over a set of guidelines for the restriction of the export of certain sensitive items. It was also their intention to try to reach agreement on a more extensive application of international safeguards. In the course of several meetings between 1975 and 1977, the NSG finalized its "Guidelines for the Export of Nuclear Material, Equipment and Technology" in September 1977. These guidelines major features are the following: in addition to reprocessing and enrichment in the previous trigger list, heavy water production facilities were added to the sensitive facilities; in addition to transferred items, the guidelines specified control of the utilization of transferred technology or derived technology from the transferred technology, including design, construction or operating process under the IAEA safeguards; specification of particular special export controls on sensitive material technology; the recipient was required to agree that neither the transferred facility, nor any facility based on such technology would be designed and operated to produce greater than 20 percent enriched uranium without the consent of the supplier nation.

During the NSG process, the United States began to unilaterally strengthen its non-proliferation policy as it was dissatisfied with the NSG meeting. In October 1976, President Ford initiated a major policy for the application of full-scope safeguards, suspension of US reprocessing and recycling of plutonium, and development of an alternative nuclear fuel cycle. Based on this, the Nuclear Non-proliferation Act (NNPA) came into force in March 1978. This NNPA of 1978 stipulated:

- Cutting off of all US nuclear exports to NNWS with no full-scope safeguards after two years' grace;
- Cutting off of nuclear exports to NNWS that detonated or engaged in manufacturing or acquiring nuclear explosive devices;
- Prohibiting reprocessing and retransferring of US exported material without the prior consent of the United States.

Responding to this policy, the Nonproliferation Alternative Systems Assessment Program (NASAP) by the United States Department of Energy (DOE) begun in late 1976 and the International Nuclear Fuel Cycle Evaluation (INFCE) by the international community were launched in October 1977.

Since there are no nuclear energy systems, encompassing all types of reactors and nuclear fuel cycles, which can be completely proof against diversion of nuclear material for weapons purpose, the proliferation resistance is emphasized. The proliferation resistance is characteristics of nuclear energy systems that makes difficulty in diversion or production of weapons-usable material and its study firstly received its political impetus from the Carter's nonproliferation policy [79, 80].

In the 1980s, the international “Convention of Physical Protection of Nuclear Material” to prevent unauthorized use and handling was held. Moreover, France and the USSR permitted the application of the IAEA safeguards to specified nuclear plants in 1981, and China became a member of the IAEA in 1982. In addition, 16 more countries became parties to the NPT between 1980 and 1985.

After NASAP and INFCE [81], there have been several prominent associated studies on the assessment of the proliferation resistance: Plutonium Disposition by the United States National Academy of Science in the mid-1990s, the Technical Opportunities for Increasing the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS) by the U.S. DOE in early 2000s, and the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) Methodology by the IAEA and Generation IV nuclear energy systems (Gen IV) by the Gen IV International Forum (GIF) undergoing since early 2000s [82].

1.1 Previous works

The PRPP approach adopted by TOPS was entirely qualitative, based on breaking down the fuel cycle into stages and using a tabular method whereby the barriers applicable at each stage are listed and ranked according to a five-point scale from Ineffective, Low, Medium, High and Very High. The tables so constructed can then be used to identify priority areas for maximizing overall effectiveness. Its purpose was to use the comparative analysis to highlight the key technical questions that a fully developed methodology would need to address.

Japan Atomic Energy Agency (JAEA) also uses the TOPS tabular approach, but the barrier scoring is carried out by a panel of experts whose scores are then averaged to arrive at a numerical ranking. This is an attempt to make the process less affected by individual subjectivity. Although the outcome is a numerical score, the method is still qualitative and therefore unable to provide reliable relative rankings between options or sensitivities, but it is applicable to any stage of the fuel cycle and like TOPS can highlight where the vulnerabilities are [83, 82].

The IAEA’s INPRO has developed a set of guidelines to assist developers of new nuclear systems with all aspects of system design: safety; infrastructure; environment; waste management; physical protection; economics and PRPP. The aim is essentially to establish best practice for nuclear system designers to follow when developing new reactors and their associated fuel cycles. For all of the technical areas covered by INPRO, a set of Basic Principles and User Requirements are defined; in particular, for PRPP the basic principle is:

> *Proliferation resistance intrinsic features and extrinsic measures shall be implemented throughout the full life cycle for innovative nuclear energy systems to help ensure that innovative nuclear systems (INS) will continue to be an unattractive means to acquire fissile material for a nuclear weapons program. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself. [83, 84, 85]*

The Generation IV Forum methodology has some similarities to the INPRO methodology, being largely qualitative and based on prescriptive categorizations, but is currently more developed, provides a semi-quantitative outcome and is perhaps somewhat less subjective [86, 87]. It can also be used to analyze different threat scenarios. It is a rigorous process starting with the threat pathway definition, and the consequence analysis of the proliferation risk based on a set of six metrics: Technical Difficulty (TD); Proliferation Cost (PC); Proliferation Time (PT); Fissile Material Type (MT); Detection Probability (DP) and Detection Resource Efficiency (DE). To assign scores against each of the six metrics clear guidelines as to which category is applicable given the materials in the fuel cycle are to follow. The results provide a qualitative guide to comparing different proliferation pathways for a given reactor/fuel cycle. The method does not use weighting functions to aggregate the different metrics, so that no single overall numerical score is provided [88, 89, 90, 91, 92]. A full example of application of this methodology is done using the Example Sodium Fast Reactor (ESFR) [93].

World-wide, a large number of PRPP methodologies have been developed, influenced by and designed to be consistent with one or more of the frameworks above. Their distinguishing feature is that they aim to combine all the different metrics to provide a single quantitative figure of merit with which to compare different systems. In principle, this also allows sensitivity and uncertainty analysis to be performed, which is difficult to do in any meaningful way with the qualitative approaches. However, care is required because, though these quantitative methods may give the appearance of being rigorously objective, in many cases the process still involves a degree of subjectivity. Examples summarized below are the multi-attribute utility analysis (MAUA), Markovian methods and Risk Informed Probabilistic Analysis (RIPA): Multi-Attribute Utility Analysis (MAUA) is a long standing method that has been used to aggregate the assessment of multiple attributes. For proliferation resistance analysis, MAUA has been developed most fully by Texas A&M University (TAMU) [83, 94, 95, 96].

1.2 Definitions

According to previous publications [88, 97, 98, 90, 87], definitions of proliferation resistance and physical protection can be expressed as follows.

<u>Proliferation resistance</u> (PR) is that characteristic of a nuclear energy system (NES) that impedes the diversion or undeclared production of nuclear material or misuse of technology by the Host State seeking to acquire nuclear weapons or other nuclear explosive devices.

Resistance to a Host State‘s acquisition of nuclear weapons by concealed diversion of material from declared flows and inventories; overt diversion of material from declared flows and inventories; concealed material production or processing in declared facilities; overt material

production or processing in declared facilities; concealed material production or processing by replication of declared equipment in clandestine facilities.
The nuclear energy system is regarded to be the facilities that comprise it, their safeguards, their physical security, the fuel supply and take-back services among its participants, and the corresponding transportation of nuclear materials or sensitive technology.

Physical protection (PP) or Robustness is that characteristic of an NES that impedes the theft of materials suitable for nuclear explosives or radiation dispersal devices (RDDs) and the sabotage of facilities and transportation by sub-national entities and other non-Host State adversaries.
Physical Protection (robustness) by theft of nuclear weapons-usable material from facilities or transportation; theft of hazardous radioactive material from facilities or transportation for use in a dispersion weapon; sabotage at a nuclear facility or during transportation with the objective to release radioactive material to harm the public, damage facilities, or disrupt operations.

1.3 Objectives

Proliferation resistance and physical protection consider means for controlling and securing nuclear material and nuclear facilities. According to the previous definitions (see above section 1.2), the PR&PP technology goals for Generation IV NESs can be expressed as follows [98]:

- A Generation IV NES is to be the least desirable route to proliferation by hindering the diversion of nuclear material from the system and hindering the misuse of the NES and its technology in the production of nuclear weapons or other nuclear explosive devices;
- A Generation IV NES is to provide enhanced protection against theft of materials suitable for nuclear explosives or RDDs and enhanced protection against sabotage of facilities and transportation.

The benefits of meeting these goals include:

- Providing continued effective proliferation resistance of nuclear energy systems through improved design features and other measures;
- Increasing physical protection against terrorism by increasing the robustness of new facilities.

Very similar goals, both for proliferation resistance and physical protection, could be also found in some development targets. In general, a development target describes the requirements for the future energy system in ensuring safety, reduction of environmental burden, economic competitiveness, efficient utilization of resources, and enhancement of nuclear non-proliferation. As an example, the Japanese development target, described in the Japanese Fast Reactor Cycle Technology Development Project (FaCT Project) [5], says that a Fast Breeder Reactor (FBR) cycle system can be internationally accepted by achieving proliferation resistance to material diversion and facility misuse similar or superior to domestic and international advanced LWR

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[5] The FaCT project is the follow up of the previous one called "Feasibility Study on Commercialized Fast Reactor Cycle Systems" and started in 2001 with the aim to present an appropriate conceptual design for a commercial FR cycle system by 2015.

cycle and next generation nuclear system [99, 100, 101].

Following the methodology proposed by the PR&PP Working Group applicable to evaluate the PR&PP robustness of Generation IV NESs, the main objective on the basis of this work is to show an example on how to use results coming from the application of the PR&PP evaluation methodology to address both the GIF goal and the generic development target.

The following actions were performed to achieve this objective.

1. Implement the evaluation methodology based on the study's assumptions (see Tab. 1.1).
2. Characterize the PR&PP for the nuclear energy system applying the methodology to the study system.
3. Compare the study system with a reference one.

Following this analysis, recommendations for system designers were identified.

The present work is focused on the reactor site to show how to use results from the PR&PP evaluation methodology to meet the objectives described above.

The study system is a hypothetical commercial Sodium Fast Reactor(SFR) based on the Japanese Sodium Fast Reactor (JSFR) and its prototype Monju. The system was completely designed during this study and will be presented in Section 2; however, due to the presence of classified information, not all the evaluations done for this study could be available.

As the reference system it was decided to choose an hypothetical light water reactor (LWR) based on the European Pressurizer Reactor (EPR) with an open-through fuel cycle. This choice is done both because LWR are used all over the world and because previous works using different methodology, as summarized in [82], have shown that the open cycle for a LWR, even if some proliferation risks exist, is more proliferation resistant than other fuel cycles. In my study, the reactor building and the connected spent fuel pool will be included in the methodology application.

Regarding the step 2, this study will apply the methodology to the FBR considering results separate and verify if these systems meet the target of PR and PP (GIF target).

Regarding the step 3, instead, a comparison between the two systems will be performed to evaluate if and how it will be possible to improve the PR&PP of the FBR (development target).

Tab. 1.1: Assumptions under the study.

Description	Assumption
SFR layout	Based on the JSFR
SFR safeguards system	Based on the Japanese prototype Monju
LWR layout	Based on the EPR
LWR safeguards system	Based on the LWR common practice
Development target	PR similar or superior to advanced LWR
State capability	Based on Japan's situation; participant of the International Community

1.4 Approaches

The Technology Goals for Generation IV nuclear energy systems (NESs) highlight PR&PP as one of the four goal areas along with Sustainability, Safety and Reliability, and Economics:

> *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. [98]*

For a given system, analysts define a set of challenges, analyze system response to these challenges, and assess outcomes (see Fig. 1.1 and Fig. 1.2). The challenges to the NES are the threats posed by potential proliferant States and by sub-national adversaries. The technical and institutional characteristics of the Generation IV systems are used to evaluate the response of the system and determine its resistance to proliferation threats and robustness against sabotage and terrorism threats. The outcomes of the system response are expressed in terms of PR&PP measures and assessed. In the following paragraphs, a detail description of the methodology, its measure and its application for this study to the two systems, LWR and SFR, will be presented.

The first step of the methodology is the threat definition. For both PR and PP, the threat definition describes the challenges that the system may face and includes characteristics of both the actor and the actor’s strategy.

When threats have been sufficiently detailed for the particular evaluation, analysts assess system response, which has four components.

1. *System Element Identification*. The NES is decomposed into smaller elements or subsystems at a level amenable to further analysis. The elements can comprise a facility (in the systems engineering sense), part of a facility, a collection of facilities, or a transportation system within the identified NES where acquisition (diversion) or processing (PR) or theft/sabotage (PP) could take place.
2. *Target Identification and Categorization*. Target identification is conducted by systematically examining the NES for the role that materials, equipment, and processes in each element could play in each of the strategies identified in the threat definition. PR targets are nuclear material, equipment, and processes to material, equipment, or information to be protected from threats of theft and sabotage. Targets are categorized to create representative or bounding sets for further analysis.
3. *Pathway Identification and Refinement*. Pathways are potential sequences of events and actions followed by the actor to achieve objectives. For each target, individual pathways are divided into segments through a systematic process, and analyzed at a high level. Segments are then connected into full pathways and analyzed in detail. Selection of appropriate pathways will depend on the scenarios themselves, the state of design information, the quality and applicability of available information, and the analyst's preferences.

4. *Estimation of Measures*. The results of the system response are expressed in terms of PR&PP measures. Measures are the high-level characteristics of a pathway that affect the likely decisions and actions of an actor and therefore are used to evaluate the actor's likely behavior and the outcomes. For each measure, the results for each pathway segment are aggregated as appropriate to compare pathways and assess the system so that significant pathways can be identified and highlighted for further assessment and decision making.

Fig. 1.1: Basic framework for the PR&PP evaluation methodology.

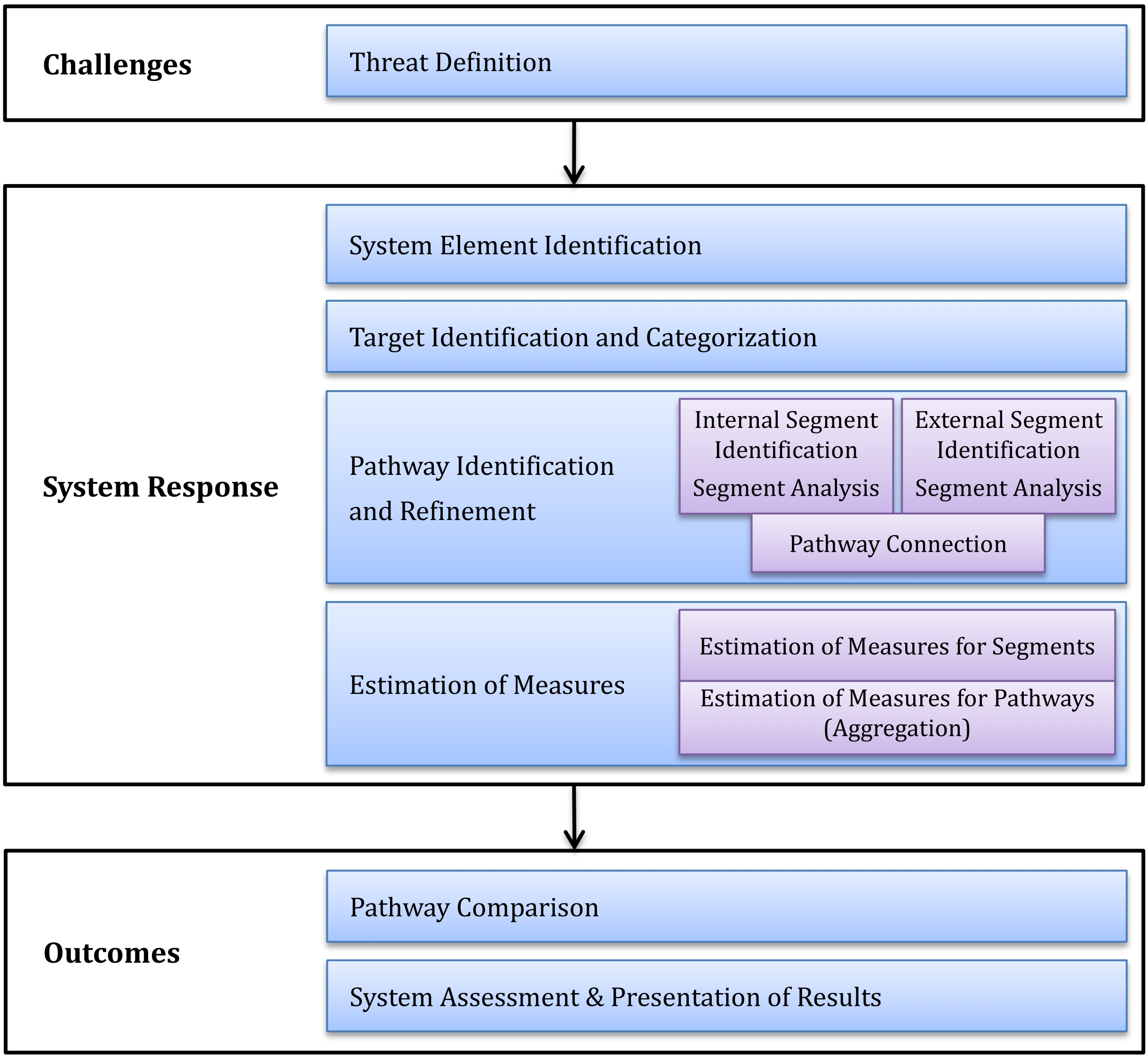


Fig. 1.2: Framework for the PR&PP evaluation methodology.

PR&PP measures

For PR, the measures are

- *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 NES.

For PP, the measures are (summarize in Tab. 1.2)

- *Probability of Adversary Success*: the probability that an adversary will successfully complete the actions described by a pathway and will generate a consequence.
- *Consequences*: the effects resulting from the successful completion of the adversary's action described by a pathway.
- *Physical Protection Resources*: the staffing, capabilities, and costs required to provide PP, such as background screening, detection, interruption, and neutralization, and the sensitivity of these resources to changes in the threat sophistication and capability.

For assessing each PR measure, it could be possible to apply the representative metrics given in Tab. 1.3 using the following process:

1. Given a pathway segment or an entire pathway, the value for a specific PR measure can be estimated according to the selected metric, yielding an estimated measure value in terms of the metric

   PR measure → metric → estimated measure value

2. Bins have been defined for grouping ranges of estimated measure values. A PR qualitative descriptor is attached to each bin, describing the proliferation resistance associated with the estimated measure value range. PR qualitative descriptors range, very low, low, medium, high and very high (VL, L, M, H, VH).

   Estimated measure value → bin → PR qualitative descriptor

From Tab. 1.4 to Tab. 1.9 a summary of characteristics for each measure will be presented.

Tab. 1.2: Proposed PP qualitative measures for the evaluation of conceptual nuclear facility designs.

PP Measures	Metric scales bins (median)	Physical protection qualitative description
Probability of Adversary Success (P_s)	$0.1 > P_s = 0$ (0.05)	No
	$0.5 > P_s \geq 0.1$ (0.3)	Low
	$0.8 > P_s \geq 0.5$ (0.65)	Medium
	$1 > P_s \geq 0.8$ (0.9)	High
PP Resources (PPR) It is evaluated as the % of operating cost.	0	No
	5% > PPR > 0% (1%)	Low
	10% > PPR > 0% (5%)	Medium
	PPR > 10% (10%)	High
Consequences (C_R) Reactor radiological consequences.	No Radiological Release (No Core Damage)	No
	Building Release ($CDF<10^{-6}$)	Low
	Onsite Release ($CDF>10^{-6}$ with mitigation)	Medium
	Offsite Release ($CDF>10^{-6}$ without mitigation)	High
Consequences (C_E) Economic consequences.	NSSS unaffected	No
	Cleanup of NSSS < 1 yr	Low
	Cleanup of NSSS > 1 yr	Medium
	Permanent loss of NSSS	High
Consequences (C_D) Radiological Dispersion Device (RDD) radiological consequences.	No radiological release	No
	Localized contamination	Low
	Urban contamination	Medium
	Urban contamination with loss of life	High
Consequences (C_t) Special Nuclear Material (SNM) theft consequences.	Unsuccessful theft	No
	1 SQ of irradiated indirect use material	Low
	1 SQ of unirradiate indirect use material	Medium
	1 SQ of unirradiated or irradiated direct use material	High

Tab. 1.3: Example metrics and estimated measure values for PR measures.

Measures and metrics	Metric scales bins (median)	Proliferation resistance qualitative description [b]
Proliferation Technical Difficulty (TD) Example metric: Probability of segment or pathway failure from inherent technical difficulty considering threat capabilities	0-5% (2%)	Very Low
	5-25% (10%)	Low
	25-75% (50%)	Medium
	75-95% (90%)	High
	95-100% (98%)	Very High
Proliferation Cost (PC) Example metric: Fraction of national military budget required to execute the proliferation segment or pathway, amortized on an annual basis over the Proliferation Time	0-5% (2%)	Very Low
	5-25% (10%)	Low
	25-75% (50%)	Medium
	75-100% (90%)	High
	>100% (>100%)	Very High
Proliferation Time (PT) Example metric: Total time to complete segment or pathway, starting with the first action taken to initiate the pathway	0-3 mon (2 mon)	Very Low
	3 mon-1 yr (8 mon)	Low
	1-10 yr (5 yr)	Medium
	10 yr-30 yr (20 yr)	High
	>30 yr (>30 yr)	Very High
Fissile Material Type (MT) Example metric: Dimensionless ranked categories (HEU, WG-Pu, RGPu, DB-Pu, LEU) [a]; interpolation based on material attributes (reflecting the preference for using the material and not it's usability in a nuclear explosive device)	HEU	Very Low
	WG-Pu	Low
	RG-Pu	Medium
	DB-Pu	High
	LEU	Very High
Detection Probability (DP) Example metric: Probability that safeguards will detect the execution of a diversion or misuse segment or pathway	0-5% (2%)	Very Low
	5-25% (10%)	Low
	25-75% (50%)	Medium
	75-95% (90%)	High
	95-100% (98%)	Very High
Detection Resource Efficiency (DE) Example metric: GW(e) years of capacity supported (or other normalization variable) per Person Days of Inspection (PDI) (or inspection $)	<0.01 (0.005 GWyr/PDI)	Very Low
	0.01-0.04 (0.02 GWyr/PDI)	Low
	0.04-0.1 (0.07 GWyr/PDI)	Medium
	0.1-0.3 (0.2 GWyr/PDI)m	High
	>0.3 (1.0 GWyr/PDI)	Very High

[a] HEU = high-enriched uranium (95% 235U); WG-Pu = weapons-grade plutonium (94% fissile Pu);
RG-Pu = reactor-grade plutonium (70% fissile Pu);
DB-Pu = deep burn plutonium (43% fissile Pu); LEU = low-enriched uranium (5% 235U).

[b] These qualitative descriptors are indicative of the relative value of an estimated measure for comparison against competing pathways, and should not be misinterpreted as value judgments of a given pathway or technology with respect to proliferation resistance itself.

Tab. 1.4: Summary of characteristics for the proliferation technical difficulty (TD) measure.

Characteristic	Description
Definition	Inherent difficulty of the segment
Typical attributes to be considered for estimation	Criticality hazards Radioactivity levels Availability of open information Access to specialized export-controlled components or materials
Example metric	Probability of pathway failure from inherent technical difficulty considering threat capabilities
Segments-to-pathway aggregation method	Calculate the probability of pathway failure on the basis of the segments involved

Tab. 1.5: Summary of characteristics for the proliferation cost (PC) measure.

Characteristic	Description
Definition	Total cost of segment
Typical attributes to be considered for estimation	Minimum cost for setting up the minimum needed infrastructure to complete the segment Cost from misuse of civilian infrastructure/personnel
Example metric	Fraction of national resources for military capabilities
Segments-to-pathway aggregation method	Sum of segment estimates. Can be normalized to national resources for military capabilities

Tab. 1.6: Summary of characteristics for the proliferation time (PT) measure.

Characteristic	Description
Definition	Total time required to complete segment
Typical attributes to be considered for estimation	Maximum diversion or production rate Storage duration Extent of required equipment modifications
Example metric	Total time to complete a segment/pathway (e.g., months, years)
Segments-to-pathway aggregation method	Appropriate aggregation of time needed for parallel and serial activities

Tab. 1.7: Summary of characteristics for the fissile material type (MT) measure.

Characteristic	Description
Definition	Characteristics of metal for weapons fabrication
Typical attributes to be considered for estimation	Bare-sphere critical mass Gamma radiation activity Heat generation rate Spontaneous neutron emission rate Chemical Condition
Example metric	Dimensionless ranked categories; interpolation based on material attributes
Segments-to-pathway aggregation method	Not applicable

Tab. 1.8: Summary of characteristics for the detection probability (DP) measure.

Characteristic	Description
Definition	Cumulative probability and confidence level for detection of a pathway segment
Typical attributes to be considered for estimation	Attributes important to design information verification Transparency of layout Possibility to verify changes in design information during operation Possibility to use 3-d scenario reconstruction models Possibility to have visual access to equipment while operational Comprehensiveness of facility documentation and data Attributes important to nuclear material accounting Uniqueness of material signature Hardness of radiation signature Possibility of applying passive measurement methods Possibility of applying unattended NDA systems and remote data transmission Item/bulk Throughput rate Batch/continuous process Nuclear material heat generation rate Attributes important to containment and surveillance Operational practice Extent of automation Standardization of items in transfer Possibility to apply visual monitoring Possibility to apply surveillance devices and remote monitoring Number of possible transfer routes for items in transit
Example metric	Probability that safeguards will detect diversion or misuse during the execution of a segment /pathway
Segments-to-pathway aggregation method	Calculate the probability of pathway detection on the basis of the segments involved. (e.g. the probability of pathway detection will be $P(d) = 1 - P(nd)$ where the probability of pathway non-detection, $P(nd) = \prod\left(1 - P_i(d)\right)$, with $P_i(d)$ being the probability of detection of the ith segment, under the hypothesis of the independence of detection events).

Tab. 1.9: Summary of characteristics for the fissile material type (MT) measure.

Characteristic	Description
Definition	Total inspector time or cost of safeguarding the segment
Typical attributes to be considered for estimation	As in Tab. 1.8
Example metric	GW(e) years of capacity supported (or other normalization variable) per Person Days of Inspection (PDI) (or inspection $)
Segments-to-pathway aggregation method	Aggregation to total inspection time or safeguards cost, normalized to an appropriate scale, such as nuclear energy production supported [GW(e) year]

The final step in PR&PP evaluations is to integrate the findings of the analysis and to interpret the results.

Following this scheme, he PR&PP Working Group methodology will be first applied to the LWR case to confirm the results obtained by others studies [82]. After a description of the system and its safeguards, specific threats belong to the categories shown in Tab. 1.10 will be considered and for each the PR&PP methodology will be applied. The same approach is then applied to the sodium fast reactors. In particular, the Japan sodium fast reactor, with oxide fuel and aqueous reprocessing process will be considered and a comparison between the two systems will be held.

Tab. 1.10: Threat categorization.

Categories number	Threat description
1	Concealed diversion of material
2	Concealed misuse of the facility
3	Breakout and overt diversion or misuse
4	Theft of weapons-usable material or sabotage of facility system elements

2 STUDIED SYSTEM: SODIUM FAST REACTOR

A conceptual design of a Generation IV system with sufficient information about all the elements of the fuel cycle, as well as deployment considerations, has not yet been developed. Even for the Generation IV reactor technology that is considered more mature, the sodium-cooled reactors, an off-the-shelf concept for testing the implementation of the methodology does not exist.

In this study, a hypothetical and commercial SFR based on the layout of the JSFR with a safeguards approach similar to the prototype fast breeder reactor Monju was designed. The fuel material considered for this plant is a MOX fuel type with an advanced aqueous recycle process [102].

Monju is a prototype fast breeder reactor, built and constructed in Japan near the city of Tsuruga on the west coast of the Japanese main island of Honshu (see Fig. 2.1). It is owned and operated currently by the Japan Atomic Energy Agency, formerly also called PNC and JNC. It went critical and began operation in 1994. Because it was intended to allow Japan to make more efficient use of nuclear fuel by permitting the *breeding* and *recycling* of plutonium, its name is originated in the name of a Bodhisattva called Manjushiri symbolizing wisdom and intellect [103, 104, 105].

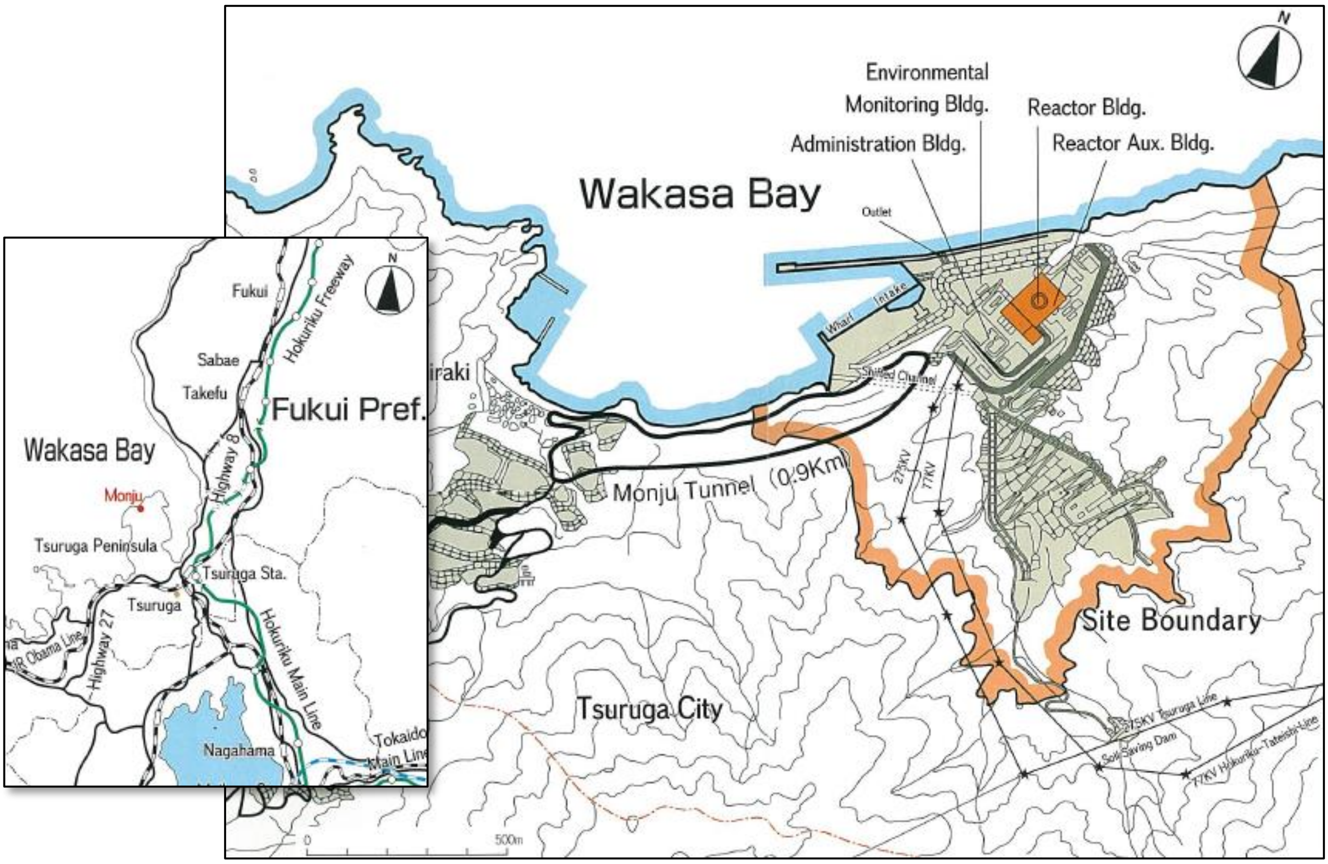


Fig. 2.1: Site arrangement of Monju.

2.1 Baseline Site Description

The studied commercial SFR is a Sodium-cooled loop-type FBR, with thermal and electric outputs respectively of 3.57 GWth and 1.5 GWe. This system consists of a Reactor Vessel (RV) containing the core fuel assemblies, blanket fuel assemblies, control rods and other structures; a primary and secondary circuit of two loops each with a large diameter piping as shown in Fig. 2.2; one circulating pump for each primary circuit loop; an Intermediate Heat Exchanger (IHX) for each loop; one SG for each secondary circuit loop composed of an Evaporator (EV) and a Super Heater (SH). The circuit has also the capability of natural circulation for the decay heat removal.

In Tab. 2.1 a comparison between Monju, SFR and a generic 1.2 GWe PWR is show. [106, 107]

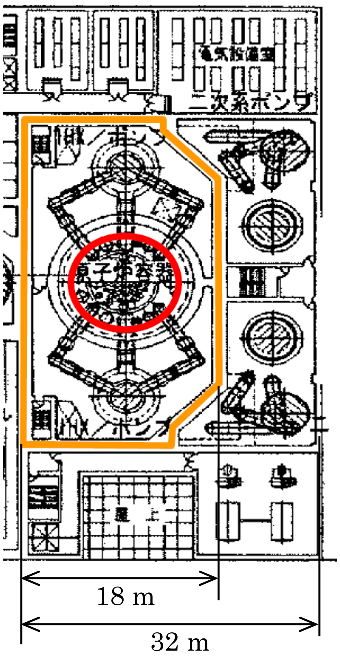


Fig. 2.2: Two-loop cooling system of SFR.

Tab. 2.1: Major piping specifications.

	SFR	Monju	PWR
Electric power [MWe]	1500	280	1160
Number of loops	2	3	4
HL Diameter [m]	1.27	0.81	0.74
HL Thickness [mm]	15.9	11.1	73
HL Velocity [m/s]	9.1	3.5	14.5
HL Temperature [°C]	550	529	325
CL Diameter [m]	0.86	0.61	0.70
CL Thickness [mm]	17.5	9.5	69.0
CL Velocity [m/s]	9.7	6.1	14.3
CL Temperature [°C]	395	397	289

SFR plant consists of a reactor building, a turbine building, a fresh water treatment building, a waste water treatment building, an incinerator building, a solid waste storage building, an office building, a switch yard and a ship yard. The design chose in this study is shown in Fig. 2.3

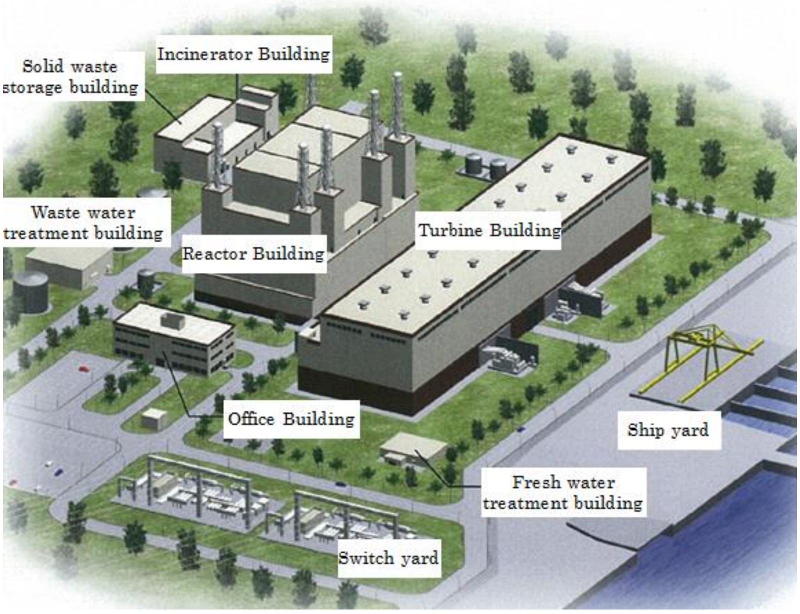


Fig. 2.3: View of the studied hypothetical and commercial SFR site.

The Monju reactor building consists of an outer-shield building, a Reactor Containment Vessel (CV) and a concrete interior structure. The reinforced concrete outer-shield building covers the cylindrical and upper hemispherical parts of the CV. The CV has an internal diameter of 50 m and a height of 80 m and it is a welded steel plate structure composed of a hemispherical upper part and a cylindrical vessel with and-plate and stands on the hard bed-rock. The concrete interior structure supports and contains the RV and a Primary Heat Transport System (PHTS) inside the CV. The reactor auxiliary building is a rectangular shape with 98×113 m plane area surrounding the reactor building, which it positioned almost at the center. It is a reinforced concrete structure built on the hard bed-rock and contains the Secondary Heat Transport System (SHTS) and the fresh/spent fuel handling system. The maintenance & waste treatment building and the solid waste storage building are both a reinforced concrete constructions with the liquid/solid waste treatment facilities (the first one) and storage of radioactive solid waste (the second one). Also the diesel building is a reinforced structure, while the turbine building is a steel structure above the ground and a reinforced construction below the ground. It has a plane area of 37×83 m and it is high 17 m above ground.

For the design of the studied SFR, the CV is rectangular with a consequent volume reduction. The building size is 104 m x 77 m with a height of 70 m. The steel plate reinforced concrete structure of the containment vessel (SCCV) has a final dimension of 19 m x 36 m with a height of 36 m. In Fig. 2.4 and Fig. 2.5 the cross section and the plane section of the reactor building of a twin-unit plant are shown.

In this study both the fabrication and the reprocessing plants are not co-located within the reactor site. Due to the fact that the operation cycle is considered to be 26 months, the number of shipments between the facilities is considered to be less than 2 times per year.

The flow of fuel assemblies for the system is shown in Fig. 2.6, while in Fig. 2.7 the closed fuel cycle considering the reprocessing plant using an advanced aqueous technology is shown [102, 104, 105, 108, 109, 110].

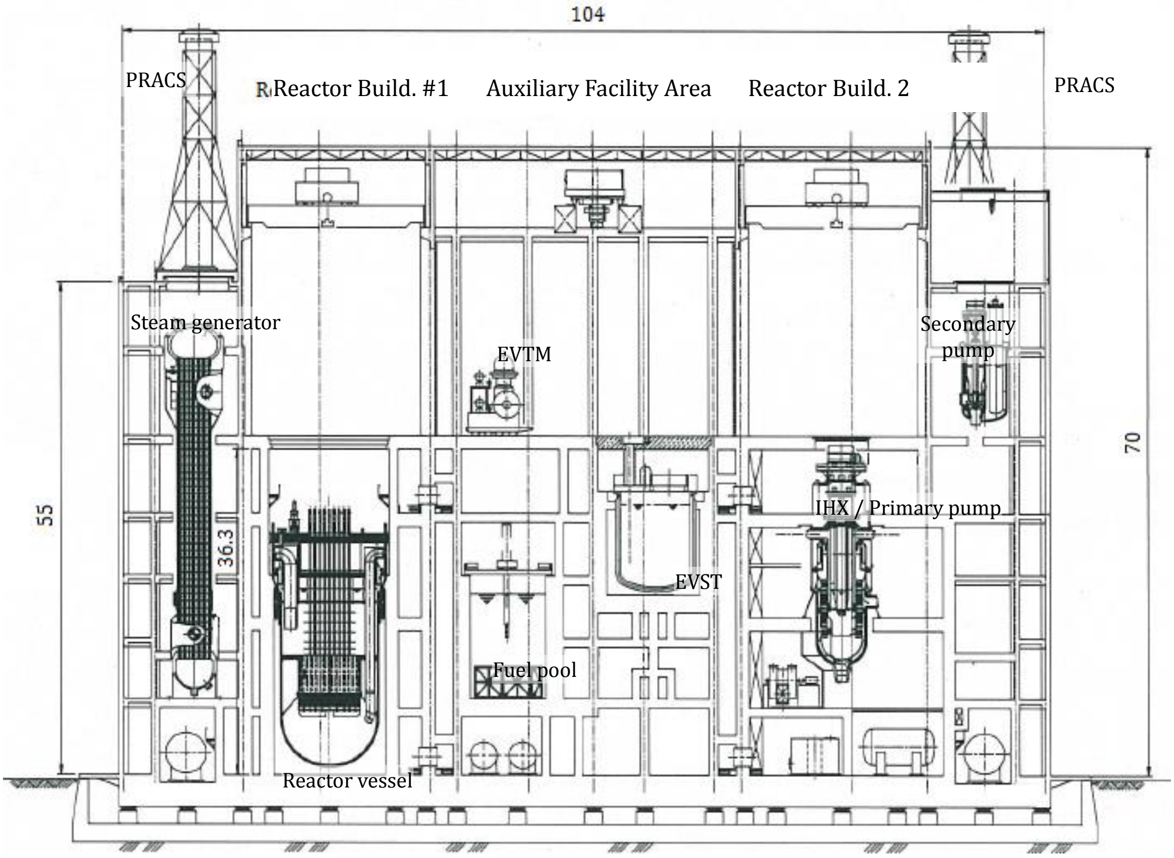


Fig. 2.4: Reactor building layout, cross section.

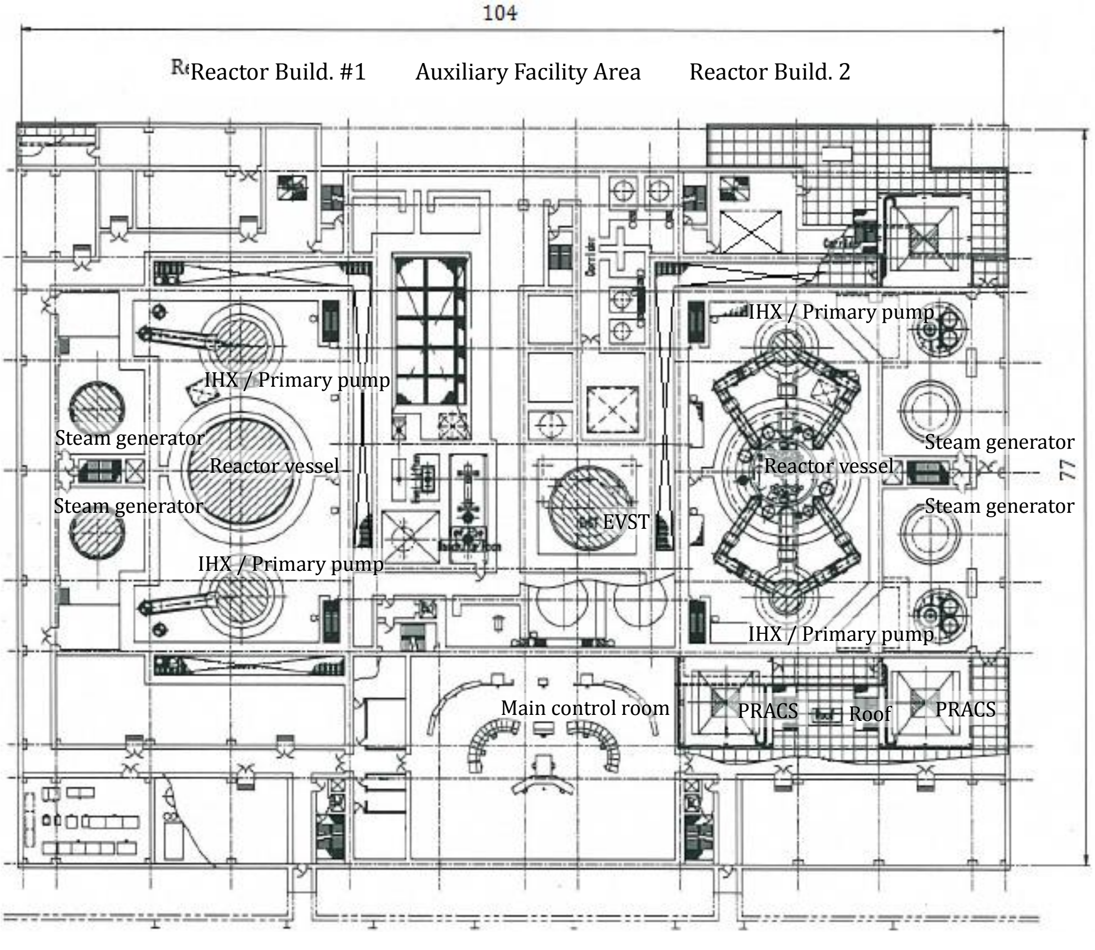


Fig. 2.5: Reactor building layout, plane section.

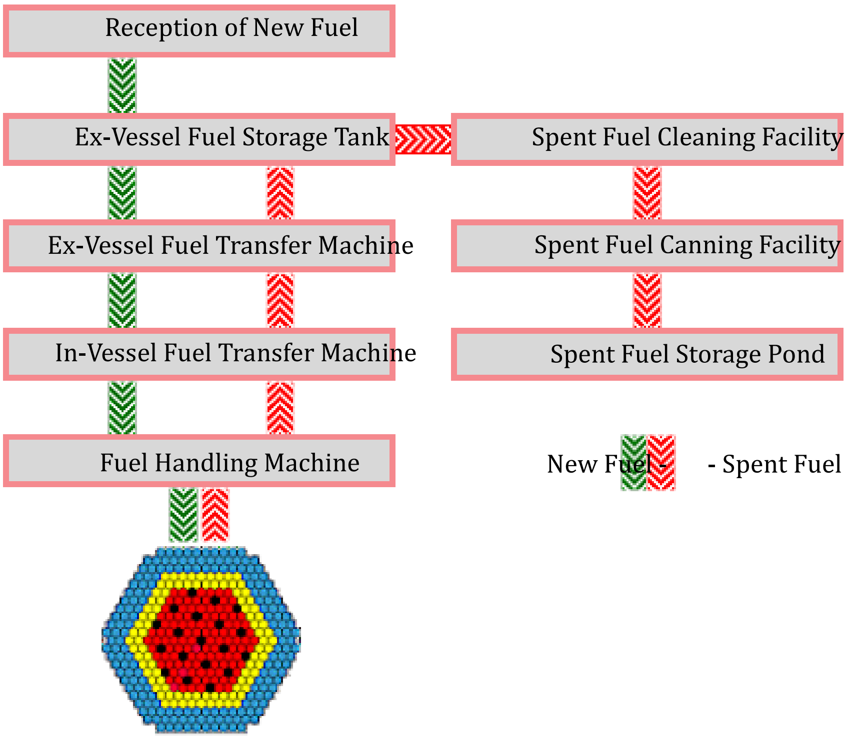


Fig. 2.6: Scheme of the route taken by each fuel assembly.

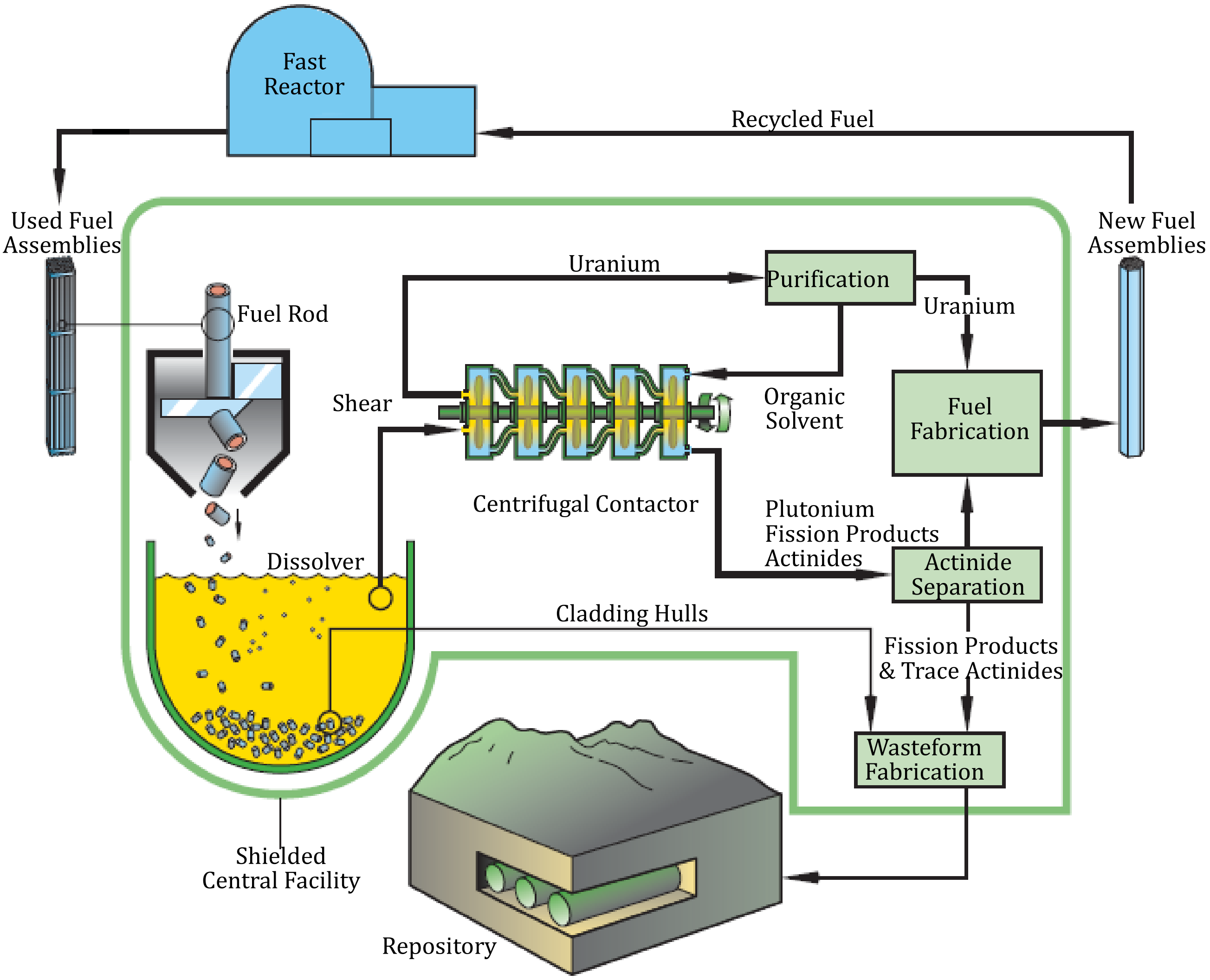


Fig. 2.7: Scheme of a closed fuel cycle with advanced aqueous technology.

2.2 System Elements Identification

According to IAEA Additional Protocol that defines a facility as "(i) A reactor, a critical facility, a conversion plant, a fabrication plant, a reprocessing plant, an isotope separation plant or a separate storage installation; or (ii) Any location where nuclear material in amounts greater than one effective kilogram is customarily used", the term system elements is defined as a collection of facilities inside the identified nuclear energy system where diversion/acquisition and/or processing could take place.

The following system elements are identified using the layout previously designed: the reactor building, the reactor auxiliary building, the waste building and facility and the diesel building. It must be underlined that the reactor auxiliary building is considered to be inside the reactor building. These are the facilities inside the site containing nuclear material or process that could be attractive for proliferation or theft and/or sabotage. In my hypothesis, there is no reprocessing plant inside the reactor site, so it would be important to consider all the shipment between the plant and the external facilities.

Moreover, an interim storage pool will be introduced in the layout of the plant. It was assumed that it is similar to the spent fuel storage pool inside the auxiliary building. Here spent fuel will be moved after two years spent in the first storage pool and leaved there until its final shipment to the reprocessing plant or permanent storage.

In Fig. 2.8 a diagram of the systems elements identified is shown.

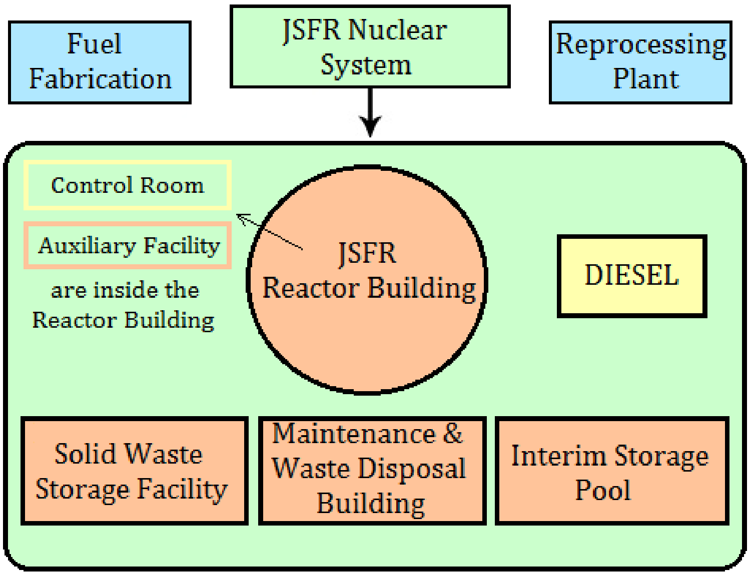


Fig. 2.8: Diagram of the SFR nuclear system elements.

2.3 Reactor Facility Description

The commercial SFR designed in this work is a Sodium-cooled loop-type fast breeder reactor fueled with MOX. This system consists of a RV containing the core fuel assemblies, blanket fuel assemblies, control rods and other structures; a primary and secondary circuit of two loop each; one circulating pump for each primary circuit loop integrated within the IHX; one IHX for each loop; one SG for each secondary circuit loop composed of an EV and a SH. In Tab. 2.2 the main characteristics of these systems are shown.

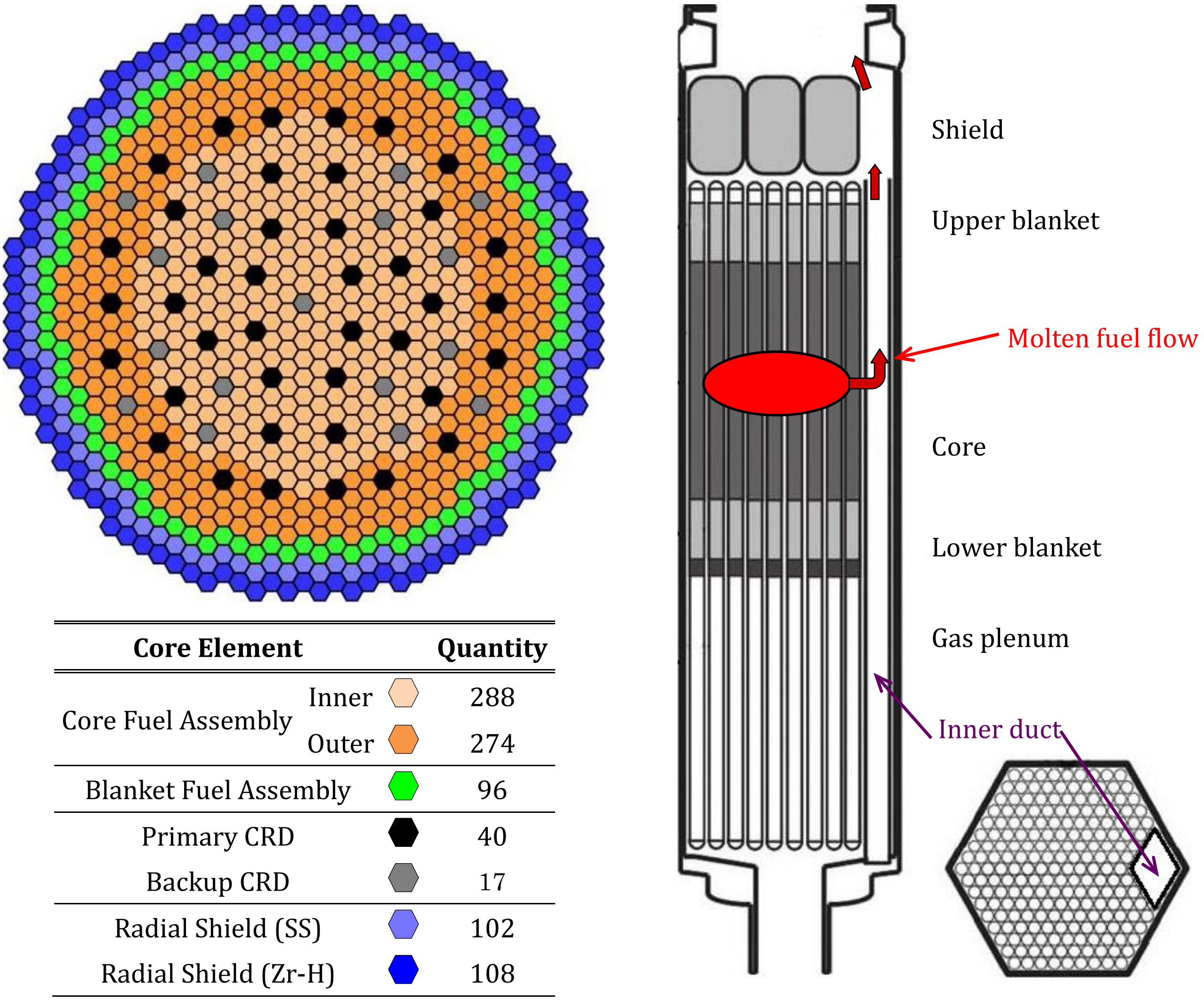
A newly designed FAIDUS (Fuel Assembly with Inner Duct Structure) type assembly concept is adopted as shown in Fig. 2.9. The inner duct is installed at a comer of the assembly and a part of upper shielding element is removed in FAIDUS. In the transition phase of CDA, the molten fuel enters the inner duct channel and escapes from the core region passing through the upper shielding. The FAIDUS type assembly is expected to have superior performance for molten fuel release at CDA. The core is composed of 288 inner core fuel subassemblies, 274 outer core fuel subassemblies, 96 radial blanket subassemblies and 57 control rods. The target for the maximum breeding ratio is from 1.1 to 1.2. The high breeding core with breeding ratio of 1.2 is achieved by changing the fuel specifications with the same fuel assembly size as the low breeding core and the same core layout. The major fuel specifications of the high breeding core are the core height of 75 cm, the pin length of 2.690 mm. The number of fuel pins per fuel assembly is 315, in order to avoid an increase in linear heat rate. The summary of core concept is shown in Tab. 2.3 [109, 111, 112, 113, 114].

Tab. 2.2: Main characteristics of the commercial SFR.

Design life [years]	60
Thermal output [MW]	3570
Electrical output [MW]	1500
Thermal characteristics	
Primary sodium temperature inlet [°C]	395
Primary sodium temperature outlet [°C]	550
Secondary sodium temperature IHX inlet [°C]	335
Secondary sodium temperature outlet [°C]	520
Intermediate heat exchanger	
Type	Cross flow of Sodium straight tube-type
Number	2 (one for each loop)
Capacity [MW]	1765
Number of tubes	9360
Outer diameter of tube [mm]	25.4
Steam conditions	
Main Steam pressure [MPa]	18.7
Main Steam temperature [°C]	495
Primary circulating pumps	2 (one for each loop - integrated with the IHX)
Steam generators	2 (one for each loop)
Turbine generator	1

Tab. 2.3: Core and fuel specification.

Items	High breeding	
Fuel type	MOX	
Core height [cm]	75	
Axial blanket length (upper / lower) [cm]	90 (40 / 50)	
Number of pins per FA	315	
Fuel pin diameter [mm]	9.3	
Fuel pin length [mm]	2960	
Fuel assembly pitch [mm]	206	
Plutonium Isotopic Composition [wt%]	238	1.7
	239	55.9
	240	30.5
	241	3.4
	242	3.3
Pu-Fissile Enrichment [%]	Inner	21.9
	Outer	24.3



Core Element			Quantity
Core Fuel Assembly	Inner	⬡	288
	Outer	🟧	274
Blanket Fuel Assembly		🟩	96
Primary CRD		⬛	40
Backup CRD		◼	17
Radial Shield (SS)		🟪	102
Radial Shield (Zr-H)		🟦	108

Fig. 2.9: Core layout and FAIDUS type fuel assembly.

2.4 Fuel Cycle and Flow Material Description

In case of a FBR, the fuel cycle to be considered includes a reprocessing of fuel (see Fig. 2.10 for a schematic representation of the fuel cycle). In our case, both the fuel fabrication facility and the reprocessing facility are not co-located within the reactor site so they will be not considered for the safeguards approach. However, they must be included in the evaluation of flow mass materials.

In Fig. 2.10 a scheme of the complete fuel cycle is shown. It must be noted that the FBR is considered working together with some LWR, which it was considered to have the same characteristics of reference LWR described in section 3.

The mass flow that appeared Fig. 2.11 is obtained using data summarized in and Tab. 2.4.

Tab. 2.4: Characteristics of SFR with MOX fuel and high burnup.

	Data used in this scenario
Thermal Power [GWth]	Q = 3.57 GWth
Electric Power [GWe]	Pe = 1.5 GWe
Capacity factor	CF = 0.95
Thermal efficiency	ηth = 0.42
Discharge burnup [GWd/MTU]	BUd = 150 GWd/MTU
Cycle length	24 months

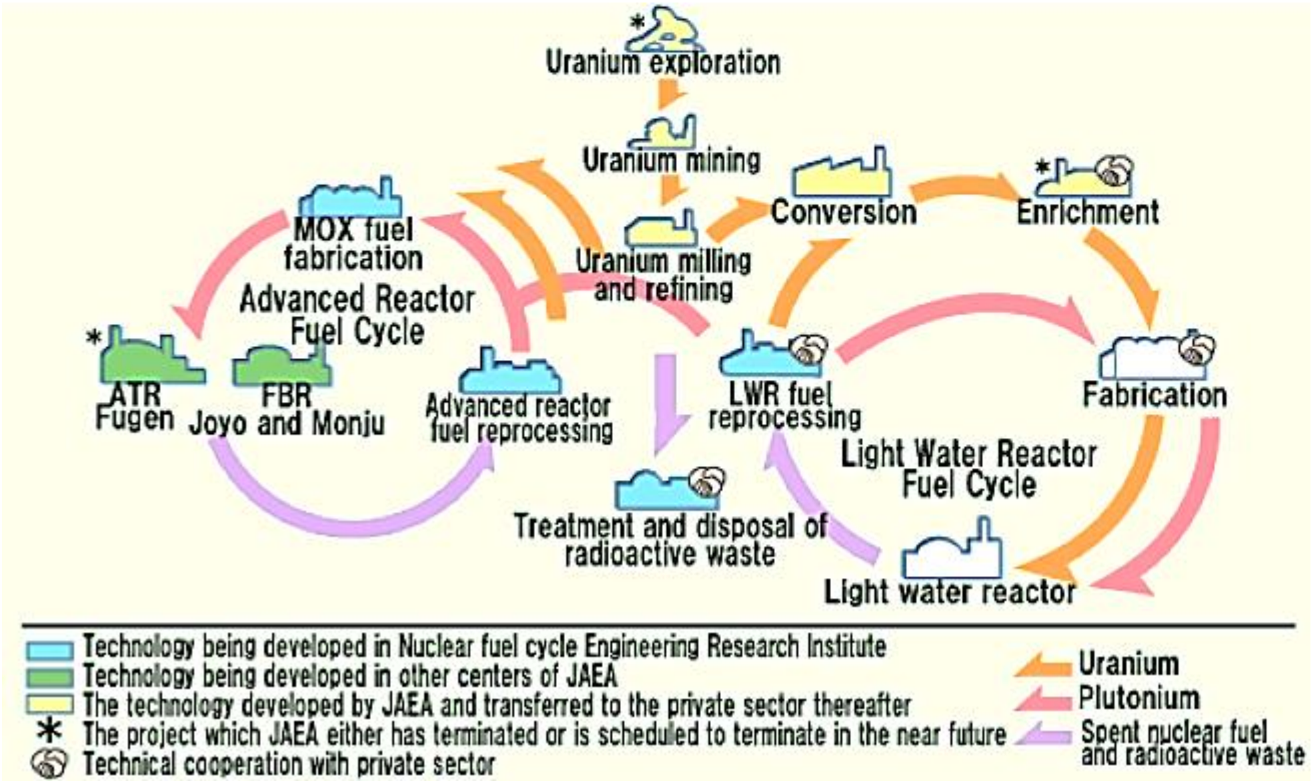
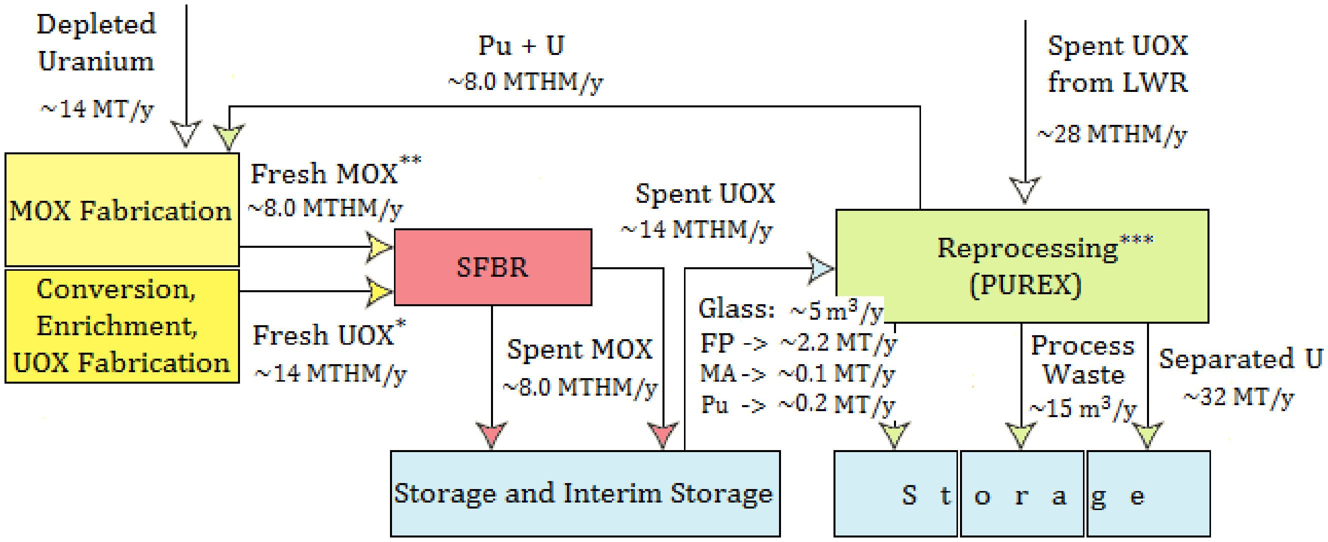


Fig. 2.10: Schematic view of nuclear fuel cycle in Japan.



* UOX for FBR is depleted Uranium, in spent blanket there is a content of [redacted] of Pu [redacted]

** Pu content inside fresh MOX fuel is about [redacted], while in spent MOX is about [redacted] (breeding ration of 1.2);

*** Two different reprocessing plants are required for reprocessing fuel from LWR and FBR.

Fig. 2.11: Simplified reprocessing fuel cycle.

3 SAFEGUARDING THE SFR NUCLEAR ENERGY SYSTEM

One of the main functions of IAEA is to apply, under the NPT and other international treaties, mandatory comprehensive safeguards in NNWS parties to such treaties. In particular, Article III of the NPT requires NNWS parties to the NPT to accept safeguards administered by the IAEA

As can been read in the INFCIRC/153, "The Agreement should contain, in accordance with Article III. 1 of the Treaty on the Non-Proliferation of Nuclear Weapons, an undertaking by the State to accept safeguards, in accordance with the terms of the Agreement, on all source or special fissionable material in all peaceful nuclear activities within its territory, under its jurisdiction or carried out under its control anywhere, for the exclusive purpose of verifying that such material is not diverted to nuclear weapons or other nuclear explosive devices." [115, 116, 117].

Moreover, the INFCIRC/153 defines the objective of safeguards as "the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection." [118].

The Agreement between the State and the Agency should provide that safeguards shall be implemented in a manner designed to avoid hampering the economic and technological development of the State or international co-operation in the field of peaceful nuclear activities, including international exchange of nuclear material; to avoid undue interference in the State's peaceful nuclear activities, and in particular in the operation of facilities; to be consistent with prudent management practices required for the economic and safe conduct of nuclear activities.

The Agency shall take full account of technological developments in the field of safeguards, and shall make every effort to ensure optimum cost-effectiveness and the application of the principle of safeguarding effectively the flow of nuclear material subject to safeguards by use of instruments and other techniques at certain strategic points[6] (the Key Measurement Points, KMP[7]) to the extent that present or future technology permits.. In particular, in order to ensure optimum cost-effectiveness, use should be made, for example, of such means as containment as a means of defining Material Balance Areas (MBA)[8] for accounting purposes; statistical techniques and random sampling in evaluating the flow of nuclear material; and concentration of verification procedures on those stages in the nuclear fuel cycle involving the production, processing, use or storage of nuclear material from which nuclear weapons or other nuclear explosive devices could readily be made, and minimization of verification procedures in respect

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[6] From the INFCIRC/153, a Strategic Points means a location selected during examination of design information where, under normal conditions and when combined with the information from all "strategic points" taken together, the information necessary and sufficient for the implementation of safeguards measures is obtained and verified; a "strategic point" may include any location where key measurements related to material balance accountancy are made and where containment and surveillance measures are executed.

[7] From the INFCIRC/153, a KMP means a location where nuclear material appears in such a form that it may be measured to determine material flow or inventory. KMP thus include, but are not limited to, the inputs and outputs (including measured discards) and storages in material balance areas.

[8] From the INFCIRC/153, a MBA is an area in or outside of a facility such that:
  (a) The quantity of nuclear material in each transfer into or out of each MBA can be determined; and
  (b) The physical inventory of nuclear material in each MBA can be determined when necessary, in accordance with specified procedures,
in order that the material balance for Agency safeguards purposes can be established.

of other nuclear material, on condition that this does not hamper the Agency in applying safeguards under the Agreement.

The Agreement should provide that the State shall establish and maintain a system of accounting for and control of all nuclear material subject to safeguards under the Agreement, and that such safeguards shall be applied in such a manner as to enable the Agency to verify, in ascertaining that there has been no diversion of nuclear material from peaceful uses to nuclear weapons or other nuclear explosive devices, findings of the State's system.

It is important to underline that the Agency shall operating under the concept of “Safeguards Confidential” taking every precaution to protect commercial and industrial secrets and other confidential information [118, 119].

For the safeguards implementation and design during this study, the experience coming from the prototype Monju is used. The safeguards approach for Monju was developed in the context of an INFCIRC/153-type comprehensive safeguards agreement concluded between Japan and the IAEA. The international safeguards objective is the timely detection of the possible diversion of the plutonium-bearing TRU-fuel at Monju.

The safeguards approach used in this study is based on the following:

- Defined MBAs for nuclear material accounting;
- Defined KMPs for measuring the flow and inventory of nuclear material;
- Defined Strategic Points for containment and surveillance and other verification measures
- Nuclear Material Accountancy, via review of operating records and state reports;
- Annual PIV – typically a “shutdown” inventory taking during semi-annual fuel reloading;
- Verification of domestic and international transfers of nuclear material
- Statistical evaluation of the nuclear material balance to determine Material Unaccounted for (MUF);
- Routine, (monthly) Interim Inventory Verifications (IIVs) for the timely detection of possible diversion of nuclear material;
- Verification of facility design information;
- Verification of the operator’s measurement system.

Additional features were provided to ensure robust safeguarding of the TRU-fuel.

- Hardened secured storage locations for the TRU-fuel assemblies.
- Advanced redundant containment and surveillance systems, consisting of several kinds of sensors, gamma-detectors, neutron detectors, and surveillance cameras. The digital data from these systems are reviewed by a super-fast image processing review system to detect changes in the areas under surveillance, in a semi-automated manner.
- Continuous, unattended custom-designed non-destructive assay “NDA” systems to monitor the movement of TRU fuel in the facility and to determine by interpreting the gamma and neutron radiation if the fuel is a non-fuel dummy, fresh TRU-fuel, DU blanket fuel, or spent TRU fuel.

3.1 Significance Quantities of Nuclear Material and Timeliness of Detection

Over the years the IAEA has developed a means of defining the proliferation risk involved in various types, amounts, and forms of nuclear material. The term Significant Quantity (SQ) denotes an amount of a type of nuclear material that can create one nuclear weapon. The IAEA definitions of nuclear materials and their attendant significant quantities are as shown in Tab. 3.1. It is important to notice that the isotopic purity of plutonium is not taken into account in this definition of SQ, because the IAEA has taken the conservative approach and considered all Pu capable of being formed into a weapon with the exception of Pu that is 80% or more Pu^{238}, which is not considered to be nuclear material due to its large heat generation caused by Pu^{238} alpha decay. Thorium and natural uranium are considered source materials for U^{233}, U^{235}, and Pu, but due the fact that it takes time to convert thorium and uranium into weapons-usable materials, the concept of timeliness of detection evolved in the safeguards approaches: more time and effort should be spent safeguarding material that can be quickly converted into a weapon. Timeliness is also contingent on the amount of material. In cases where the material quantities at an installation are small (under 1 SQ), the timeliness goals can be relaxed. The IAEA established conversion times (see Tab. 3.2) from estimates of the time to convert the different types and forms of nuclear materials. From these conversion times, the IAEA established the timeliness goals (see Tab. 3.2).

Moreover, the INFCIRC/153 states that "in the case of facilities and material balance areas outside facilities with a content or annual throughput, whichever is greater, of nuclear material not exceeding five effective kilograms, routine inspections shall not exceed one per year. For other facilities the number, intensity, duration, timing and mode of inspections shall be determined on the basis that in the maximum or limiting case the inspection regime shall be no more intensive than is necessary and sufficient to maintain continuity of knowledge of the flow and inventory of nuclear material." Tab. 3.3 contains definitions for an effective kilogram of nuclear material for all the forms of nuclear material.

In this study, the goal quantity for detection is 1 SQ in the form of TRU-fuel, fuel rods, or portions thereof. Safeguards also apply to uranium, but to a lesser extent.

The timeliness goal for detecting the possible diversion depends on whether the plutonium is in un-irradiated fresh or irradiated spent fuel. In the former case, the timeliness goal is one month, while, in the latter case, the timeliness goal is three months. The former essentially dictates the need for monthly field inspections by the IAEA inspectors, but possible variations from these can be applied. [118, 103, 120]

Tab. 3.1: Definition of significant quantities for IAEA nuclear material types.

Nuclear Material Type	SQ Amount [kg]
Pu (< 80% Pu^{238})	8 kg Pu
U^{233}	8 kg U^{233}
HEU (=>20% U^{235}) 25 kg U^{235}	25 kg U^{235}
LEU (<20% U^{235} including natural U and depleted U)	75 kg U^{235} (or 10 t natural U or 20 t depleted U)
Thorium	20 t Thorium

Tab. 3.2: Definition of timeliness goals for IAEA nuclear material types.

Nuclear Material Type	Material Form	Conversion Time	IAEA Timeliness Goals
Pu, HEU or U-233	Metal	Few days (7–10)	1 month
Pure Pu components	Oxide (PuO2)	Few weeks (1–3)	
Pure HEU or U-233 compounds	Oxide (UO2)	Few weeks (1–3)	
MOX	Non-irradiated fresh fuel	Few weeks (1–3)	
Pu, HEU or U-233	In scrap	Few weeks (1–3)	
Pu, HEU or U-233	In irradiated fuel	Few months (1–3)	3 months
LEU, Nat. U, Dep. U, Th	Un-irradiated fresh fuel	Order of 1 year	1 year

Tab. 3.3: IAEA effective kilogram [ekg] definition.

Material Type	Definition of Effective Kilogram
Plutonium	Weight in kilograms
Uranium with an enrichment of 1% and above	Weight in kilograms multiplied by the square of the enrichment of the material
Uranium with an enrichment below 1% and above 0.5%	Weight in kilograms multiplied by 0.0001
Depleted uranium with an enrichment of 0.5% or below	Weight in kilograms multiplied by 0.00005
Thorium	Weight in kilograms multiplied by 0.00005

3.2 MBA and KMP identification

As said above, the INFCIRC/153 states that the aforementioned design information shall not only identify the features and nuclear material relevant to safeguards, as discussed previously, but shall "determine material balance areas to be used for Agency accounting purposes and to select those strategic points which are key measurement points and which will be used to determine the nuclear material flows and inventories." The para. 46 of INFCIRC/153, shows how the Agency intends to implement safeguards using the design information from an operator to negotiate specific MBAs and KMPs in a facility to enable the IAEA to get the information needed to verify the facility's declarations and to protect the operator's sensitive information:

"The Agreement should provide that the design information made available to the Agency shall be used for the following purposes:

(a) To identify the features of facilities and nuclear material relevant to the application of safeguards to nuclear material in sufficient detail to facilitate verification;

(b) To determine material balance areas to be used for Agency accounting purposes and to select those strategic points which are key measurement points and which will be used to determine the nuclear material flows and inventories; in determining such material balance areas the Agency shall, inter alia, use the following criteria:
    (i) The size of the material balance area should be related to the accuracy with which the material balance can be established;
    (ii) In determining the material balance area advantage should be taken of any opportunity to use containment and surveillance to help ensure the completeness of flow measurements and thereby simplify the application of safeguards and concentrate measurement efforts at key measurement points;
    (iii) A number of material balance areas in use at a facility or at distinct sites may be combined in one material balance area to be used for Agency accounting purposes when the Agency determines that this is consistent with its verification requirements; and
    (iv) If the State so requests, a special material balance area around a process step involving commercially sensitive information may be established;

(c) To establish the nominal timing and procedures for taking of physical inventory for Agency accounting purposes;

(d) To establish the records and reports requirements and records evaluation procedures;

(e) To establish requirements and procedures for verification of the quantity and location of nuclear material; and

(f) To select appropriate combinations of containment and surveillance methods and techniques and the strategic points at which they are to be applied.

It should further be provided that the results of the examination of the design information shall be included in the Subsidiary Arrangements." [118].

In setting up the MBA and KMP structures in a facility, it is important to take into account the safeguards concerns and possible diversion scenarios in the facility.

In the studied SFR reactor one MBA containing both the reactor core and the fresh and spent fuel pools is identified. The labeling of MBA is generally made of four characters following this taxonomy: *AB(B)(n)n* where A is related to the State in which the nuclear system is placed, B identify the nuclear system, (n)n are one or two numbers identifying the various MBAs inside the nuclear system. In this case, the following taxomony is used: XSn, where X identify a fictitious State x, S identify the SFR system and n is a progressive number given to the MBAs inside the system. The MBA identified is so labeled as XS01 (see Fig. 3.1). The level of accessibility for this MBA is considered to be low for the reactor building and normal elsewhere. Due to the fact that the interim storage pool is co-located within the reactor site, a second MBA is defined and labeled as XS02 (see Fig. 3.1).

The necessary measurements and data fetching can be performed. It should be noted that two different type of KMPs exist: the flow and the inventory one. A flow KMP is a KMP in which material passes into and out of the facility, while an inventory KMP is a KMP in which material is stored or used in the facility. Inside each MBA a number of strategic points, in particular the KMPs, are identified. For the labeling of strategic points the chosen taxonomy foresees six characters, the first four being the name of the MBA inside which the strategic point is located, the fifth one being a "-" symbol and the final character being a progressive number identifying univocally the strategic point inside the considered MBA: XSnn-m.

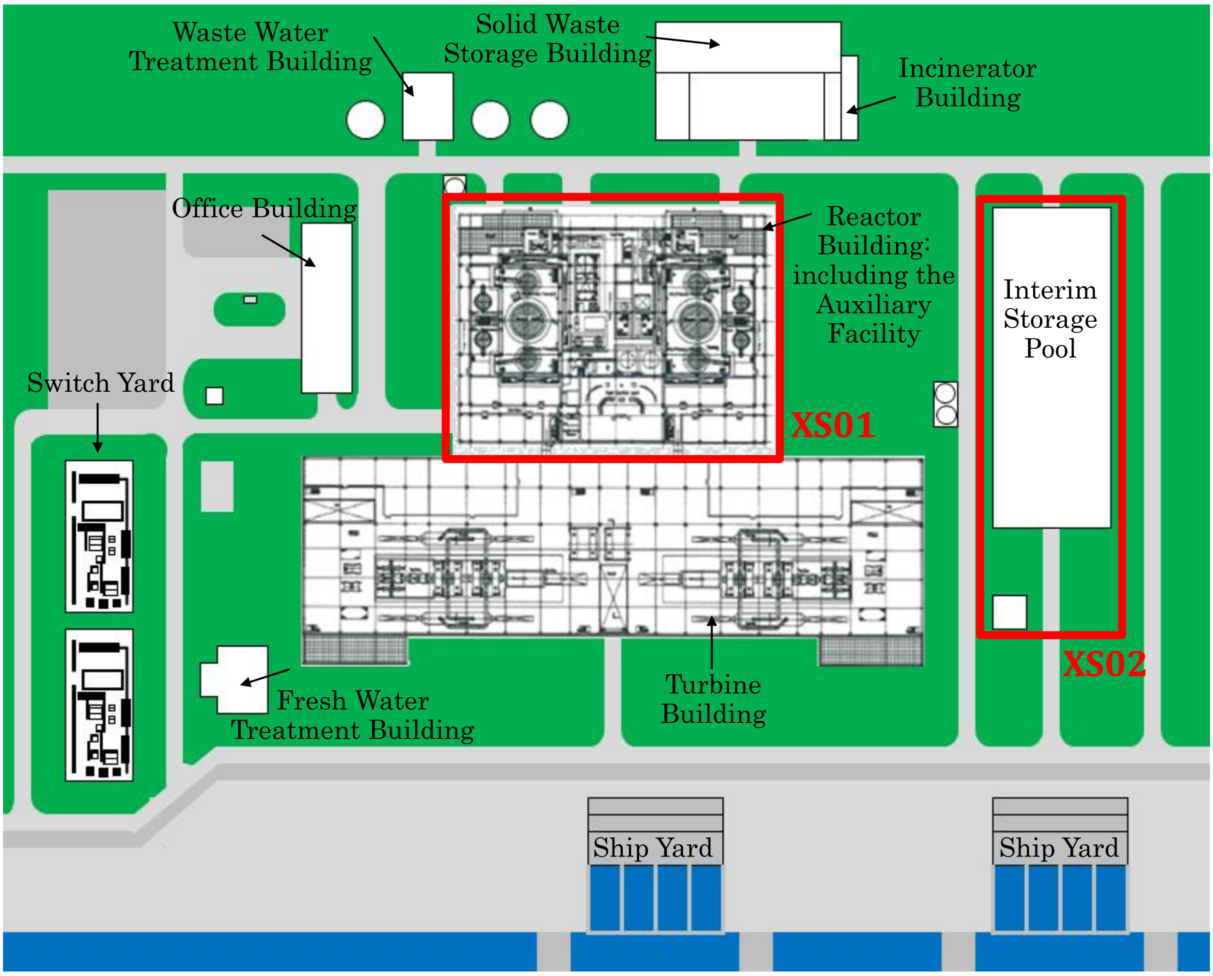


Fig. 3.1: SFR Material Balance Area.

XS01

In order to describe the KMP of this MBA, it is important to understand the route that that the fuel, both fresh and spent, follow inside the site. In Fig. 3.2 and Fig. 3.3 the routes of fresh fuel and spent fuel respectively are shown as well as the safeguards equipment adopted.

Fresh fuel (see Fig. 3.2) is received in a sealed fresh fuel cask and is unloaded under redundant surveillance into the fresh fuel storage pits. The plutonium-content of the fresh TRU-fuel in this case it is assumed as previously verified at the TRU fuel fabrication plant. The fresh TRU fuel is unloaded under the presence of inspectors and is stored in the fresh fuel storage pits under redundant. For reloading the core, fresh fuel would be unsealed under redundant video surveillance and transferred through an NDA station, the Entrance Gate Monitor (ENGM). Due to the fact that the measurement resolution of the existing NDA stations cannot determine accurately the plutonium content of the fuel, it is used to item count the number of assemblies transferred and to verify the facility operator's declaration. The fresh fuel assembly is then transferred by an under-floor transporter and is uplifted into one of the transport wells of the Ex-Vessel Transfer Machine (EVTM), which shuttles the fresh TRU-fuel to the Ex-Vessel Storage Tank (EVST). The presence of the fuel and the type of fuel is determined by the neutron and gamma radiation as detected by the Ex-Vessel Radiation Monitors (EVRM), which sit adjacent to the two fuel transfer wells of the EVTM transfer machine. Additional EVST monitors also confirm that TRU fuel is being transferred in or out of the EVST storage tank. The fresh TRU fuel is stored in liquid sodium in the EVST storage tank and is transferred to the reactor vessel during fuel the fuel reloading activity.

The transfer of spent fuel (see Fig. 3.3) from the reactor vessel follows a similar path, although in reverse: Spent fuel is picked up by the ex-vessel transfer machine and shuttled to the ex-vessel storage tank. Also in this case, the EVRM and the EVST radiation monitors will detect the fuel movement. After interim holding and cooling in the EVST, the spent fuel is shuttled by the EVTM to the storage wells of the spent fuel cleaning and canning station for removal of any sodium on the spent fuel assembly. The spent fuel passes through an Exit Gate Monitor (EXGM) and is transferred through an underwater channel for storage in the spent fuel storage pond, which is under redundant surveillance. All the fuel movements are deduced from the radiation emissions and characteristic movement of the EVTM. In Tab. 3.4 all the devices used are presented [103, 121, 122, 123, 124].

Following the route of both the fresh and spent fuel, three different flows KMPs and four inventories KMPs can be identified inside the MBA XS01. As usual, they will be labeled with a sequential number after the name of the MBA. These KMPs are shown in Fig. 3.4 and described in Tab. 3.5.

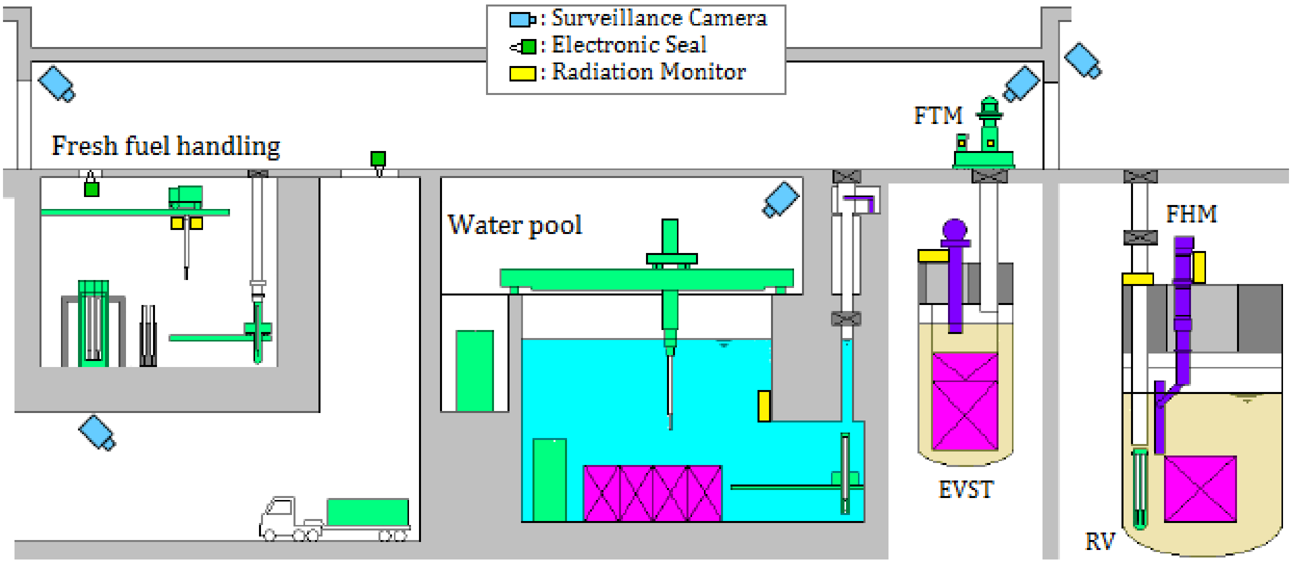


Fig. 3.2: SFR fuel handling system.

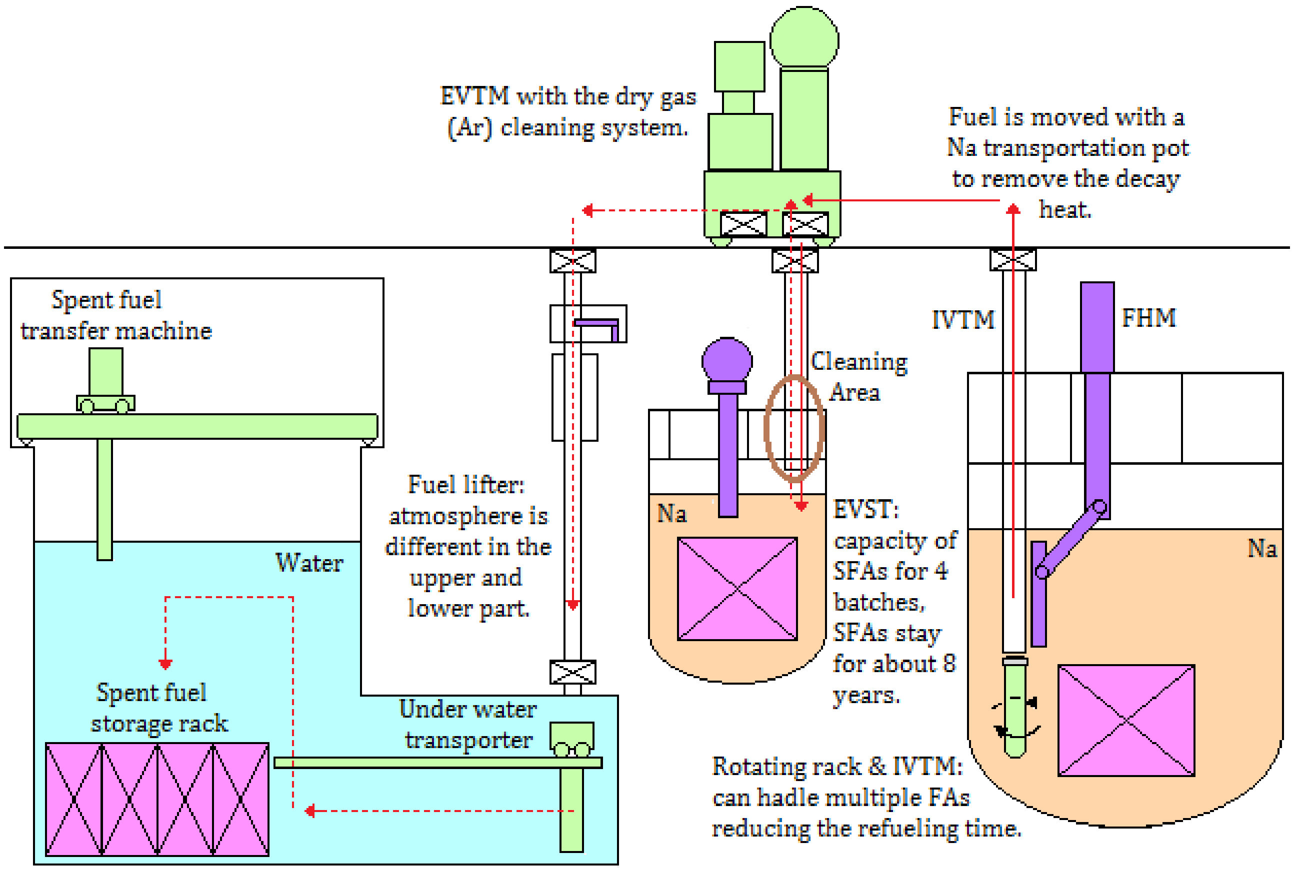


Fig. 3.3: Detail of the SFR fuel handling system, spent fuel road.

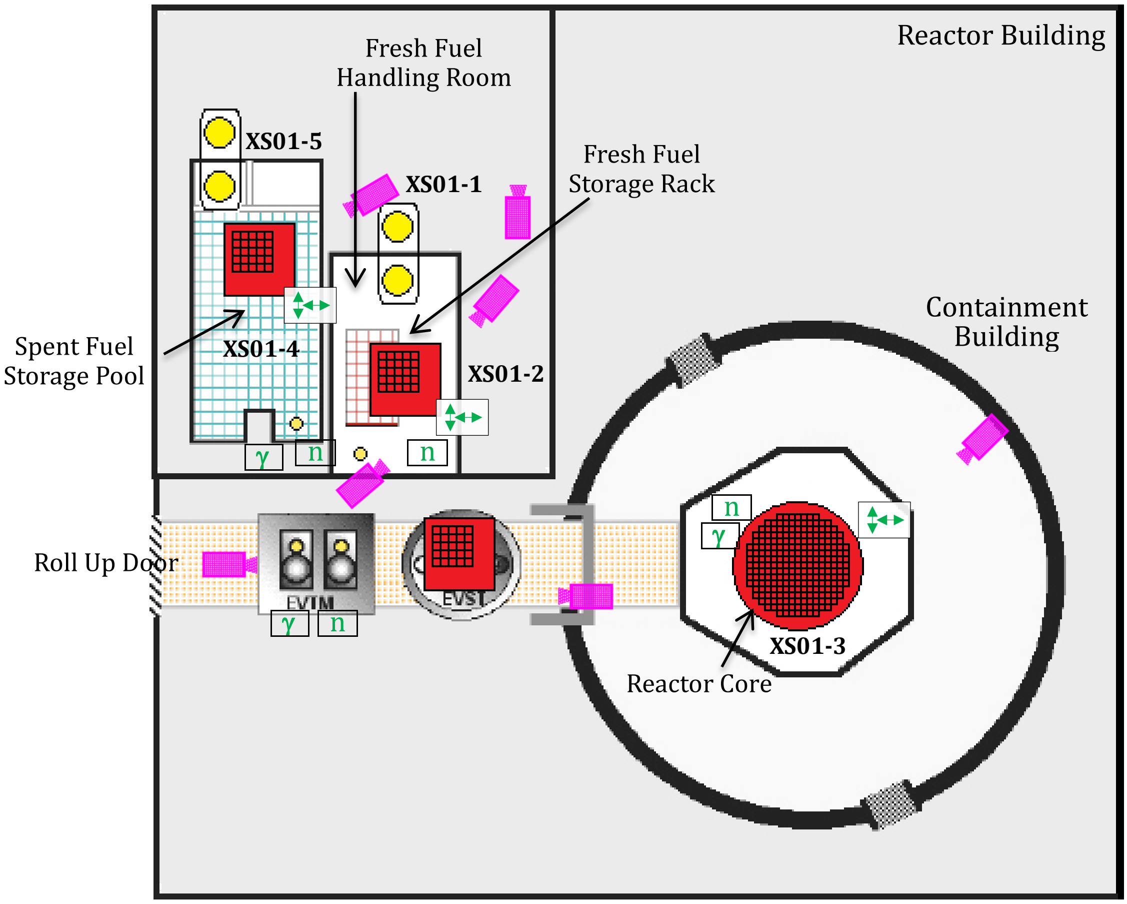


Fig. 3.4: Detail of the MBA XS01 for the SFR reactor.

Tab. 3.4: Safeguards equipment.

Equipment division		Equipment name	Installation site
Containment equipment		Metal seal	Fresh Fuel Storage Rack Fresh Fuel Storage Room Door Detector
		Variable Coding Seal System (VACOSS)	Fresh Fuel Storage Rack Fresh Fuel Storage Room Door Fresh Fuel Transport Container Spent Fuel Transport Container
Monitoring equipment	Video Camera Monitoring System	Digital Multi Camera Optical Surveillance System (DMOS)	Fuel Loading & Unloading Area Fresh Fuel Handling Room Ex-Vessel Transfer Machine
		Digital Single Camera Optical Surveillance System (DSOS)	Reactor Containment Vessel
	Radiation Monitor	Entrance Gate Monitor (ENGM) Neutron detector	Fresh Fuel Handling Room
		EVTM Radiation Monitor (EVRM) Neutron and γ detector	Ex-Vessel Transfer Machine
		EVST Radiation Monitor (EVSM) Neutron detector	Adjacent to Access Portals for EVST
		Monju Core Radiation Monitor (MCRM) Neutron and γ detector	Top of the Reactor Vessel
		Exit Gate Monitor (EXGM) Neutron and γ detector	Spent Fuel Pool

Tab. 3.5: XS01 Strategic Points.

KMP label	Description	Scope	Action taken	Technique adopted
XS01-1	Flow KMP located in the shipping cask receiving and shipping station	To keep track of the fuel elements movements (both receiving and shipping)	Seal is verified; Continuity of knowledge has to be maintained for all the duration of the unloading & transfer	A set of cameras monitoring the operations
XS01-2	Inventory KMP located at the fresh fuel storage rack	To allow the fuel inventory inside the storage	Assemblies are item counted; The C/S system is evaluated	A set of cameras monitoring the stored assemblies; A XYZ positioning system that keeps track of the positioning of the handling machines used for transferring the fuel elements inside and outside the storage; Neutron detector for activity measure before transferring fuel
XS01-3	Inventory KMP located in the reactor core	To allow the fuel elements inventory inside the storage pit; To keep track of the fuel elements movements	The C/S system is evaluated; NDA techniques are used to identify and perform attribute verification on the assemblies	HRGS coupled with passive neutron measurements; A set of cameras monitoring the stored assemblies; A XYZ positioning system that keeps track of the positioning of the handling machines used for transferring the fuel elements in and out the storage pit
XS01-4	Inventory KMP located in the spent fuel storage pool	To allow the fuel inventory inside the storage	Assemblies are item counted; The C/S system is evaluated	A set of cameras monitoring the stored assemblies; A XYZ positioning system that keeps track of the positioning of the handling machines used for transferring the fuel elements inside and outside the storage
XS01-5	Flow KMP located at the exit of the spent fuel storage pool	To characterise the material in transit	Check against Pu diversion	Neutron detector is present

XS02

This MBA covers the interim fuel storage pool co-located with the reactor in the nuclear site. A similar geometry to the LWR one is considered, but taking into account the different material. The nuclear material contained inside this MBA is only spent fuel that is already cool down for at least 8 years inside the spent fuel pool located inside the auxiliary building and it is considered to have a normal accessibility. Same three strategic points are identified for this MBA with the reminder that in the XS02-1 the action taken is the check against Pu diversion, so a neutron detector is needed.

3.3 Physical Inventory Verification

Considering a State under the international agreement for safeguards, the facility's physical inventory is determined by the operator as a result of a Physical Inventory Taking (PIT) and is reported to the IAEA in the Physical Inventory Listing (PIL). The physical inventory is verified by the IAEA during the Physical Inventory Verification (PIV) inspection. The Agency and the operator center the yearly PIV around the refueling. As a general rule, no more than 14 months should pass between two consecutive PIVs. During each PIV the following actions should be performed.

- Fresh fuel which is not in a difficult to access area and which is under single C/S should be item counted, verified by serial number identification (if possible) and re-measured with 10% detection probability for gross defects. In case where dual C/S is available, only evaluation of both C/S systems might be performed.
- Fresh fuel which is in a difficult to access area: a dual C/S system is required, and verification should be performed through evaluation of both C/S systems. Inventory is calculated via difference of items entered in the area and items exited from the area.
- Spent fuel which is not in a difficult to access area and which is under single C/S: evaluation of the C/S system should be performed, together with item counting.
- Spent fuel which is in a difficult to access area: a dual C/S system is required, and verification should be performed through evaluation of both C/S systems. Inventory is calculated via difference of items entered in the area and items exited from the area.
- Core fuel: a dual C/S system is required, and verification should be performed through evaluation of both C/S systems.

Moreover, any time fresh or irradiated fuel enters or leaves a difficult to access area, the following actions should be taken.

- Fresh fuel entering a difficult to access area: measures are taken to confirm operator's declaration regarding the transfers, and items are verified with high detection probability for gross defect. Since assemblies are transferred inside casks, casks should be item counted and non-destructive techniques used for determining the content of the casks.
- Spent fuel leaving a difficult to access area: measures are taken to confirm operator's

declaration regarding the transfers, and items are verified with high detection probability for gross defect. Since assemblies are transferred inside casks, casks should be item counted and non-destructive techniques used for determining the content of the casks.

Also interim inspections should be performed. The following is the suggested scheme.

- Core fuel should be verified four times in each calendar year at quarterly intervals.
- Spent and fresh fuel should be verified four times per year at quarterly intervals. For items under dual C/S, evaluation of both C/S systems should be performed, for items under single C/S, evaluation of the C/S system and item counting should be performed.

Tab. 3.6 presents a résumé of the assumed inspection activities in terms of frequencies of inspections and activities performed.

Tab. 3.6: Inspection activity.

	Interim Inventory Verification	**Physical Inventory verification**
Frequency	One every three months	One per year
Activity	Book audit C/S verification Item counting	Same activity as IIV NDA measurement

4 SFR PHYSICAL PROTECTION SYSTEM

The physical protection of nuclear facilities should be considered as an institutional process or regime. The physical protection regime (PPR) includes all physical protection activities of a State for the protection of nuclear material and nuclear facilities (including transport). The PPR encompasses the legislative and regulatory framework, designation of competent authorities, defining the responsibilities between the state and the owner/operator in regard to PP, the administrative measures and technical features at a facility (or transport) to prevent the unauthorized removal of nuclear material and the sabotage of nuclear facilities or transports, and the measures taken to facilitate the mitigation of the consequences of such a malicious act were it to occur. A basic principle of Physical Protection is to implement a Physical Protection Regime that is effective and efficient for the full lifecycle of nuclear facilities.
A graphical representation of the PPS methodology is shown in Fig. 4.1 [93, 119].

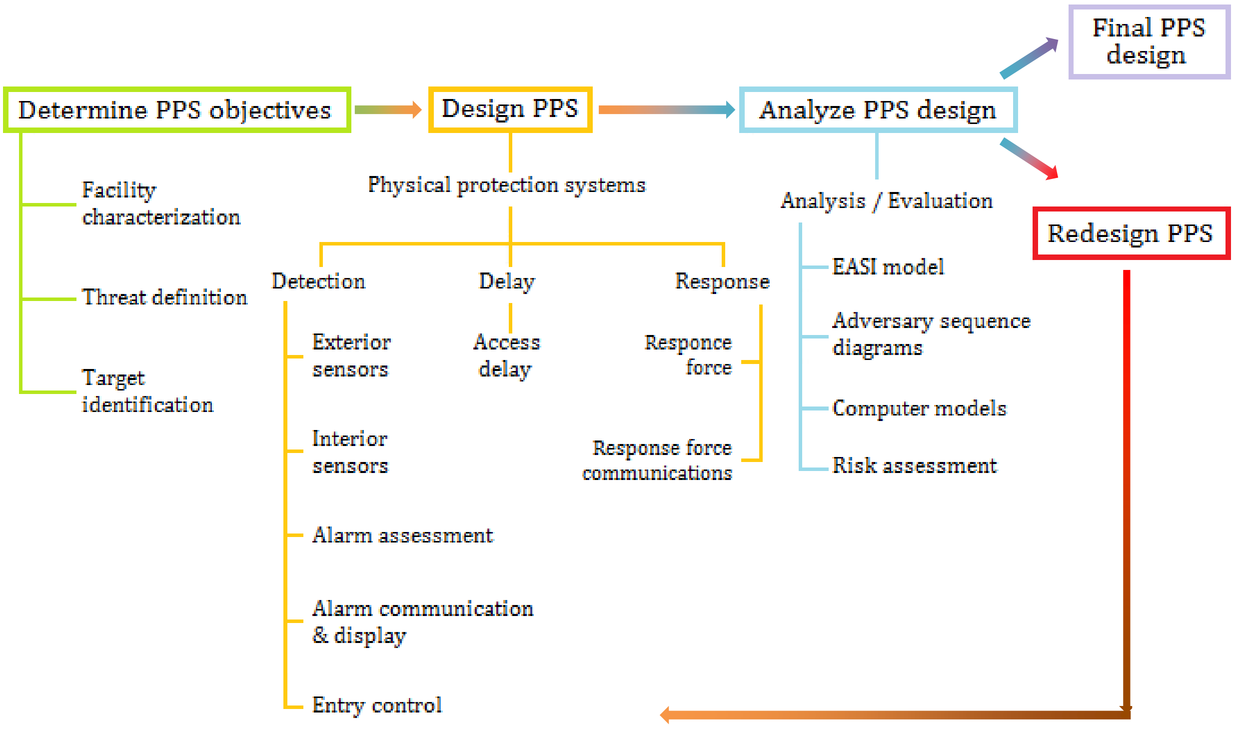


Fig. 4.1: Design and evaluation process for physical protection systems.

The physical protection of a nuclear facility is the responsibility of the Host State of the facility. Protection against theft or unauthorized removal of nuclear material by a sub-national group is provided by Host State security personnel and systems. Additionally, if such theft or removal were to occur, it is primarily the Host State resources that would be applied to securing and returning the material to proper control. The level of rigor applied to the physical protection of the facility will be a function of the type of nuclear material at the facility, the total quantity, how difficult it would be to remove, and knowledge of local conditions and threats, as well as other considerations that concern the Host State.
The IAEA is interested in the physical protection measures in place at nuclear facilities to ensure that they are complete and thorough, and that the facility is indeed protected. Guidelines have

been created against which a given physical protection regime can be compared. Stated broadly the objectives of a Host State physical protection program is to minimize the possibilities for unauthorized removal of nuclear material or for sabotage, and provide information and assistance in support of rapidly recovering missing nuclear material or minimizing the consequences of sabotage.

4.1 Elements of a Host State Physical Protection regime

The following elements need to be present as part of the Host State physical protection regime:

- Appropriate Legislation and Regulation
- Responsibility, Authority, and Sanctions
- Licensing and Other Procedures to Grant Authorization
- Analysis of Threats
- Physical Protection Requirements for Nuclear Material in Use and Storage and During Transport and for Nuclear Facilities
- Additional Physical Protection Requirements for Nuclear Material During Transport
- Nuclear Facility siting, layout, and design
- Trustworthiness Program
- Reporting of Information
- Confidentiality
- Evaluation of the Implementation of Physical Protection Measures

These elements need to be present to varying degrees based upon the Host State's design basis threat, and the category of the nuclear material to be protected.

4.2 Standards elements of a Physical Security implementation

The implementation of physical security at any nuclear facility will have many common elements:

- Design Basis Threat Definition
- Outer boundary
- Site Area
- Limited Area
- Protected Area
- Exclusion Area
- Restricted Area
- Vital Areas
- Security and Response Force Personnel
- Detectors

- Barriers (active and passive)
- Alarm Assessment Tools

These elements form a defense in depth against sub-national attempts at theft of nuclear material or sabotage. For reactors, the primary vital areas to consider in regards to theft of nuclear material will be the fresh fuel storage area and the spent fuel storage area.
The fresh fuel storage area and the spent fuel storage area are located in the reactor building that is a reinforced concrete structure.
Another building in which spent fuel will be located is the interim storage pool that is also a reinforced concrete structure.
Both these two areas fell within the site wide physical protection systems.

4.3 Site wide Physical Protection approach

The site wide physical protection approach includes different protection system.

- Site boundary fences (see Fig. 4.2) and high security fences (see Fig. 4.3).
- Sensors (camera, motion) and alarms that cover the site boundary.
- A PIDAS (Perimeter Intrusion Detection and Assessment System) that surrounds the target areas (either individually or as a whole).
- Access control (both vehicular and personnel) at the site boundary.

These mostly extrinsic security features provide the ability to detect a threat before any nuclear material is at risk, observe and track the threat as the scenario progresses, and the security forces and capability to deter neutralize the threat.

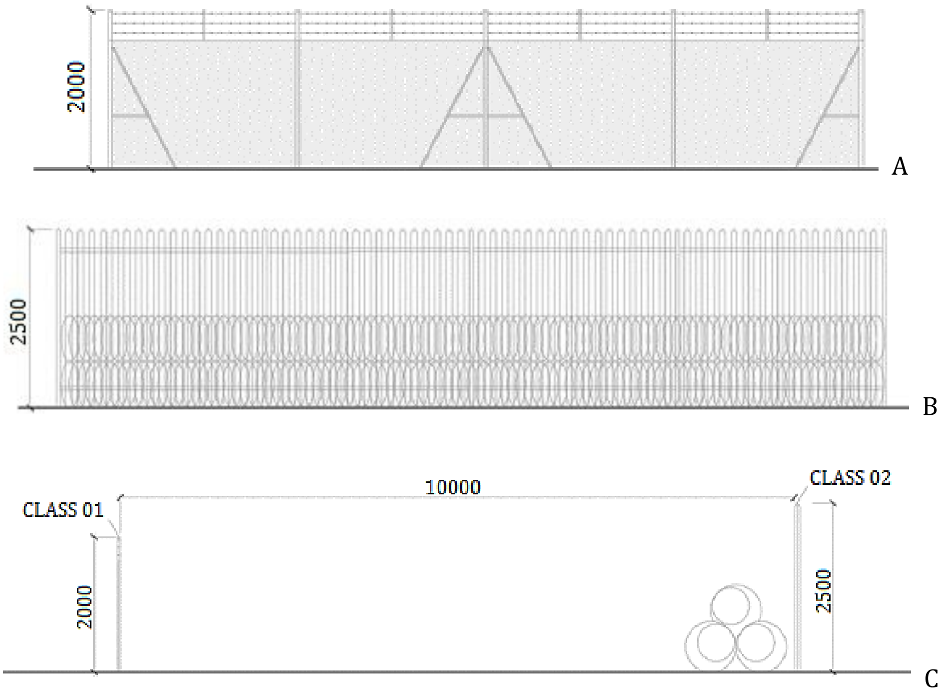


Fig. 4.2: Perimeter fence class 01 and 02 (scale 1:50).

A. Part elevation fence class 01; B. Part elevation fence class 02; C. Section of class 01 and 02 fence types.

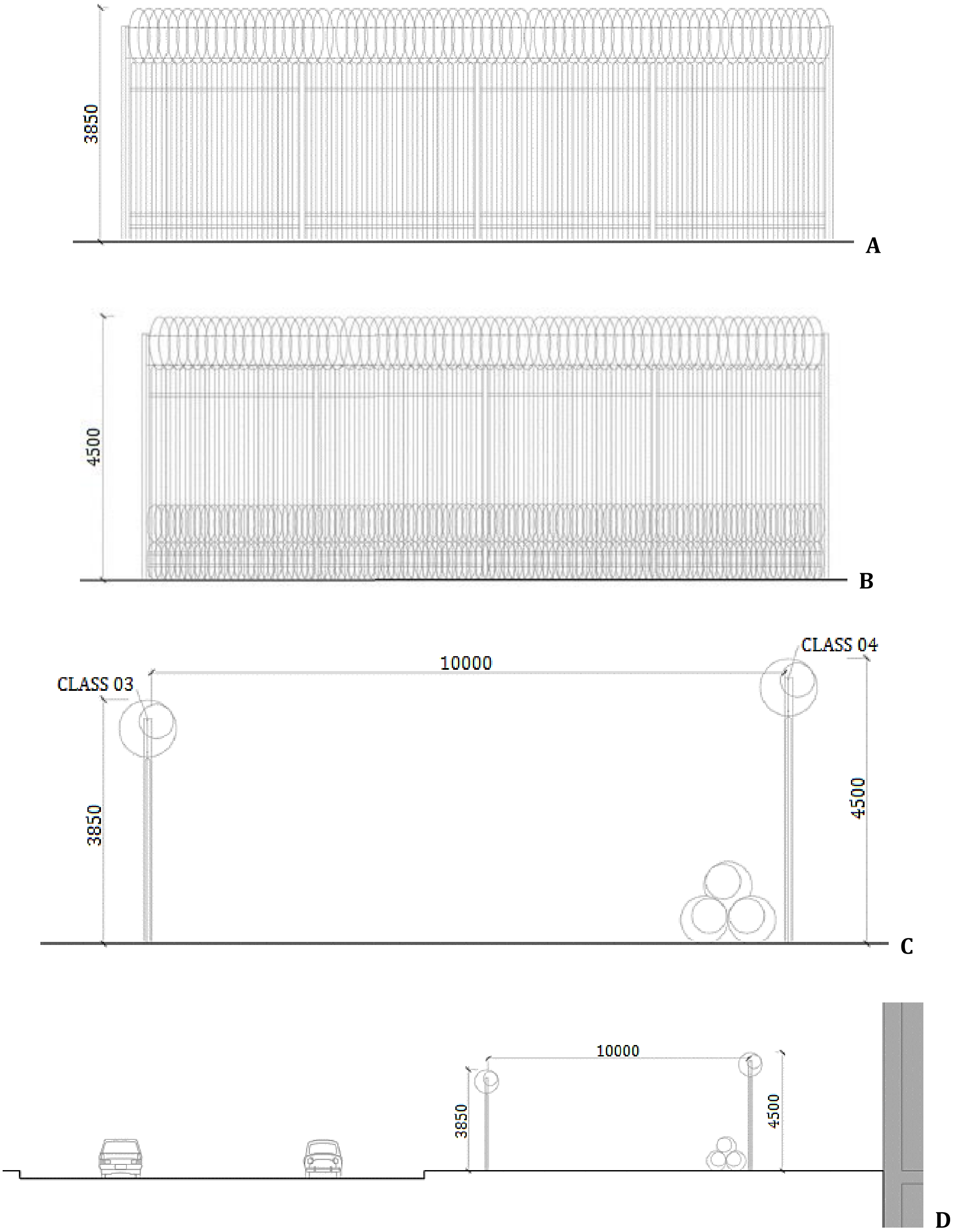


Fig. 4.3: High security fence class 03 and 04 (scale 1:50).

A. Part elevation fence class 03; B. Part elevation fence class 04; C. Section of class 03 and 04 fence types;

D. Section of class 03 and 04 fence types for the nuclear island.

4.4 Identification of potential threats

Shipping cask receiving and shipping station

While this area is the most accessible to an adversary, it is contain the fuel that is still inside the shipping cask and so it is the least attractive material. In fact, when casks are fully closed and secured provide barriers to nuclear material access. However, since radiological sabotage, must also be considered a threat, this area must be protected. It is adjacent to the auxiliary building;

detection can include numerous types of sensors and visual observation. It is inside the PIDAS, which is a fencing and detection system, and have access controls to ensure only authorized personnel can enter or exit. This system must include an element of 3D space, that is, detection and potentially barricades must go vertically above grade and below if, such is accessible to the adversary. Heavier steel fencing can enclose the most vehicle-accessible areas. Raise-able concrete or steel barricades can be placed in access roads at access points.

Fresh fuel handling room

This area contain the most attractive material, in fact, fresh MOX fuel are no more inside the shipping cask are not all ready burned. It is located inside the reactor building in the auxiliary facility area so it is within the PIDAS. Additionally, detection can be placed on access doors and equipment ports into the facility. Cameras and sensors can observe the internal volumes. Assembly lifting devices (cranes) can be locked out or disabled. Vault-type doors can be installed on vehicle and equipment access openings that are large enough for the assemblies. The facility walls and roof can be hardened. Pitched roofs instead of flat can be used to limit access. Rooftop barriers can be placed to prevent aircraft access.

Spent fuel pool

This area contains material still attractive for adversary, and it is also located inside the auxiliary facility area so all the previous consideration are still valid.

Interim storage pool

This area contains material still attractive for adversary and even if it is not located inside the auxiliary building, also the interim storage must be inside the PIDAS.

Radiological Sabotage Targets

The identification of equipment targets for sabotage requires a more complex and analytical process. Typically, for successful sabotage resulting in radiological release, an adversary must disable the functions of a number of different pieces of equipment. An equipment target set is defined as a minimum set of equipment that must be disabled to successfully sabotage a facility. A facility will often contain multiple possible equipment target sets. The number and diversity of equipment functions in each equipment target set provide a measure of the system's redundancy and diversity.

Radiological sabotage involves the deliberate damage of systems with the goal of generating radiological releases to harm the public or workers. The design of nuclear systems includes systematic safety assessments to identify potential initiating events and equipment and operational failures, which could also generate radiological releases. Therefore, these safety assessments provide a starting point for the identification of potential radiological sabotage targets.

To identify potential pathways for radiological sabotage, the probabilistic risk assessment for system safety is modified in two important ways. First, for sabotage, the probability of multiple, simultaneous failures of diverse and redundant components may be increased substantially. Second, for sabotage the probability of failure may increase substantially for the failure of passive components with normally high reliability (walls, fire barriers, doors, vessels, etc.). Target identification involves two steps:

- The systematic search for sets of equipment that, if disabled, could result in the subsequent release of radionuclides (vital equipment identification)
- The definition of vital areas associated with these vital equipment sets to identify access paths.

For the reactor target, five main types of attack strategies should be considered. These are loss of cooling, reactivity, direct attack, fire/chemical, and other forms of attack. For example, for an attack intended to lead to loss of cooling, two methods to create this situation possible actions are the sabotage of the decay heat removal capability or the primary coolant pool drainage.

5 REFERENCE CASE: LIGHT WATER REACTOR (EPR-LIKE)

The EPR reactor is the direct descendant of the well proven N4 and KONVOI reactors used in France and Germany. Its design is based on experience from several thousand reactor-years of light water reactor operation worldwide. It also incorporates results from the R&D work being carried out by the French Atomic Energy Commission (CEA), German Research Institutes, AREVA and EDF.

The EPR™ reactor has already secured construction licenses from the world's most demanding safety authorities in France, Finland and China:

- The Finnish electricity utility Teollisuuden Voima Oy (TVO) signed a contract with the AREVA and Siemens consortium to build a turnkey EPR™ unit at the Olkiluoto site in Finland. The construction license was obtained on February 2005.
- On January 23, 2007, EDF ordered AREVA's 100th nuclear reactor, which is being built in France, on the Flamanville site. The construction license was awarded on April 10, 2007.
- On November 26, 2007, AREVA and CGNPC signed a contract for the supply of two EPR Units on the new site of Taishan in China in the context of a long-term cooperation agreement. The construction license was awarded on August 2009.
- On August 2007 AREVA and EDF jointly launched the certification of the EPR reactor in the UK with the submittal of generic Safety and Environmental reports to the British Nuclear Regulators Health and Safety Executive (HSE) and Environment Agency (EA). On December 2011, the Office of Nuclear Regulation and the Environment Agency issued an Interim statement for the EPR design.

On June 2012, AREVA successfully completed the third phase – out of six – of the U.S. EPR™ Design Certification Application review. Final design certification is scheduled for end 2014 [125, 126].

For this study, an EPR-like reactor is designed.

5.1 Baseline Site Description

The power plant site consists of one EPR-like nominally of 1600 MWe, with a four-loop, pressurized water, reactor coolant system (RCS). This system consists of a reactor vessel that contains the fuel assemblies, a pressurizer (PZR) with control systems to maintain system pressure, one reactor coolant pump (RCP) per loop, one steam generator (SG) per loop, associated piping, and related control and protection systems. The site consist of the reactor building (1), the fuel building (2), the safeguards (3) and diesel buildings (4), the nuclear auxiliary buildings (5), the waste buildings (6) and the turbine buildings (7) as shown in Fig. 5.1 and in Fig. 5.2 [127, 128, 129].

The reactor building (number 1 in Fig. 5.1 and in Fig. 5.2) is located at the center of the nuclear island (NI). See Fig. 5.4 and Fig. 5.5 for more details. The reactor building consists of a cylindrical reinforced concrete outer shield building; a cylindrical, post-tensioned concrete inner containment building with a 0.25 inch thick steel liner; and an annular space between the two buildings. The shield building protects the containment building from external hazards.

The fuel building (number 2 in Fig. 5.1 and in Fig. 5.2) is located on the same common basement as the reactor building and the safeguard buildings and houses the fresh fuel, the spent fuel in an interim fuel storage pool and associated handling equipment. Operating compartments and passageways, equipment compartments, valve compartments and the connecting pipe ducts are separated within the building. Moreover, areas of high activity are separated from areas of low activity by means of shielding facilities. The fuel building is enclosed by a hardened concrete protection shield, which prevents damage to the building from external hazards. The fuel building interior structures, systems, and components are further protected from the impact forces of an aircraft hazard by structural decoupling from the outer hardened walls above the basement elevation. Building isolation and filtering occurs in the event of a release of radioactivity inside the building.

There are four safeguard buildings (numbers 3 in Fig. 5.1 and in Fig. 5.2), each containing one of the redundant safety system divisions. The arrangement of these buildings achieves physical separation of the systems that they house. The safeguard buildings are located adjacent to the reactor building and contain the following systems:

- Component cooling water system (CCWS);
- Emergency feed-water system (EFWS);
- Safety injection system and residual heat removal (SIS/RHR);
- Severe accident heat removal system (SAHRS) in safeguard building 4;
- Main control room (MCR) in safeguard building 2 and RSS in safeguard building 3;
- Equipment for I&C and electrical systems of the NI;
- Safeguard building ventilation and safety chilled water systems.

There are two diesel buildings (numbers 4 in Fig. 5.1 and in Fig. 5.2) that shelter the four emergency diesel generators and their support systems, and supply electricity to the safeguard trains in the event of a complete loss of electrical power. The physical separation of these two buildings provides additional protection.

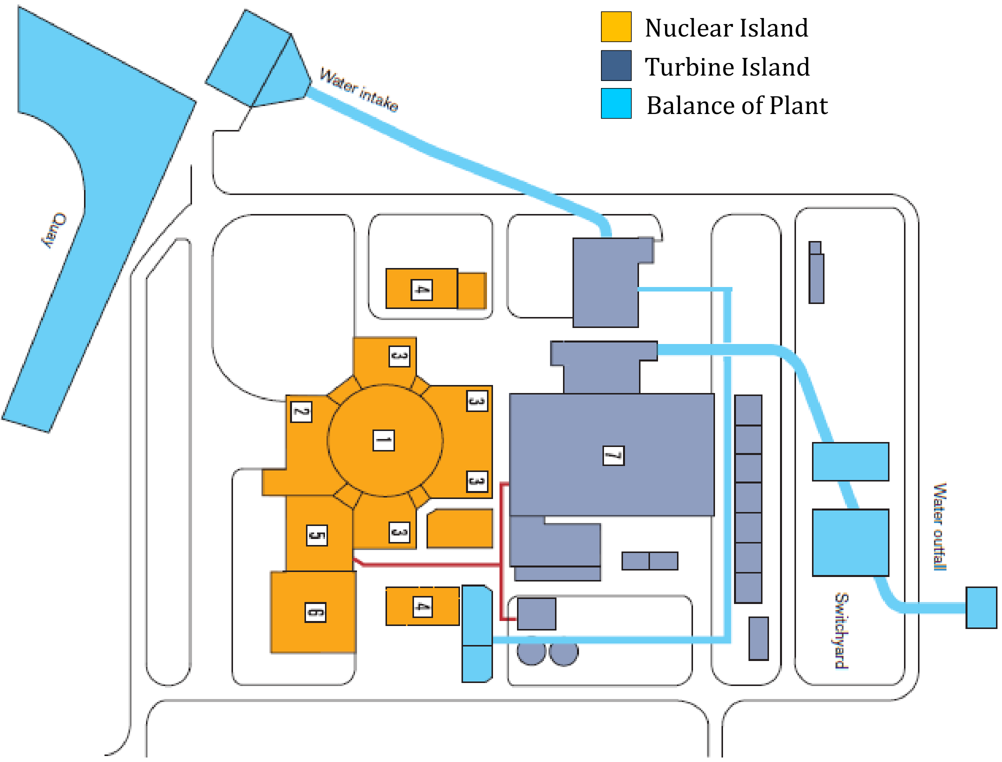
The Nuclear Auxiliary Building (NAB) (number 5 in Fig. 5.1 and in Fig. 5.2) houses the nuclear operation systems and the maintenance areas. The main systems installed in the nuclear auxiliary building are the treatment system for primary (TEP or CSTS), the pool-water treatment system (PTR or FPPS), the gaseous effluent treatment system (TEG or GWPS), part of the steam generator blow-down treatment and cooling system (APG or SGBS) and the operational ventilation and chilled water systems of the nuclear auxiliary building. A section of the building is designed as a radiological uncontrolled area, and part of the chilled-water system is within this area. The special systems sampling laboratories are on the lowest level of the building. All air discharged by ventilating radiologically-controlled areas in the nuclear island buildings is channeled to the nuclear auxiliary building where it is collected and checked before being discharged to atmosphere via the stack. A large space is available in the “workshop area” of the nuclear auxiliary building, which can be used for installation of decontamination facilities that may be required during outages.

The waste building (number 6 in Fig. 5.1 and in Fig. 5.2) is used to collect, store and treat liquid and solid radioactive waste.

The turbine building (number 7 in Fig. 5.1 and in Fig. 5.2) houses all the main components of the steam-condensate-feedwater cycle. It contains, in particular, the turbine, the generator set, the condenser and their auxiliary systems [130, 131, 132, 133, 134].

In Fig. 5.3 a detailed description of the hypothetical EPR-like site is shown.

Fig. 5.1: Generic site view for an EPR.



1 Reactor building
2 Fuel building
3 Safeguards buildings
4 Diesel buildings
5 Nuclear auxiliary buildings
6 Waste buildings
7 Turbine buildings

Fig. 5.2: Generic overall site plant.

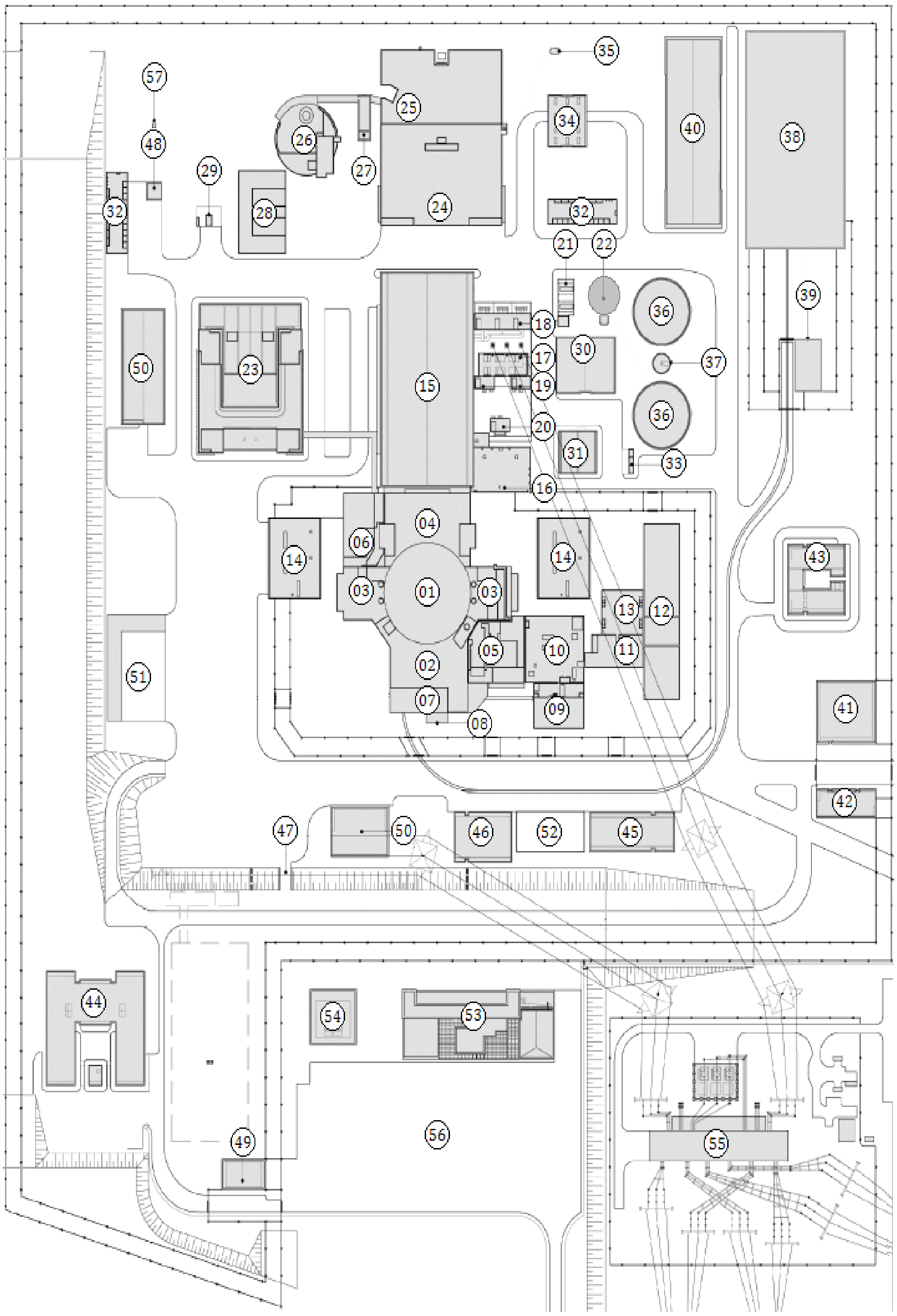


Fig. 5.3: Detailed overall site plant of the EPR-like.

1	Reactor building
2	Fuel building
3	Safeguard building
4	Safeguards buildings
5	Nuclear auxiliary building
6	Access tower
7	Fuel building hall
8	Boron storage
9	Radioactive waste storage building
10	Radioactive waste process building
11	Hot laundry
12	Hot workshop/warehouse
13	Effluent tanks
14	Emergency diesel generators
15	Turbine hall & sky-bridges
16	Non-classified electrical buildings
17	Gas insulated switch gear
18	Main transformer
19	Unit transformer
20	Auxiliary transformer
21	Hydrazine/Ammonia storage
22	Auxiliary feedwater storage
23	Operational service center
24	Cooling water pump house
25	Fore-bay
26	Outfall pond
27	Filtering debris recovery pit
28	Firefighting water building
29	Attenuation pond
30	Demineralization station
31	Auxiliary boilers
32	Hydrogen storage
33	Oxygen storage
34	Chemical products storage
35	Sewage treatment plant
36	Conventional island water storage tank
37	Nuclear island water storage tank
38	Interim spent fuel storage
39	Access control building
40	ILW interim storage facility
41	Main access control building
42	Entry relay building
45	Garage for handling facilities
46	Oil & Grace storage
47	Raw water and potable water supply
48	Meteorological station
49	Outage access control building
50	Contaminated tools storage
51	Conventional waste storage
52	Transit area for VLW and LLW
55	National grid substation
57	Meteorological station mask

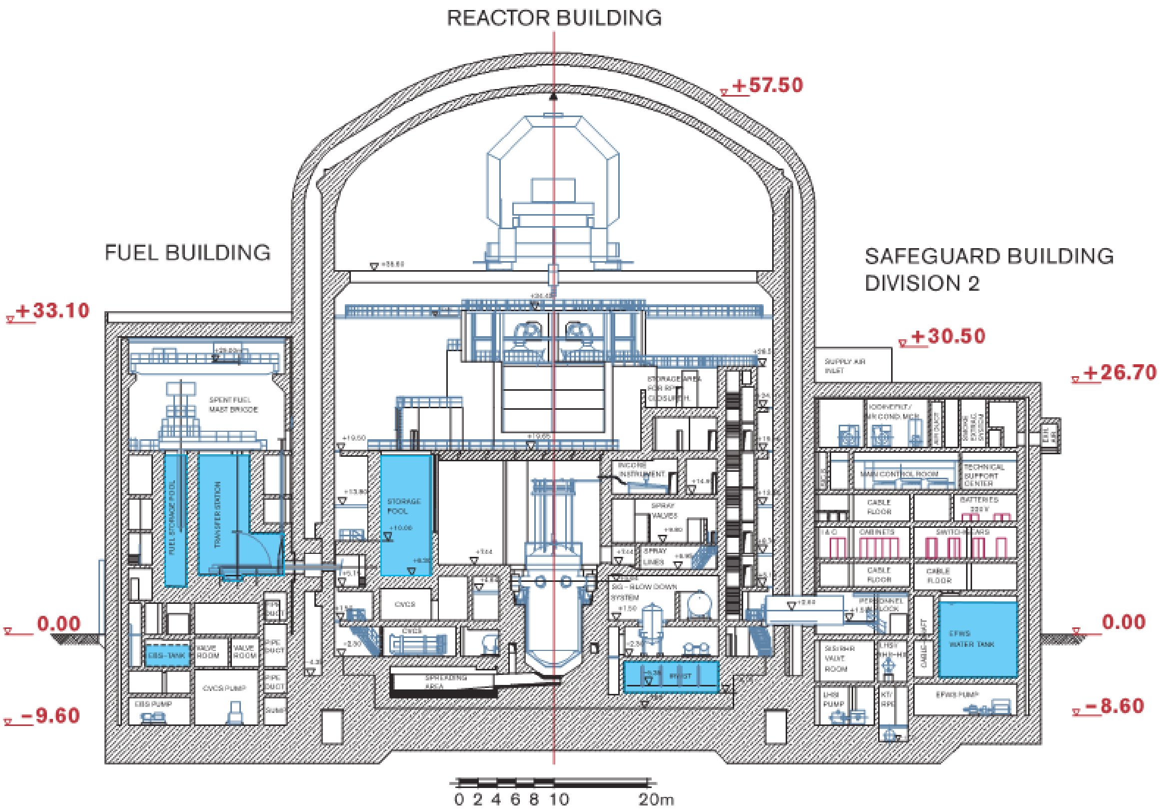


Fig. 5.4: Nuclear island building arrangement.

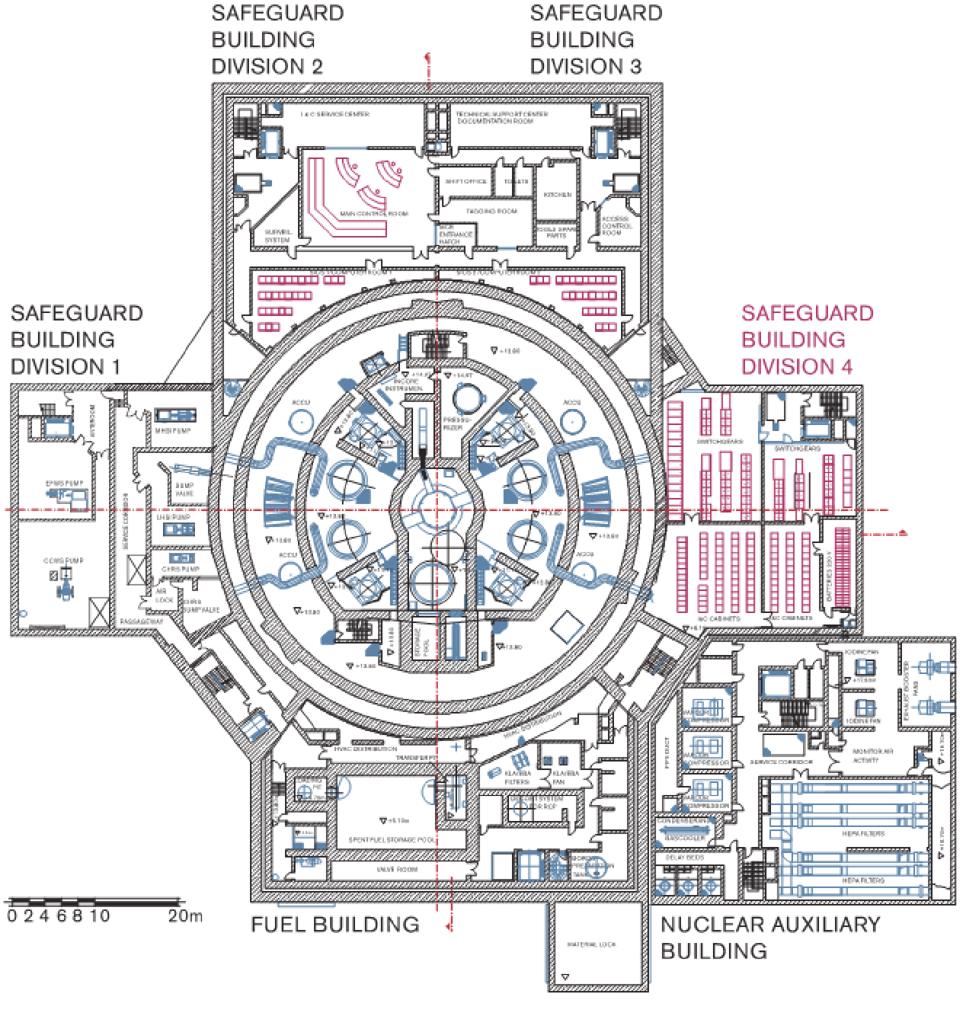


Fig. 5.5: Site plan view.

In the site the fuel elements fabrication and the fuel reprocessing plant are not present. In fact, for the following analysis, the fresh fuel comes from the outside and it is stored inside the fuel building; spent fuels, after a period of 10 years inside the fuel building, are sent to the interim storage that is co-located with the NPP. They will be there for 100 years and after that they will be sent to the conditioning plant and to the final repository following a once-through cycle. In the open or once-through fuel cycle, in fact, the spent fuel discharged from the reactor is treated as waste (see Fig. 5.6). More details about flow materials in the fuel cycle will give in the section 5.5 [135, 136].

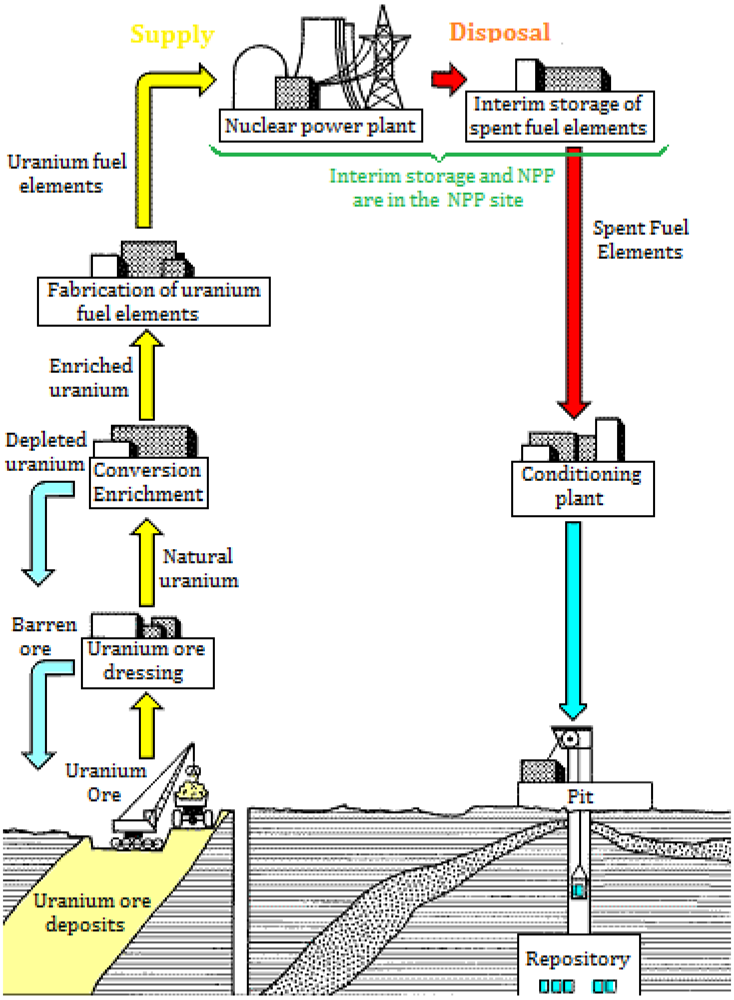


Fig. 5.6: The open once-through nuclear fuel cycle.

5.2 Interim Storage Facility

The spent fuel scheduled for storage at the facility arises from the nuclear power plant that possesses 241 combustible assemblies per core, renewed by third every 18 months, which corresponds to approximately 3400 assemblies to be stored at the conclusion of 60 years of operation. The fuel assembly, without hold-down spring, is 4.8 m long with a cross section of 214 mm x 214 mm; the thermal power dissipated by an assembly at the end of a period of 10 years decay in the pool reactor will be about 1.4 kW. After this period, spent fuels can be moved to the interim storage (see Fig. 5.7). This facility will allow the storage of spent fuel coming from the LWR nuclear plant unit during its 60 years' operating time and it will be designed to be in operation for up to 100 years. Different solutions are proposed for the location of the interim storage, but, for this report, this second pool is considered to be parallel to the length of the reception hall (see Fig. 5.8) and each pool is equipped with one unloading device. In this configuration, the handling operations are minimized because the assemblies are unloaded from the shipping cask to be directly loaded in the appropriate storage pool. Moreover, it is considered the installation at ground level, buildings lay on the ground, and this implies that physical protection against external hazards will be considered [137, 138, 139].

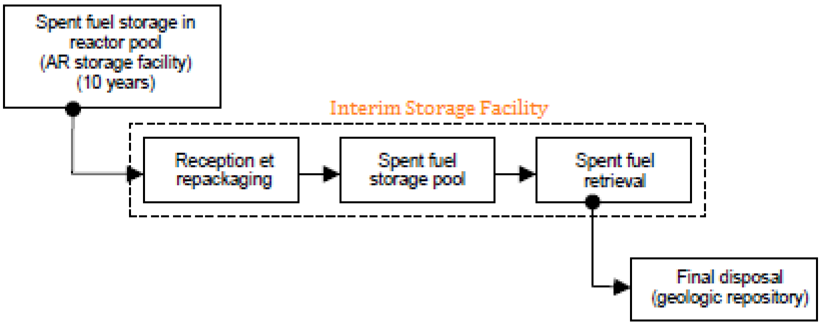


Fig. 5.7: Schematic view of movement of spent fuel between storage facilities.

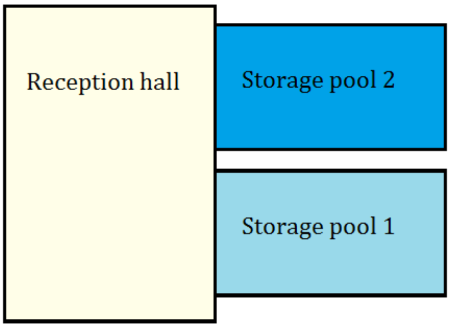


Fig. 5.8: Disposition of storage pools.

The interim storage is an underwater unloading with casks under the pool facility as in the AR ponds of the nuclear plant units PWR 1400 and 1650MW in Chooz B and Civaux in France. A scheme of this pool is shown in Fig. 5.9 and in Fig. 5.10. Moreover, it was considered that the storage is composed of removable racks in a square geometry 4x4 for a total of 16 cells.

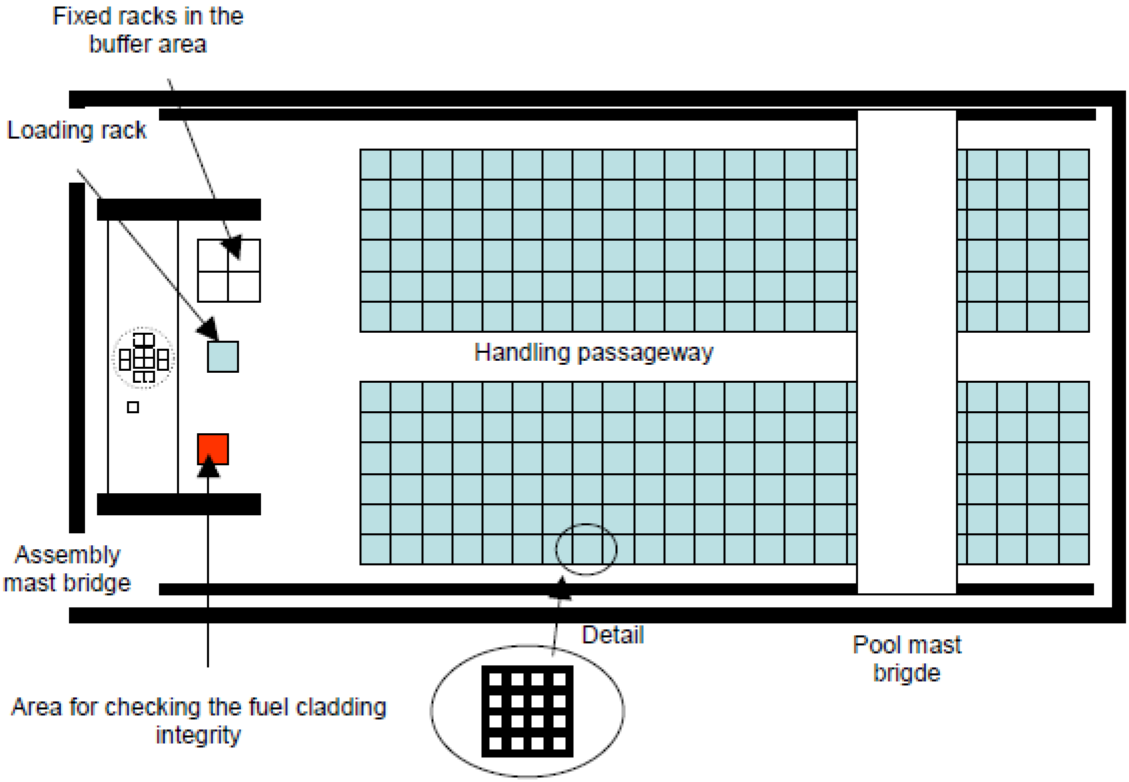
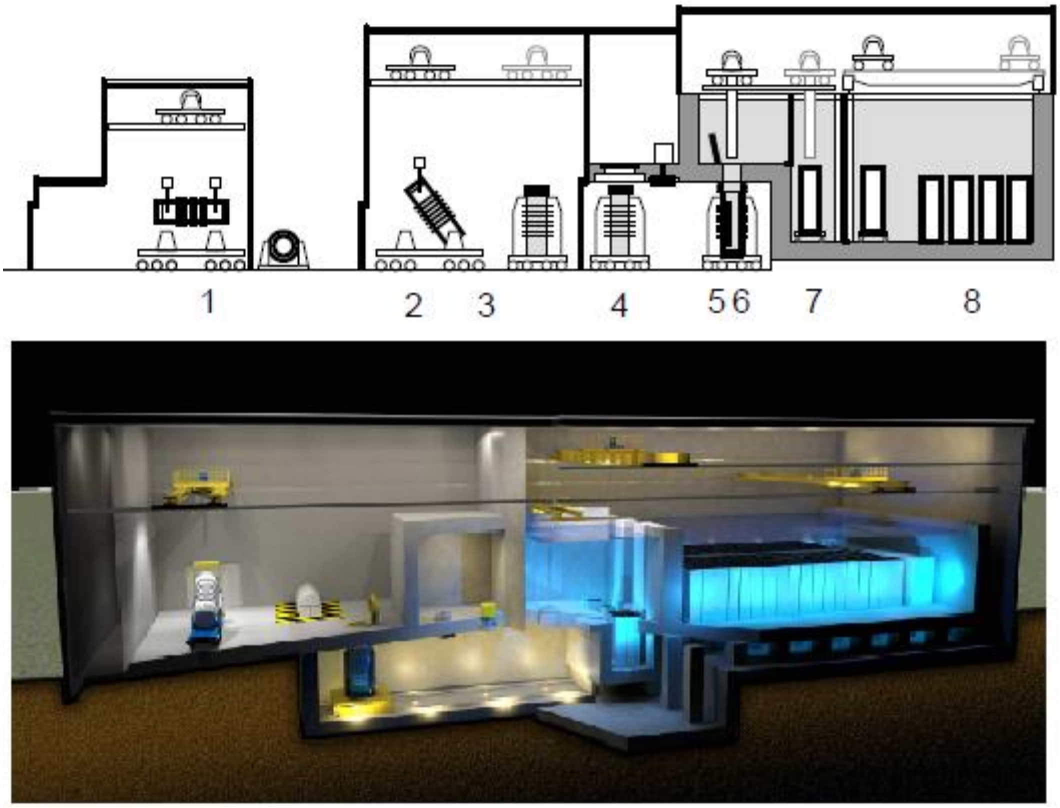


Fig. 5.9: Schematic view of the interim storage pool layout.

Point 4 in Fig. 5.10 is very important. Here the cask on the trolley is moved into the shielded cell and the shield door is shut. The cask protection cover is removed after a contamination check of the atmosphere between the protective cover and the plug (sealing systems). After removal, a contamination check is carried out on the top of the plug. This activity is performed by operators accessing the top of the flask from a cell above. A measurement of the activity concentration of the cask internal cavity is performed at the preparation area to detect any abnormal activity. If abnormal activity is detected the following will be implemented: the implementation of special procedures aimed at limiting the dispersal of this activity and, during assembly unloading, the individual inspection of the fuel cladding integrity of all the cask assemblies [137, 140].



1. Cask reception and storage in buffer area
2. Cask entrance into the unloading hall
3. Reception and lifting on the cask
4. Preparation area: activity control, filling of the internal cavity with water, opening of the cask, etc.
5. Coupling to the unloading cell (connection device)
6. Immersion of the connection device
7. Handling of the spent fuels into the storage racks
8. Handling of the racks to the storage pool

Fig. 5.10: Location of different area inside the interim storage facility.

As said before, the function of this pool is to safely and securely store the spent fuel for up to 100 years. The floor and walls of the main storage pool, along with the other smaller ones (unloading pit), are lined with layers of stainless steel to prevent leakage of water. Auxiliary systems include: water cooling and purification, ventilation, instrumentation, leakage monitoring. In order to ensure radiological shielding for operators, the side walls of the pool are 1 meter thick and the water cover is 4 meters thick. The height of the storage pool is 10m, which is the sum of the rack height, the water cover required for the radiological protection and clearances for handling racks. The cask unloading pits and rack loading pits are about 15m deep, since the height of the assembly necessary for loading the assemblies into the racks is added. Finally, the storage pool will have the following characteristics:

- Capacity: 3400 spent fuel assemblies, that is 213 storage racks (16 assemblies per rack);
- Length: 51m;

- Width: 21m;
- Depth: 10m;
- Volume of water: 10700m^3.

A detailed layout of the interim storage pool is given in Fig. 5.11.

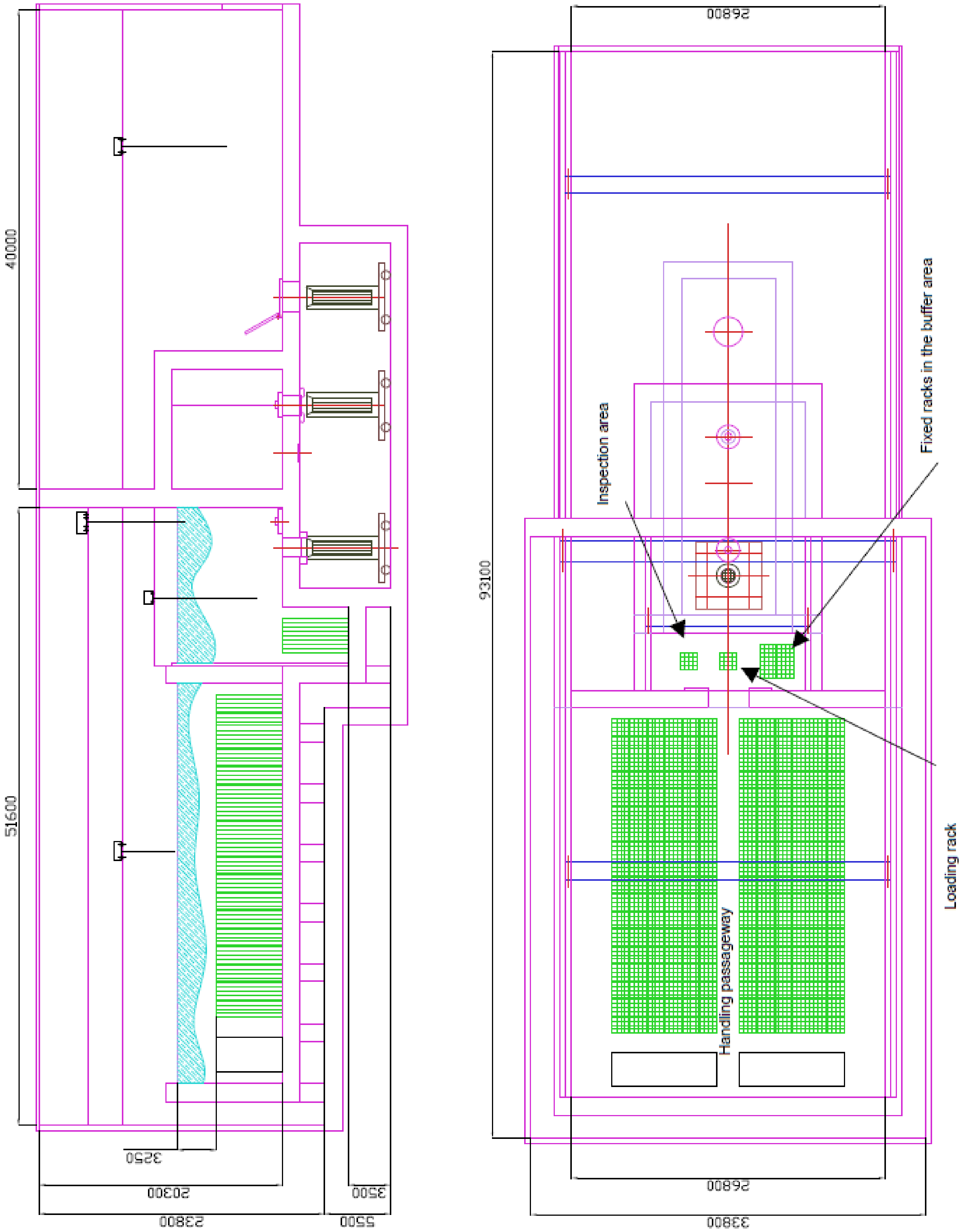


Fig. 5.11: Plant of the interim storage pool.

5.3 System Elements Identification

In the EPR-like design secribed, the following system elements are identified: the reactor building, the fuel building, the waste building, the safeguards buildings, the diesel buildings, as described in section 5.1, and the interim storage pool (see section 5.2 for details). These are the facilities inside the system containing nuclear material or process that could be attractive for proliferation or theft and/or sabotage. In our hypothesis, there is no reprocessing plant inside the site, so it would be important to consider all the shipment between the plant and the external facilities. In Fig. 5.12 the LWR nuclear system including all the systems elements listed above is shown.

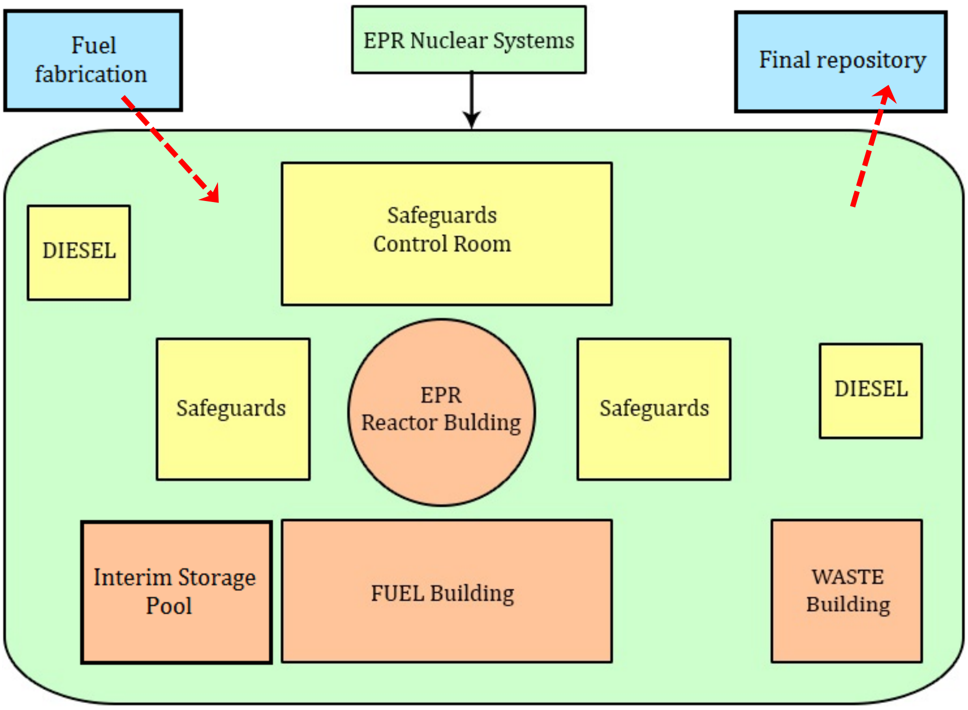


Fig. 5.12: Diagram of LWR nuclear system elements.

5.4 Reactor Facilities Description

The EPR-like is pressurized water reactor with a four-loop, pressurized water, reactor coolant system. This system consists of a reactor vessel that contains the fuel assemblies, a pressurizer with control systems to maintain system pressure, one reactor coolant pump per loop, one steam generator per loop, associated piping, and related control and protection systems.
In Tab. 5.1 the main characteristics of these systems are shown.

Tab. 5.1: Main characteristics of the LWR nuclear power plant.

Design life [years]	60
Reactor coolant system	
Number of loops	4
Coolant flow per loop [m^3/h]	28330
Reactor pressure vessel inlet temperature [°C]	295.9
Reactor pressure vessel outlet temperature [°C]	327.2
Primary side design pressure [bar]	176
Secondary side design pressure [bar]	100
Saturation pressure at nominal conditions [bar]	78
Main steam pressure at hot standby [bar]	90
Steam generators (see Fig. 5.13)	
Number	4
Primary design pressure [bar]	176
Primary design temperature [°C]	351
Secondary design pressure [bar]	100
Secondary design temperature [°C]	311
Others	
Total mass [t]	500
Feedwater temperature [°C]	230
Moisture carry – over	0.1%
Main steam flow at nominal conditions [kg/s]	2554
Main steam temperature [°C]	293
Saturation pressure at nominal conditions [bar]	78
Pressure at hot stand by [bar]	90
Reactor coolant pumps	
Number	4
Design pressure [bar]	176
Design temperature [°C]	351
Speed [rpm]	1485
Motor Rated power [kW]	9,000
Motor Frequency [Hz]	50
Pressurizer	
Design pressure [bar]	176
Design temperature [°C]	362
Number of heaters	108
Number and capacity of safety valve trains [t/h]	3 x 300
Depressurization valves capacity [t/h]	900

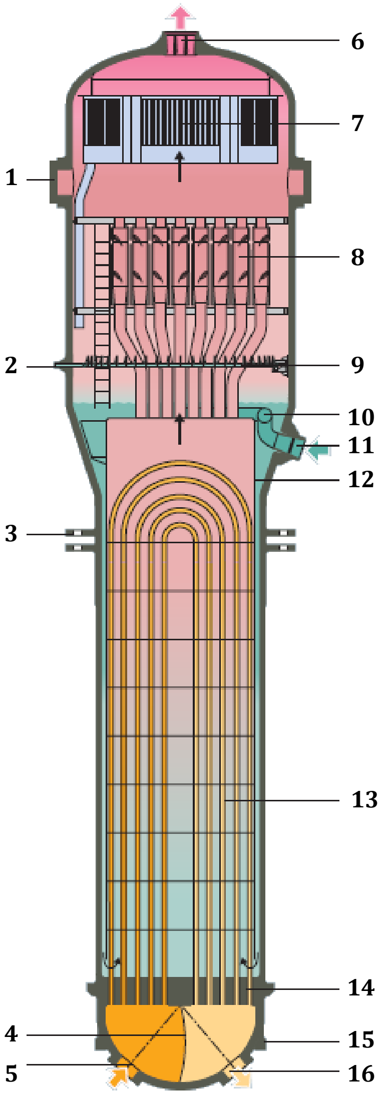


Fig. 5.13: Section through steam generator.

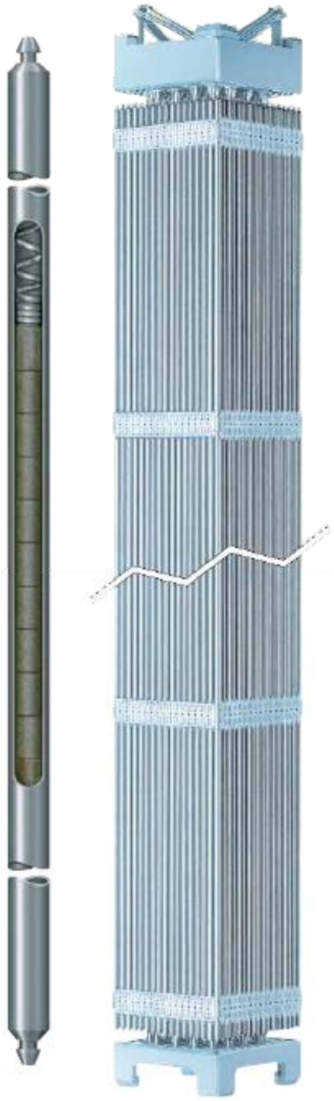


Fig. 5.14: Fuel rod and 17x17 FA scheme.

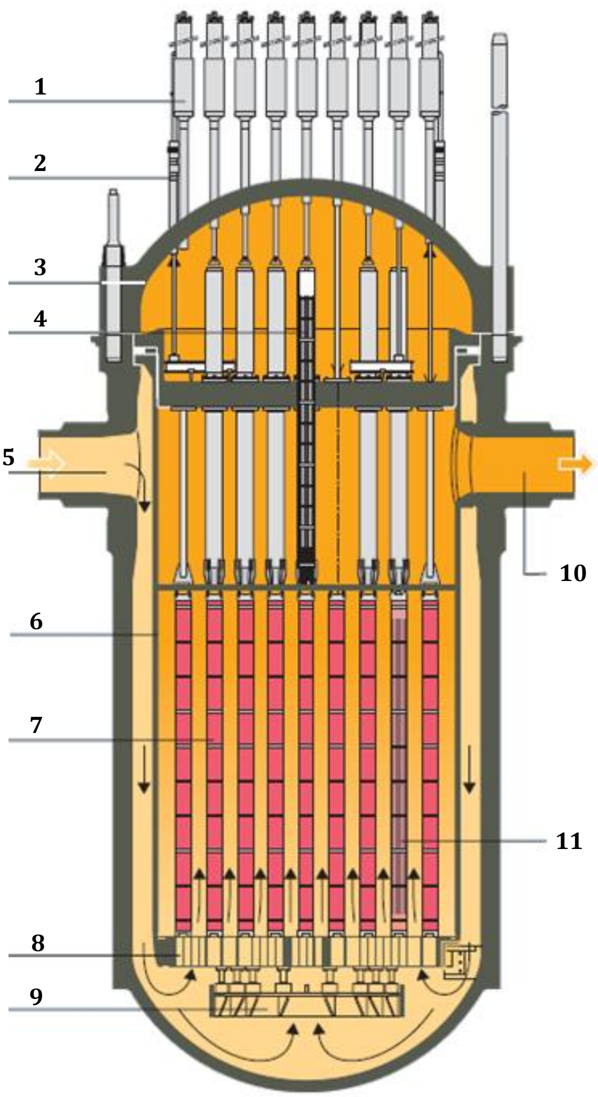


Fig. 5.15: Section through reactor pressure vessel.

1	Secondary man-way
2	Emergency feedwater nozzle
3	Horizontal supports
4	Divider plate
5	Coolant inlet nozzle
6	Steam outlet nozzle
7	Steam dryer
8	Steam separator
9	Emergency feedwater sparger
10	Feedwater sparger
11	Feedwater nozzle
12	Tube bundle shroud
13	Tube bundle
14	Tube sheet
15	Vertical supports
16	Coolant outlet nozzle

8	Control rod drive mechanism
9	Liquid level probe
10	RPV closure head
11	Control rod guide assembly
12	Coolant inlet nozzle
13	Core barrel
14	Fuel assembly
15	Lower core support grid
16	Flow distribution plate
17	Coolant outlet nozzle
18	Fuel assembly with inserted control rod

The reactor core contains the fuel material in which the fission reaction takes place, releasing energy. The reactor internal structures serve to physically support this fissile material, control the fission reaction and channel the coolant. The core is cooled and moderated by light water at a pressure of 155 bar and a temperature in the range of 300 °C. The coolant contains soluble Boron as a neutron absorber. The Boron concentration in the coolant is varied as required to control relatively slow reactivity changes, including the effects of fuel burn-up. Additional neutron absorbers (Gadolinium), in the form of burnable absorber-bearing fuel rods, are used to adjust the initial reactivity and power distribution. Instrumentation is located inside and outside the core to monitor its nuclear and thermal-hydraulic performance and to provide input for control functions. The EPR-like core consists of 241 fuel assemblies (FA). For the first core, assemblies are split into groups with different enrichments. In this case the loading patter is composed of 17 FA containing UO_2 2.10 % and no Gadolinium bars, 80 FA containing UO_2 2.10 % and 8 Gadolinium bars, 24 FA containing UO_2 3.20 % and 16 Gadolinium bars, 48 FA containing UO_2 3.20 % and 20 Gadolinium bars and others 72 FA containing UO_2 4.20 % and 16 Gadolinium bars. In Fig. 5.16 the first core loading pattern is shown.

For reload cores, the number and characteristics of the fresh assemblies depend on the type of fuel management scheme selected. For this case a cycle of 18 months is chosen so the reload scheme is the following: 24 FA containing UO_2 5.0 % and 8 Gadolinium bars, 24 FA containing UO_2 5.0 % and 12 Gadolinium bars and others 24 FA containing UO_2 5.0 % and 16 Gadolinium bars. In Fig. 5.17 the 18 months reload pattern scheme is shown.

Each FA consists of 265 fuel rods and 24 guide thimbles; the thimbles can be used for control rods or for core instrumentation thimbles. They are arranged in a 17 x 17 array and the main characteristics are listed in Tab. 5.2 [141, 142, 143].

The guide thimbles provide channels for inserting a Rod Cluster Control Assemblies (RCCA). The fuel rods are maintained within a supporting structure consisting of the 24 guide thimbles, the top and bottom nozzles, and grid assemblies distributed along the fuel rod height. The fuel rods are loaded into the fuel assembly structure so that there is clearance between the fuel rod ends and the top and bottom nozzles. Each fuel assembly is installed vertically in the reactor vessel and stands upright on the lower core plate, which is fitted with a device to locate and orient the assembly. After all fuel assemblies are set in place, the upper support structure is installed. Alignment pins, built into the upper core plate, engage and locate the upper ends of the fuel assemblies. The upper core plate then bears downward against the hold-down springs on the top nozzle of each fuel assembly to hold the fuel assemblies in place. A visual confirmation of the orientation of the fuel assemblies within the core is provided by an identification mark.

Even if fuel rods can be composed of slightly enriched uranium dioxide pellets with or without burnable poison (Gd), or MOX (U and Pu) dioxide pellets, in this study the case of UO_2 fuels is considered. The fuel is contained in a closed tube made of M5 hermetically sealed at its ends. A plenum is provided, at the top and bottom ends to contain fission gas. The fuel pellets are held in place by a spring bearing down on the top end of the pellet stack. The ends of each pellet are dished in order to compensate for the differential deformation between the pellet's center and periphery during operation. The gap between the pellets and the cladding, the initial pressurization, and the density of the pellets are specified so as to minimize the interaction between the pellet and the cladding. In Fig. 5.14 the fuel rod and FA is shown, in Fig. 5.15 the section of reactor pressure vessel is shown.

	J	K	L	M	N	P	R	S	T
09	2.10%	2.1% 8Gd	3.2% 16Gd	2.1% 8Gd	3.2% 20Gd	2.1% 8Gd	3.2% 20Gd	2.1% 8Gd	4.2% 16Gd
08	2.1% 8Gd	3.2% 16Gd	2.1% 8Gd	3.2% 20Gd	2.10%	3.2% 20Gd	2.1% 8Gd	4.2% 16Gd	4.2% 16Gd
07	3.2% 16Gd	2.1% 8Gd	3.2% 16Gd	2.1% 8Gd	3.2% 16Gd	2.1% 8Gd	3.2% 20Gd	2.1% 8Gd	4.2% 16Gd
06	2.1% 8Gd	3.2% 20Gd	2.1% 8Gd	3.2% 20Gd	2.10%	3.2% 20Gd	2.1% 8Gd	4.2% 16Gd	4.2% 16Gd
05	3.2% 20Gd	2.10%	3.2% 16Gd	2.10%	3.2% 20Gd	2.1% 8Gd	2.1% 8Gd	4.2% 16Gd	
04	2.1% 8Gd	3.2% 20Gd	2.1% 8Gd	3.2% 20Gd	2.1% 8Gd	3.2% 16Gd	4.2% 16Gd	4.2% 16Gd	
03	3.2% 20Gd	2.1% 8Gd	3.2% 20Gd	2.1% 8Gd	2.1% 8Gd	4.2% 16Gd	4.2% 16Gd		
02	2.1% 8Gd	4.2% 16Gd	2.1% 8Gd	4.2% 16Gd	4.2% 16Gd	4.2% 16Gd			
01	4.2% 16Gd	4.2% 16Gd	4.2% 16Gd	4.2% 16Gd					

Fig. 5.16: First core loading pattern.

	J	K	L	M	N	P	R	S	T
09	N5	P14	M9	**5.0% 16gd**	P9	**5.0% 16gd**	K11	**5.0% 12gd**	H11
08	P4	J5	S6	R6	P7	N7	R4	**5.0% 16gd**	J1
07	J6	M2	J7	R5	**5.0% 16gd**	L16	N6	**5.0% 12gd**	M8
06	**5.0% 16gd**	M3	N3	J2	S8	P8	**5.0% 12gd**	**5.0% 8gd**	T7
05	J4	L4	**5.0% 16gd**	K2	M6	R8	**5.0% 8gd**	M7	
04	**5.0% 16gd**	L5	B7	K4	K3	**5.0% 12gd**	**5.0% 8gd**	S5	
03	L8	P3	M5	**5.0% 12gd**	**5.0% 8gd**	**5.0% 8gd**	J8		
02	**5.0% 12gd**	**5.0% 16gd**	**5.0% 12gd**	**5.0% 8gd**	L6	N2			
01	L10	R3	K6	L1					

Fig. 5.17: Reloading pattern for UO_2 – INOUT – 18 month equilibrium cycle.

Tab. 5.2: Reactor core description data (Dimensions are at cold conditions, 20°C).

Active core:	
Equivalent diameter (mm)	3767
Average active height of the core fuel (mm)	4200
Height/diameter ratio	1,115
Total surface area (cm2)	111440
Radial heavy reflector:	
Thickness (mm)	Between 77 and 297 (average 194)
Composition (% volume)	About 95.6% steel – 4.4% water
Fuel assemblies:	
Number	241
Rod array	17x17
Number of rods per assembly	265
Lattice pitch (mm)	12.6
Assembly overall dimensions (mm)	214x214
Weight of fuel for each assembly (kg)	598 UO2, 527.5 U
Number of grids per assembly	10
Composition of grids	Zircaloy & Inconel
Number of guide thimbles per assembly	24
Composition of the guide thimbles	Zircaloy
Diameter of guide thimbles, upper part (mm)	11.45 inside 12.45 outside
Fuel rods:	
Number	63865
Outside diameter (mm)	9.50
Diametrical gap (mm)	0.17
Thickness of the cladding (mm)	0.57
Cladding material	M5 type
Fuel pellet:	
Material	UO2 or MOX
Density of the UO2 (% of theoretical density)	95
Density of the UO2 + PuO2 (% of theoretical density)	94.5
Diameter (mm)	8.19
Theoretical density of the UO2 (g/cm^3)	10.96
Theoretical density of the PuO2 (g/cm^3)	11.46
Enrichment of fuel for the UO2 assemblies (% by weight) (see also Fig. 5.16 and Fig. 5.17)	
Zone 1 of cycle 1	2.1%
Zone 2 of cycle 1	3.2%
Zone 3 of cycle 1	4.2%
New assemblies for the UO2 – IN/OUT – 18 months	5.0%

Tab. 2.2 (continue): Reactor core description data (Dimensions are at cold conditions, 20°C).

Absorber:	
AIC part:	
AIC composition (%wt) Ag/In/Cd	80/15/5
AIC density (g/cm^3)	10.17
AIC upper part absorber outer diameter (mm)	8.66
AIC upper part length (mm)	2400
AIC lower part absorber outer diameter (mm)	8.53
AIC lower part length (mm)	500
B_4C part:	
B_4C composition	19.9 %wt of B-10
B_4C density (g/cm^3)	1.79
B_4C part absorber outer diameter (mm)	8.47
B_4C part length (mm)	1340
Cladding:	
Cladding outer diameter (mm)	9.68
Cladding inner diameter (mm)	8.74
Cladding thickness (mm)	0.47
Cladding material	Stainless steel
Lower end plug material	Stainless steel
Distance between the bottom of the active height and the bottom of the absorber column:	
Cluster fully inserted (mm)	90
Cluster fully removed (mm)	4200
Number of Rod Cluster Control Assemblies	89
Number of absorber rods per cluster	24

5.5 Fuel Cycle and Flow Material Description

In this study, the LWR once-through fuel cycle using enriched uranium is considered because the majority of the world's nuclear electricity is based on it. This fuel cycle is represented in Fig. 5.6, but for the purpose of this study it is simplified (see Fig. 5.18) by lumping together all the front-end operations, all the back-end operations, and neglecting losses (typically about 0.5% in any given stage). In addition, the enrichment tails are of little interest because, although they are produced in significant amounts, they are low level wastes and can be managed easily.

The mass flows that appear in Fig. 5.18 are obtained from the analysis presented next using data showed in Tab. 5.3.

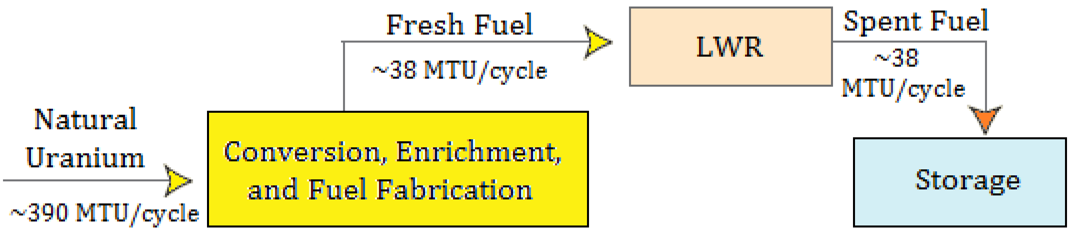


Fig. 5.18: Once-through fuel cycle (simplified)

Tab. 5.3: Characteristics of EPR (UO_2 fuel) from different sources.

	[144]	[145]	Data used in this scenario
Thermal Power [GWth]	4.59	4.59	Q = 4.59 GWth
Electric Power [GWe]		1.652	Pe = 1.65 GWe
Capacity factor	0.9	0.9	CF = 0.9
Thermal efficiency	0.355	0.36	ηth = 0.36
Discharge burnup [GWd/MTU]	59	55	BUd = 59 GWd/MTU
Cycle length	18 months	370 days	18 months
Enrichment [%wt]	4.95	4.5	ε = 4.95 %wt ^{235}U

The mass of fuel that must be loaded into the reactors per cycle is obtained as shown in equation [5.1], where the annual thermal energy output is given by equation [5.2]. Combining equations [5.1] and [5.2], it is possible to obtain the mass of fuel loaded inside the EPR-like in each cycle as shown in equation [5.3]. Using data in Tab. 5.3, the mass of fuel loaded in the reactors every cycle is 38.40 MTU that is in line with value given from AREVA for the EPR with 18 months cycle (37.00 MTU inside UO2 rods plus 1.423 MTU inside the Gd rods) [146, 147, 148, 149].

$$\mathrm{M} = \frac{Q}{BUd} \qquad [5.1]$$

$$\mathrm{Q} = \frac{P_e \cdot CF \cdot d/cycle}{\eta_{th}} \qquad [5.2]$$

$$\mathrm{M} = \frac{P_e \cdot CF \cdot d/cycle}{\eta_{th} \cdot BUd} \qquad [5.3]$$

The mass of natural uranium required for fuel production can be obtained by considering the enrichment process as represented in Fig. 5.19, where the variable x designates the enrichment. The enrichment of natural uranium is x_n=0.711%, the enrichment of tails is assumed to be x_t=0.25% and the enrichment of UO_2 is x_p=4.95%. From mass conservation of U-235 in the enrichment process, using equation [5.4] is possible to evaluate the mass of natural uranium required. With data used in this evaluation, the mass obtains is 391.2 MTU/cycle for the needed 38.40 MTU/cycle of enriched uranium to load the 1600 GWe EPR. To make this evaluation is it considered that all the fuel rods are full of UO2, without considering the presence of Gd rods and it is the possible discrepancy with the value of natural uranium given by AREVA: 385.714 MTU/cycle. However, the difference in these values is about 1.4% so results of calculations will be used for the following evaluations.

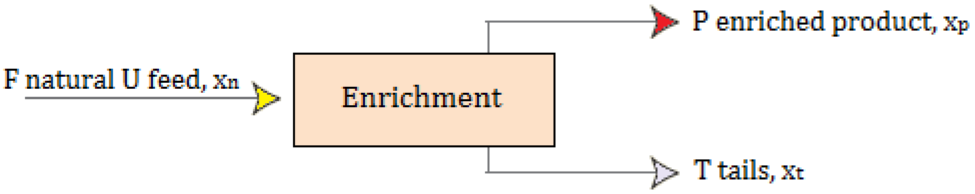


Fig. 5.19: Scheme of enrichment process.

$$\frac{F}{P} = \frac{x_p - x_t}{x_n - x_t} \qquad [5.4]$$

The isotopic composition for the discharge fuel is given in Tab. 5.4 where values are compared with literature. To evaluate the amount of materials in spent fuels the isotopic composition obtained with the code COSI for a LWR of 55 GWd/MTU is used. As it possible to see, there is a good agreement between values. For further evaluations, the literature values given for an EPR of 60GWd/MTU with an enrichment of 4.9% will be used. Using values reported in Tab. 5.4, the amount of materials expressed in ton/cycle is shown in Tab. 5.5 [150, 151, 152].

Tab. 5.4: Material flow rate in output from 1 EPR-like.

	kg/TWh$_e$ (our evaluation)	**kg/TWh$_e$ (60GWd/MTU 4.9% ^{235}U)**	**kg/TWh$_e$ (50GWd/MTU 4.2% ^{235}U)**
U	1833.4	--	--
Pu	24.46	26	29.3
Am	0.66	1.6	1.7
Np	1.76	1.9	1.9
Cu	0.32	0.28	0.2
FP	99.27	130	--

Tab. 5.5: Amount of material discharged for cycle.

	kg/TWh$_e$ (60GWd/MTU 4.9% ^{235}U)	**ton/cycle**
U	1800.1	3.525E+01
Pu	26	5.091E-01
Am	1.6	3.133E-02
Np	1.9	3.720E-02
Cu	0.28	5.483E-03
FP	130	2.545E+00

6 SAFEGUARDING THE LWR NUCLEAR ENERGY SYSTEM

6.1 MBA and KMP identification

In a LWR without MOX fuel, nuclear fuel containing uranium and plutonium, as the EPR-like considered for this study, the typical diversion scenarios exist are listed in Tab. 6.1 [119]. Because it can also used MOX fuel, it should be noted that this will complicate safeguards at a reactor since the MOX will have a timeliness of one month (as shown above in Tab. 3.2), forcing the IAEA to inspect the reactor on a monthly basis and to worry about nuclear material with a high strategic value to a potential proliferator.

Tab. 6.1: Typical LWR diversion scenarios for a PWR without MOX.

Diversion	Method	Timing/Location
LEU fresh fuel diversion	Substitution of dummy element for actual element	After fresh fuel verification, prior to core loading
Spent fuel assembly diversion	Substitution of dummy element for actual element	From reactor pool, SF pool, or SF transfer cask
Spent fuel pin diversion	Substitution of dummy element for actual element	From SF pool or SF transfer cask
Unreported Pu production	Insertion of fertile targets for irradiation in core fuel — PWR guide tubes or burnable poison rod	From reactor pool, SF pool, or SF transfer cask

According to the best practice and considering the site layout shonw in Fig. 5.3, the following two MBAs are identify for our system (see Fig. 6.1, numbers are the same that in Fig. 5.3):
XE01: this MBA contains the reactor and the related spent fuel pool located in the fuel building;
XE02: this MBA contains the interim spent fuel pool.
In Tab. 6.2 the type of material contained in each defined MBA and the corresponding level of accessibility are summirezed.
For a LWR, the flow KMPs must cover the following functions: receipts of nuclear material (nominally fresh LEU fuel); nuclear loss and nuclear production for core fuel discharged, where the nuclear loss is the reduction in uranium occurring from burnup of fuel, and the nuclear production is the production of plutonium from neutron capture in U^{238} and shipments of nuclear material (nominally spent LEU fuel to dry storage or reprocessing). The inventory KMPs, instead, must cover the following areas: fresh fuel storage (LEU fuel); reactor core (LEU fuel and plutonium); spent fuel pond (spent LEU fuel containing uranium and plutonium) and any other locations of nuclear material.

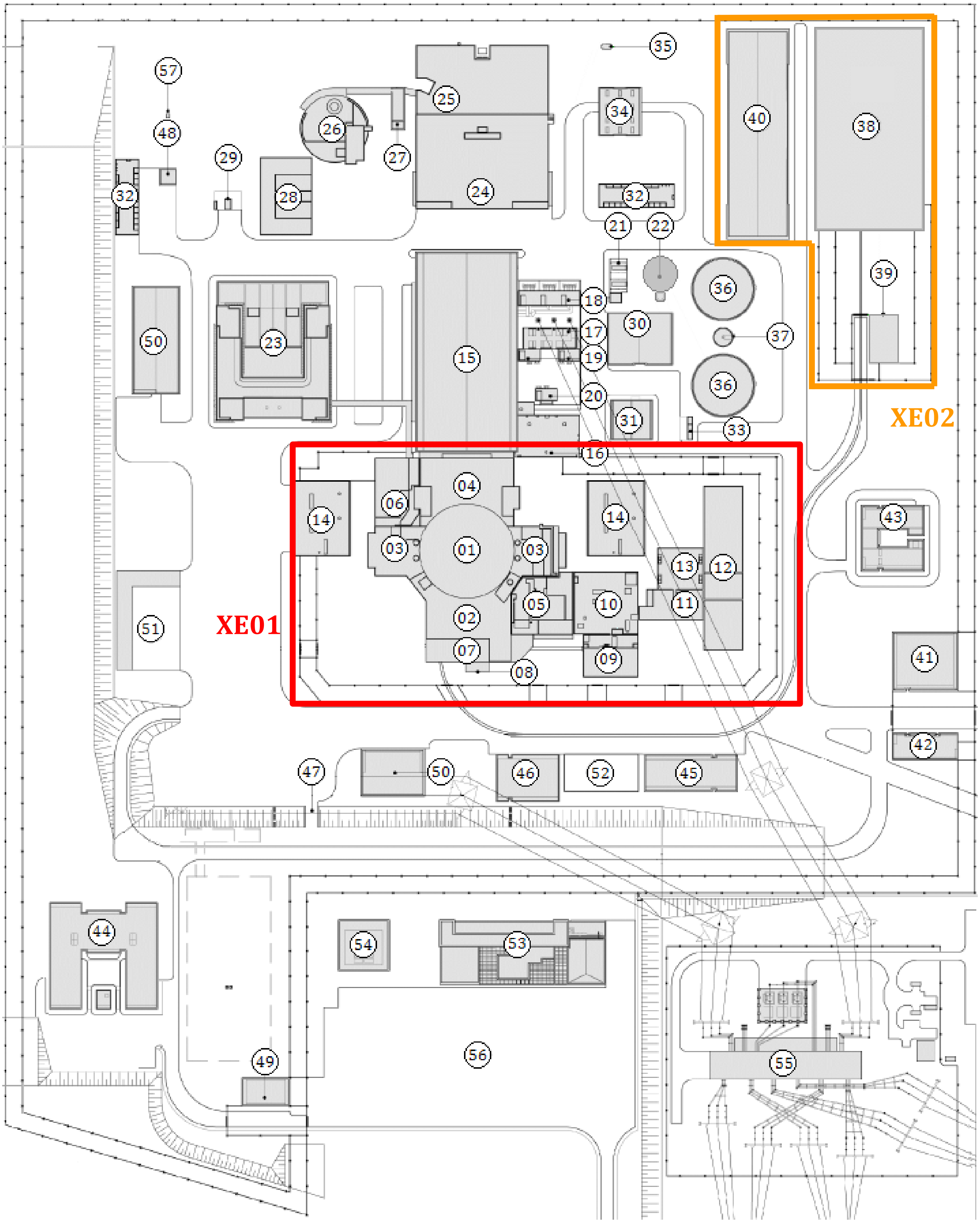


Fig. 6.1: Material Balance Areas in the EPR-like designed site.

Tab. 6.2: Type of nuclear material contained in each defined MBA and its related level of accessibility.

MBA label	Description	Type of nuclear material contained	Level of accessibility
XE01	Reactor and SF pool	Fresh fuel & spent fuel	Low for reactor building Normal elsewhere
XE02	Interim storage facility	Spent fuel after 10 years cooling	Normal

XE01

This MBA covers the Reactor core and the temporary reactor storage pool located inside the containment building and the fuel pool located in the fuel building. In Fig. 6.2 a detail of the equipment for transferring the fuel assemblies in and out the is shown, while in Fig. 6.3 a schematic representation of the MBA together with the identified strategic point is illustrated [119, 153].
From Fig. 6.2 it is possible to notice that three different fuel transfer machines operate inside the MBA:

- A fuel unloading machine used for transferring the fuel assemblies from the fuel storage pool inside the transfer station and vice versa;
- The transfer channel to move the assembly from the fuel building to the reactor storage pool and vice versa;
- A fuel unloading machine used for transferring the fuel assemblies from the reactor storage pool to the reactor core and vice versa. In this case it must be noted that the upper part of the reactor must be removed and it means that the reactor is shut down.

The nuclear material contained inside this MBA (fresh and spent fuel) is considered to have a low accessibility when inside the reactor building and normal when it is outside. Seven strategic points are identified for this MBA: their locations are shown in Fig. 6.3, their description and scope are illustrated in Tab. 6.3.

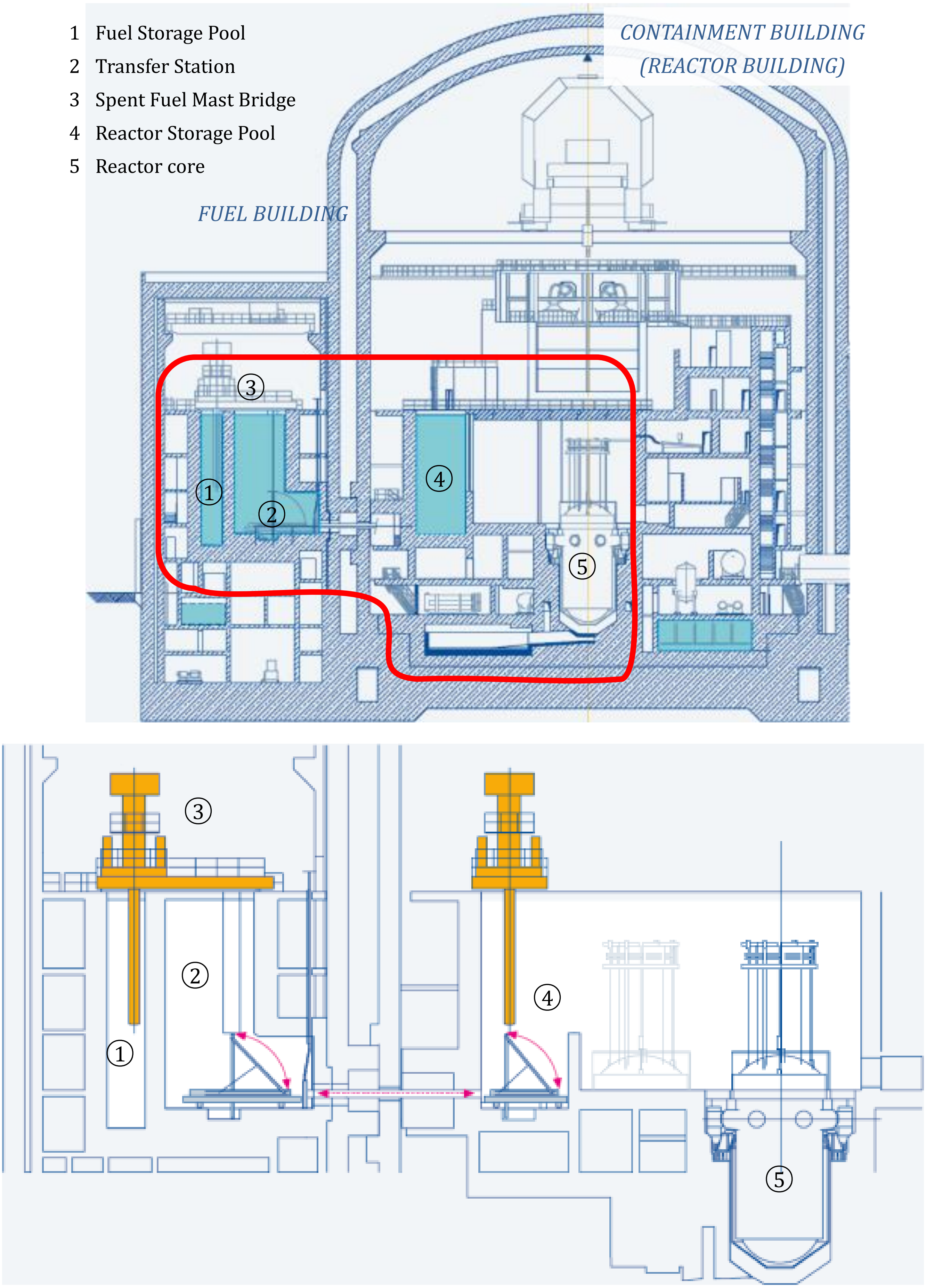


Fig. 6.2: Fuel transfer systems in the reactor building and fuel building (XE01).

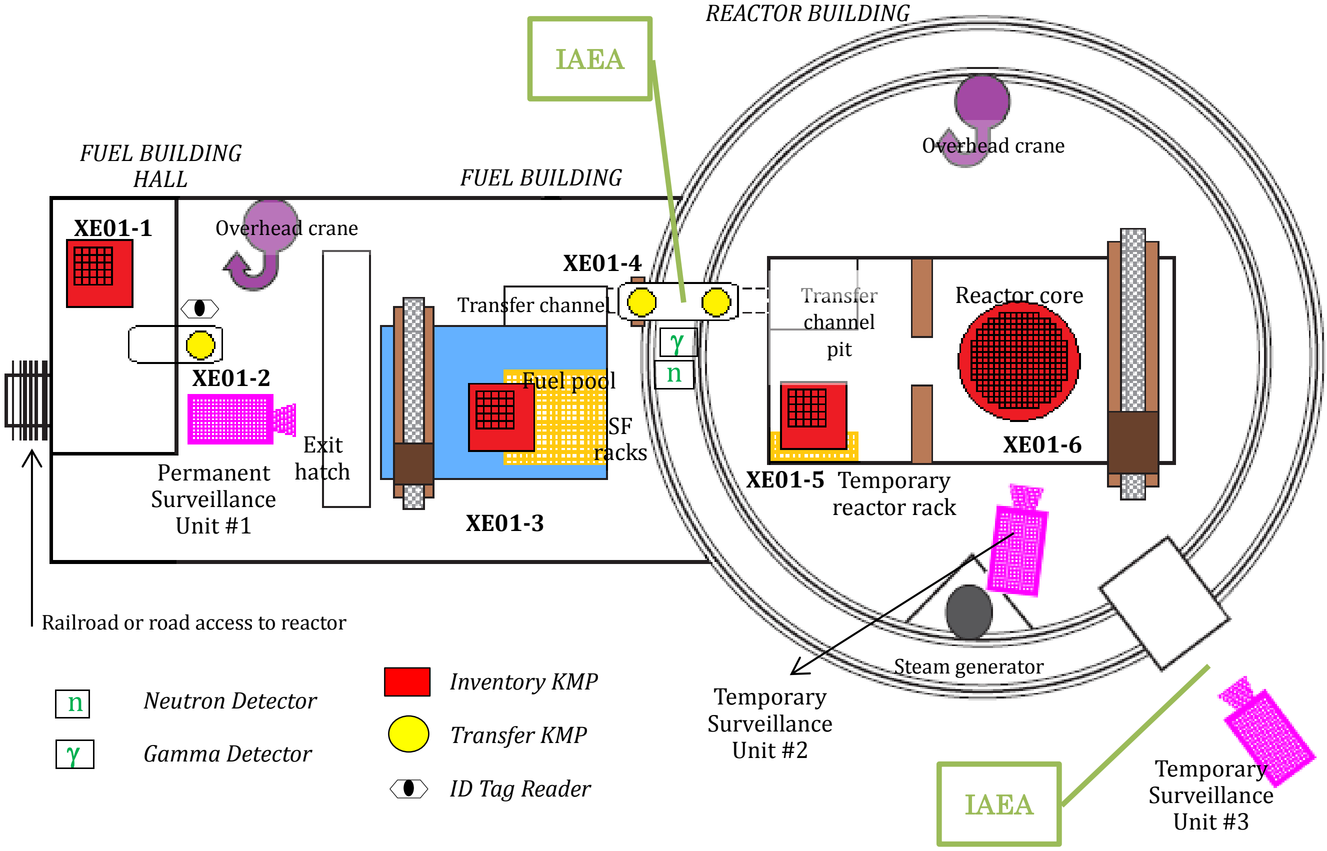


Fig. 6.3: Detail of the MBA XE01 for the LWR reactor.

Tab. 6.3: XE01 Strategic points.

KMP label	Description	Scope	Action taken	Technique adopted
XE01-1	Inventory KMP located in the fuel building hall where both new and spent fuel assemblies are received	Allow the inventory of the fuel inside the casks	It is not considered to be a storage, so no surveillance measure are considered for this area	
XE01-2	Flow KMP located at the connection between the fuel building hall and the fuel building where fuel is storage	To keep track of the fuel elements movements	Seal is verified; Continuity of knowledge has to be maintained for all the duration of the unloading & transfer	A set of cameras monitoring the operations
XE01-3	Inventory KMP located in the fuel pool both for fresh and spent fuel storage	To allow the fuel inventory inside the storage	Assemblies are item counted; The C/S system is evaluated	A set of cameras monitoring the stored assemblies; ICVD used for qualitative attribute verification of FA.

Table continues on the next page

Tab. 3.6. (continued): XE01 Strategic points.

KMP label	Description	Scope	Action taken	Technique adopted
XE01-4	Flow KMP located at the transfer channel connecting the reactor pool to the fuel building	To keep track of the fuel elements movements; To discriminate dummy, fresh and irradiate and perform attribute verification on the fuel elements in transit	FA are counted and their ID tags checked; NDA techniques are used to identify and perform attribute verification on the assemblies	HRGS coupled with passive neutron measurements
XE01-5	Inventory KMP located in the fuel reactor temporary pool	To allow the fuel elements inventory inside the storage pit; To keep track of the fuel elements movements	The C/S system is evaluated; NDA techniques are used to identify and perform attribute verification on the assemblies	HRGS coupled with passive neutron measurements ; A set of cameras monitoring the stored assemblies.
XE01-6	Inventory KMP covering the reactor core	To keep track of the fuel elements movements; To maintain continuity of knowledge of the nuclear material inventory	The C/S system is evaluated	A set of surveillance cameras monitoring equipment.

XE02

This MBA covers the interim fuel storage pool co-located with the reactor in the nuclear site (as already said in section 5.1 and shown in Fig. 5.3). In Fig. 6.4 a detail of the equipment for transferring the fuel assemblies with the identified strategic point is illustrated. It is possible to notice that at least three different fuel transfer machines operate inside the MBA:

- A casks unloading machine used for transferring casks from the buffer to the unloading hall and vice versa;
- The connection device to move the spent fuel inside the storage racks and vice versa;
- A fuel unloading machine used for transferring and moving the storage racks inside the storage pool.

The nuclear material contained inside this MBA is only spent fuel that is already cool down for 10 years inside the spent fuel pool located inside the fuel building and it is considered to have a normal accessibility. Three strategic points are identified for this MBA: their locations are shown in Fig. 6.4, their description and scope are illustrated in Tab. 6.4.

Tab. 6.4: XE02 Strategic points.

KMP label	Description	Scope	Action taken	Technique adopted
XE02-1	Flow KMP located at the connection between the external and the buffer area	To keep track of the casks movements	Seal is verified; Continuity of knowledge has to be maintained for all the duration of the unloading & transfer	A set of cameras monitoring the operations
XE02-2	Flow KMP located at the connection between the unloading hall and the fuel preparation area	To keep track of the fuel elements movements; To discriminate dummy and irradiate and perform attribute verification on the casks in transit	Casks are counted and their ID tags checked; NDA techniques are used to identify and perform attribute verification on the assemblies	A set of cameras monitoring the operations; HRGS coupled with passive neutron measurements
XE02-3	Inventory KMP located in the fuel pool	To allow the fuel inventory inside the storage	Assemblies are item counted; The C/S system is evaluated	A set of cameras monitoring the stored assemblies; ICVD used for qualitative attribute verification of FA; A XYZ positioning system that keeps track of the positioning of the handling machines used for transferring the fuel elements inside and outside the storage

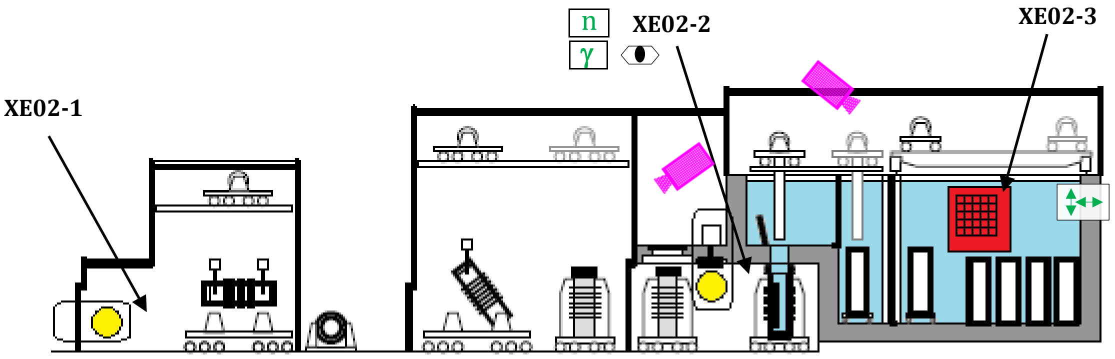


Fig. 6.4: Detail of the MBA XE02 for the LWR reactor.

6.2 Physical Inventory Verification

The facility considered here has a stretched-out refueling schedule (18 months), so a closed core PIV is done as best as possible for timeliness sake, and the core is verified during the refueling period. Usually, for a PWR, a PIV has three distinct phases: the pre-PIV, the PIV activities, and the post-PIV.

During the pre-PIV the inspector must verify the fresh fuel that the plant received since the last PIV. He will visually inspect, count, and check the serial numbers stamped on the fuel and perform NDA. For fresh fuel, the Agency does a *gross defects*[9] test, which entails testing to see if the fuel assembly does contain uranium. For fresh fuel, instead, the Agency can use a CdZnTe detector to search for the characteristic 185 keV U^{235} gamma spectrum peak.

The objective of containment and surveillance measures is to maintain what the IAEA calls Continuity of Knowledge (CofK). Once the Agency has verified nuclear material, it must either maintain a constant vigil over that material to assure that it can detect any tampering with the material or reverify the nuclear material on a required frequency.

Referring to Fig. 6.3 for locations, IAEA Tamper-Indicating Devices (TID), metal *E-Cup* seals, seal the huge equipment access hatch on the containment dome where, during refueling, equipment is moved in and out of the reactor hall and the gate that separates the spent fuel pool from the reactor core's pool. These measures provide tamper indication if the operator has opened the reactor hatch or the canal gate to access the core fuel to divert the nuclear material. Agency surveillance consists of digital cameras able to capture images in small enough time intervals to detect a diversion and to be able to store this information on a media that the inspector can access during the PIV and quarterly inspections. Hence, the Agency maintains CofK of the core fuel and spent fuel by C/S measures over the course of the year. However, during the pre-PIV, the inspector must alter the C/S environment to allow the operator to perform the refueling and to still keep the CofK. In particular, the inspector will remove the seals on the containment hatch and the canal gate to allow the operator to move old core fuel from the reactor to the spent fuel pond and bring new fresh fuel into the reactor. A temporary surveillance camera will be installed in the reactor. During the PIV activities, the inspection team receives the accountancy documents from the operator. They include the General Ledger with material accountancy summaries, fuel history cards and fuel assembly certificates for being able to track and identify fuel items, and an itemized list of the fuel assemblies located at the reactor. The operating records can include the power histogram and estimates of burnup, the all-important core and spent fuel pond maps with assembly locations, and cask shipment and crane movement information. So, the inspector can proceed to verify the core fuel by item counting of the core fuel from the core barrel edge and using the operator's underwater TV (UWTV) camera system to check off that the serial numbers of the fuel assemblies match the declared locations on the core map. Since the canal gate seal is not in place, the operator can shuffle items between the core and spent fuel ponds without the Agency's knowledge.

Regarding observations of the spent fuel pond with the SF core map and the assembly burnup

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[9] A *partial defects* test would test to see whether 50% of the assembly's nuclear material as declared is present, and a *bias defect* tests to see whether, within a small range of uncertainty, all the assembly's nuclear material as declared is present.

data, the standard technique is to use the Improved Cerenkov Viewing Device (ICVD) to observe the blue Cerenkov glow emitting from the spent fuel assemblies. It is an image intensifier viewing device that is sensitive to ultraviolet radiation in the water surrounding spent fuel assemblies (see Fig. 6.5). The ICVD is optimized for ultraviolet radiation by filtering away most of the visible light and by having an image intensifier tube primarily sensitive to the ultraviolet light frequencies[10]. With careful alignment and appropriate assessment of the object being viewed, an irradiated fuel assembly can be distinguished from a non-fuel item that may look the same to the naked eye. If some assemblies cannot be verified by ICVD or are questionable, another instrument can be used: the SF attribute tester (SFAT). It is a multichannel analyzer electronics unit and a NaI or CdZnTe detector, is used for taking measurements from the top of a fuel assembly as it sits in the storage rack (left side of Fig. 6.6). The SFAT provides a qualitative verification of the presence of spent fuel through detection of particular fission product γ rays — either from Cs^{137} (662 keV) for fuel that has cooled for longer than four years or from short lived fission products such as Zr^{95}/Nb^{95} (757/766 keV) for fuel with short cooling times. Activation products such as Co^{60} are also identifiable (right side of Fig. 6.6).

Once the verification of core fuel and spent fuel ponds is completed, inspectors may be able to service and remove the temporary cameras in the reactor hall and replace the seals on the containment hatch and the canal gate. Usually the operator will want to have the canal gate open for some time after the PIV, so, inspectors may have to schedule a separate post-PIV inspection to replace the canal gate seal. However, if the next interim inspection is within the time frame for completion of the post-PIV activities, a separate inspection may be avoided [119, 154, 155, 156].

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[10] Cerenkov radiation is derived from the intense γ radiation emanating from spent fuel, which, when absorbed in the water, produces high energy recoil electrons. In many cases these electrons exceed the speed of light in water (which is slower than the speed of light in a vacuum) and therefore must lose energy by emitting radiation (Cerenkov radiation). Spent fuel also emits β particles, adding to the Cerenkov radiation. Spent fuel assemblies are characterized by Cerenkov glow patterns that are bright in the regions immediately adjacent to the fuel rods. The variation in light intensity is apparent when viewed from a position aligned directly above the fuel rods.

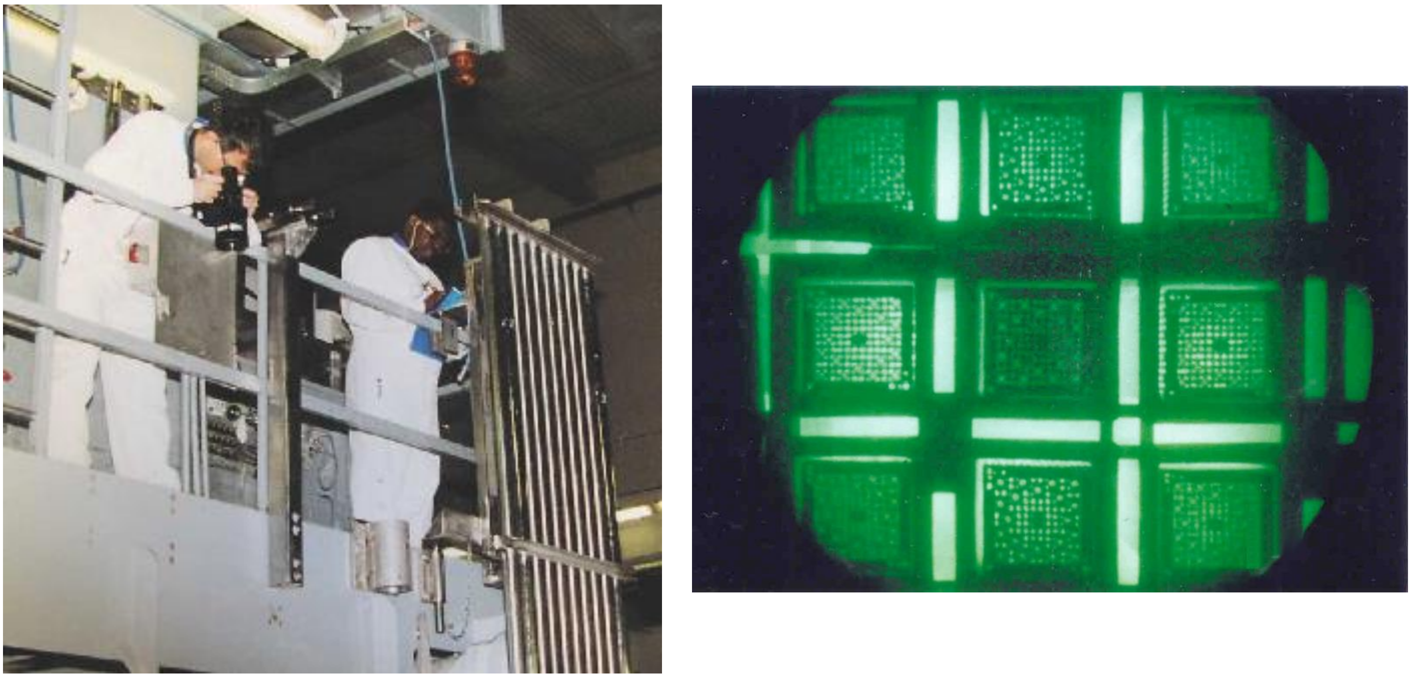


Fig. 6.5: ICVD used to verify spent fuel ponds and example of a PWR fuel design Cerenkov image.

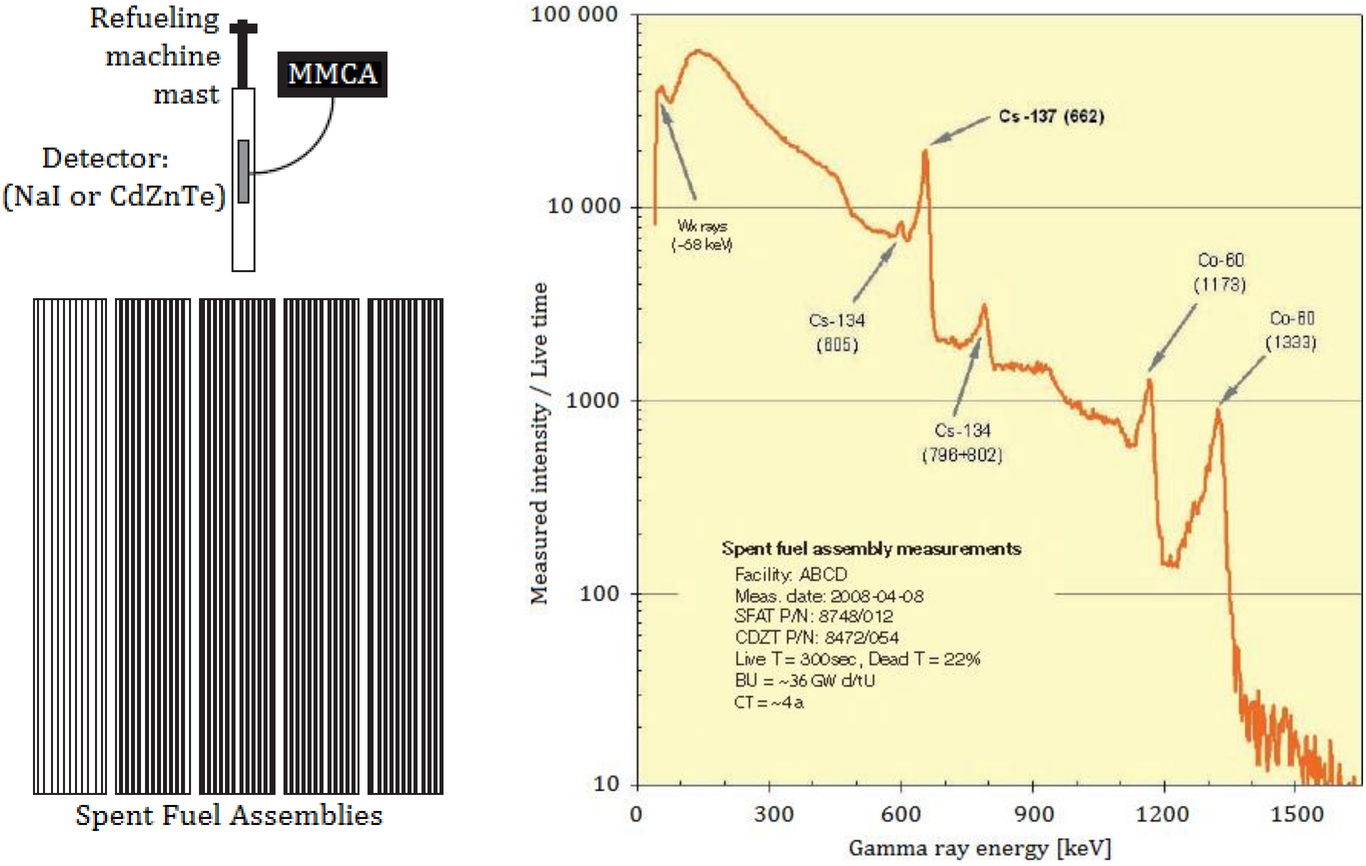


Fig. 6.6: SFAT used to verify spent fuel ponds and its typical γ ray spectrum.

7 LWR PHYSICAL PROTECTION SYSTEM

Theft of nuclear materials or information involves actions by non-Host State actors, who may be sophisticated thieves, terrorists, or agents of rogue states. Both information and material is attractive to these actors. The barriers to theft of nuclear materials and information include both intrinsic characteristic of the materials (mass, bulk, radiation levels and encryption) and intrinsic characteristics of the locations where the materials/information are stored and handled (vaults and controlled locations), as well as extrinsic measures associated with the design of the physical protection system which can detect, delay and neutralize adversaries and control the effects of insider actions (alarms, motion sensor and armed security forces). Different strategies can be implemented to reduce the risk of theft of nuclear materials or reducing the risk of sabotage releasing radioactive materials: the first one can be the achievement of a globally uniform level of PP for the plant site that is commensurate with local threats and with the intrinsic materials barriers that impede the theft of materials; the second one involves nuclear energy system R&D to increase the intrinsic material barriers that impede theft/sabotage and to improve PP system technology to achieve equivalent protection levels at a reduced cost (security by design process).

It must be underlined that the PP of a nuclear facility is the responsibility of the Host State of the facility. Protection against theft or unauthorized removal of nuclear material by a subnational group is provided by Host State security personnel and systems. Moreover, if such theft or removal were to occur, it is primarily the Host State resources that would be applied to securing and returning the material to proper control. IAEA guidelines [157, 158] have been created against which a given PP regime can be compared.

7.1 Standards elements of a Physical Security implementation

In the case of the EPR-like reactor, these two areas are located in the same building: the fuel building. This building, as said in section 5.1, is enclosed by a hardened concrete protection shield, which prevents damage to the building from external hazards. The fuel building interior structures, systems and components are further protected from the impact forces of an aircraft hazard by structural decoupling from the outer hardened walls above the basement elevation. Building isolation and filtering occurs in the event of a release of radioactivity inside the building. The other building in which spent fuel will be located is the long term interim storage pool. This building, differently from the other one, is a standard commercial building.

However, all these two areas will fall within the site wide physical protection systems.

7.2 Identification of potential threats

Fuel building and fuel building hall

In the fuel building hall and the adjacent fuel building both the fresh and spent fuel are stored. Fresh fuel considered in this study is the LEU and even if this fuel has a low attractiveness, its diversion can be happened. On the other hand, spent fuel in these areas is the next most attractive material. These areas will be within a PIDAS. Additionally, detection can be placed on access doors and equipment ports into the facility. Cameras and sensors can observe the internal volumes. Assembly lifting devices (cranes) can be locked out or disabled. Vault-type doors can be installed on vehicle and equipment access openings that are large enough for the assemblies. Moreover, due to the fact that this building is inside the nuclear island, its walls and roof are hardened also to prevent aircraft access.

Reactor pool and SF transfer rack

Even if it is possible to consider these areas as low accessible ones, here the assemblies are for sure no more inside cask, but spent fuel here are hotter than fuel present inside the spent fuel pool. These areas will be within a PIDAS. Additionally, detection can be placed on access doors and equipment ports into the facility. Cameras and sensors can observe the internal volumes. Assembly lifting devices (cranes) can be locked out or disabled. Vault-type doors can be installed on vehicle and equipment access openings that are large enough for the assemblies. Moreover, these areas are included in the reactor building that has a double layer and it is protected against aircraft access.

Interim fuel storage pool

The interim fuel building pool contains spent fuel that is cooled down for 10 years inside the SF pool. This material is more attractive for adversaries because it less hot than the SF inside the SF pool. These areas will be within a PIDAS. Additionally, detection can be placed on access doors and equipment ports into the facility. Cameras and sensors can observe the internal volumes. Assembly lifting devices (cranes) can be locked out or disabled. Vault-type doors can be installed on vehicle and equipment access openings that are large enough for the assemblies. However, differently from the previous ones, it is not protected against aircraft access.

Radiological Sabotage Targets

Considerations done for the SFR (see section 4.4) are still valid.

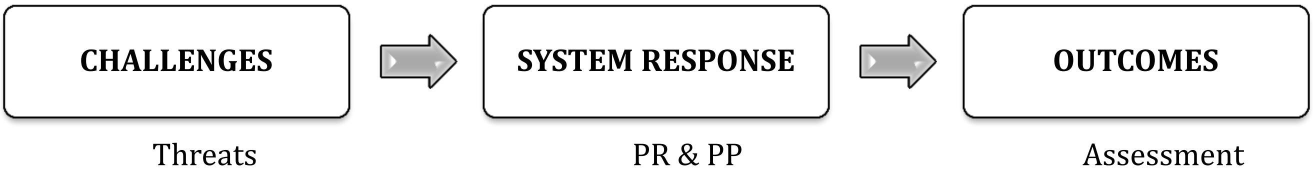
8 REPRESENTATIVE PATHWAY DESCRIPTIONS

The four sets of representative pathways identified and analyzed in this study were selected to cover a relatively large fraction of the total PR&PP threat space for the analyzed systems. They are:

- Concealed diversion of material;
- Concealed misuse of the facility;
- Breakout and overt diversion of material and misuse of the facility;
- Theft of nuclear material and sabotage of nuclear system elements.

8.1 Diversion

The approach to ESFR PR diversion analysis follows the GIF PR&PP Methodology standard paradigm:



The threat description includes not only the target material and the possible pathway, but also the description of the actor and its capabilities. In Tab. 8.1 the threat characteristics relevant to diversion are shown.

Tab. 8.1: Threat characteristics relevant to diversion scenario.

	Range of possibilities	**Threat characteristics relevant to diversion**
Actor Type	Host State	Host State
Actor Capabilities	Wide range of technical skills, resources (money, workforce, U & Th), industrial capability, nuclear capability	Capabilities of industrial nation with nuclear capabilities such as the operation of both LWR and SFR, with reprocessing plants but no enrichment
Objectives	Wide range of nuclear weapon aspirations: number, reliability ability to stockpile, deliverability, production rate	1 SQ In case of Pu mixtures, its quality must be preferably at least fuel-grade[11]
Strategies	Concealed diversion Concealed facility misuse Overt facility misuse Clandestine facilities alone	Concealed or overt removal of material from the normal, monitored process

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[11] Traditionally, the suitability of a plutonium mixture for explosive devices is determined by its Pu-240 contents. Four categories are commonly considered, but recently a fifth one is added. The different grades are: super-grade (best quality) with a quantity of $Pu^{240} < 3\%$; weapon-grade (standard material) with a quantity of Pu^{240} between 3% and 7%; fuel-grade (practically usable) with a quantity of Pu^{240} between 7% and 18%; reactor-grade (conceivably usable) with a quantity of Pu^{240} between 18% and 30%; MOX-grade (practically unusable) with a quantity of $Pu^{240} > 30\%$. [79]

Target identification for both LWR and SFR begins by breaking the reactor site into system elements for analysis as previously shown in section 5.3 for LWR and 2.2 for SFR. However, certain elements of a complete nuclear energy system are beyond the scope of this analysis, specifically, the front-end (mining and fuel fabrication) and the back-end (reprocessing and/or geological storage) facilities will not be analyzed in this study. It is important to underline that no targets for diversion were identified in the reactors because access during operations is not deemed viable.

> *A PR target is nuclear material that can be diverted, equipment and processes that can be misused to process undeclared nuclear materials, or equipment and technology that can be replicated in an undeclared facility. [98]*

The target analysis considered the different types of nuclear material in each system element, its location, and its configuration. The target analysis for LWR and SFR system elements is tabulated in Tab. 8.2 and in Tab. 8.3. In Tab. 8.4 the different targets identified are characterizes, while Tab. 8.5 displays the system elements in which the targets can be found and shows that these targets have a limited number of diversion points.

Tab. 8.2: Target analysis of MBA XE01.

Diversion points	**Target ID**	**Target Description**	**Target Material Character**	**Potential Diversion Containers**	**Container Transition**	**Normal Container Material**	**Process**	**Operational state**	**Safeguards**
XE01-1	T1	Cask of LWR fuel bundles	Fresh U^{235}	Casks	Parking area (outside)	Fresh fuel elements	Storage	Normal storage	Cameras Inventory
	T2	Cask of LWR fuel bundles	Irradiated U^{235} and TRU metal	Casks		Spent fuel elements	Storage	Normal storage	Cameras Inventory
XE01-2	T3	LWR Fuel bundle(s)	Fresh U^{235}	Casks	Transit between the fuel building hall and the fuel building	Fresh fuel elements	Loading	Normal operations	Cameras Inventory
	T4	LWR Fuel bundle(s)	Irradiated U^{235} and TRU metal	Casks		Spent fuel elements	Unloading	Normal operations	Cameras Inventory
XE01-3	T3	Individual fresh fuel bundle(s) in fuel storage rack	Fresh U^{235}	Cask/other containers	Transit between XE01-1 and XE01-2	Fresh fuel bundles	Storage in fuel rack	Normal storage	Cameras Inventory Neutron det. Gamma det.
	T4	Individual spent fuel bundle(s) in fuel storage rack	Irradiated U^{235} and TRU metal	Cask/other containers		Spent fuel bundles	Storage in fuel rack	Normal storage	Cameras Inventory Neutron det. Gamma det.

Tab. 8.3: Target analysis of MBA XS01.

Diversion points	Target ID	Target Description	Target Material Character	Potential Diversion Containers	Container Transition	Normal Container Material	Process	Operational state	Safeguards
XS01-1	T5	Cask of MOX fuel bundles	Fresh MOX	Casks	Parking area	Fresh fuel elements	Storage	Normal storage	Cameras Inventory
	T6	MOX fuel bundle(s)	Fresh MOX	Casks	Transit in the fresh fuel handling room	Fresh fuel elements	Unloading	Cask movement	Cameras Inventory
XS01-2	T6	Individual fresh fuel bundle(s) in fuel storage rack	Fresh MOX	Cask/other containers	Transit within XS01-1	Fresh fuel elements	Storage in fuel rack	Normal storage	Cameras Inventory
XS01-4	T7	Individual spent fuel bundle(s) in fuel storage rack	Irradiated MOX	Cask/other containers	Transit within XS01-5	Spent fuel elements	Storage in fuel rack	Normal storage	Cameras Inventory Neutron det. Gamma det.
	T8	Individual irradiated blanket bundle(s) in fuel storage rack	Irradiated U^{238}	Cask/other containers	Transit within XS01-5	Spent fuel elements	Storage in fuel rack	Normal storage	Cameras Inventory Neutron det. Gamma det.
XS01-5	T9	Cask of MOX fuel bundles	Irradiated MOX	Casks	Parking area	Spent fuel elements	Storage	Normal storage	Cameras Inventory
	T7	MOX fuel bundle(s)	Irradiated MOX	Casks	Transit in the shipping station	Spent fuel elements	Loading	Normal operation	Cameras Inventory

Tab. 8.4: Target description.

Target ID	Target Description	Target Material Character
T1	Cask of LWR fuel bundles	Fresh U^{235}
T2	Cask of LWR fuel bundles	Irradiated U^{235} and TRU metal
T3	LWR Fuel bundle(s)	Fresh U^{235}
T4	LWR Fuel bundle(s)	Irradiated U^{235} and TRU metal
T5	Cask of MOX fuel bundles	Fresh MOX
T6	MOX fuel bundle(s)	Fresh MOX
T7	Individual spent fuel bundle(s) in fuel storage rack	Irradiated MOX
T8	Individual irradiated blanket bundle(s) in fuel storage rack	Irradiated U^{238}
T9	Cask of MOX fuel bundles	Irradiated MOX

Tab. 8.5: Targets and related diversion points.

Target ID	Diversion points
T1	XE01-1
T2	XE01-1
T3	XE01-2 XE01-3
T4	XE01-2 XE01-3
T5	XS01-1
T6	XS01-1
T7	XS01-4 XS01-5
T8	XS01-4
T9	XS01-5

Following the PRPP methodology, the diversion analysis must proceed along the following steps:

- Examine every potential target
- Characterize the target material
- Identify the possible physical mechanisms that could be used to remove the material
- Identify the physical and design barriers to removal
- Identify the safeguards instruments and approaches that detect each physical mechanism that could be used to remove the material
- Hypothesize ways to defeat the safeguards
- Layout qualitative pathways for removal of each target
- Perform a coarse qualitative estimation of the measures for each diversion pathway.

In this study only one of the possible diversion scenarios, as result of several round tables, will be presented for LWR and SFR as described in Tab. 8.6.

Tab. 8.6: Diversion scenarios for LWR and SFR.

LWR	SFR
T4-XE01-3	T8-XS01-4
Dummy fuel assemblies present in the spent fuel swimming pool (as results of loading trial) are used to substitute at least two spent fuel assemblies. Camera may not need to be compromised, but ID reader or its data must be falsified. Casks are prepared for shipping and send to the concealed processing facility.	Dummy fuel assemblies present in the spent fuel swimming pool (as results of loading trial) are used to substitute at least one irradiated blanket from the spent fuel pool. Camera may not need to be compromised, but ID reader or its data must be falsified. Casks are prepared for shipping and send to the concealed processing facility.

The results of the evaluation will be present in section 9.1.

8.2 Misuse

Misuse threats, differently form diversion threats that deal specifically with the removal of materials already in the system, use the facility to produce or process weapon-useable materials that are outside of safeguards, possibly to avoid detection through accountancy and other safeguards measures.

There are many ways in which NPPs could contribute to Host State's weapons aspirations, but the most significant one is to use them for the covert production or processing of weapon-useable material. The success of any misuse activity depends on the capabilities and objectives of the Host State:

- Host State acquires outside the fresh fuel needed (LEU, natural uranium or depleted uranium)
- Host State prepares target uranium pins outside the NPP site
- Host State assembles final target fresh fuel assemblies made up by uranium target pins and standard fresh fuels pins outside the NPP
- Host State loads target assemblies into the core during refueling
- Host State irradiates target assemblies
- Host State unloads target assemblies from reactor cores and leaves them in the spent fuel pool for cooling
- Host State transfers target assemblies out
- Host State disassembles target assemblies and recovers target pins in the clandestine facility and separates plutonium at that clandestine facility.

Some assumptions are on the basis of this scenario:

- It is assumed that the Host State objective is to produce at least one "significant quantity" of weapon-useable material (1 SQ).
- It is assumed that the Host State has ready access to all materials and expertise needed to support the described scenarios
- It is assumed that the Host State will attempt to minimize disruption of normal facility operations during misuse of the facility.

For the misuse scenario, an irradiation of ad-hoc targets for the covert plutonium production is considered. A general scheme of the process is shown in Fig. 8.1, while the detail pathway for both LWR and SFR is described in Tab. 8.7. It must be noted that in this study the fabrication and reprocessing facilities are outside the NES, so in Fig. 8.1 all the marked entry are not included in the study itself, however, they must be taken into account when considering the entire fuel cycle for a NES.

Tab. 8.7: Misuse scenarios for LWR and SFR.

LWR	SFR
Host State will acquire LEU outside the facility as a normal operation and, consequentially, the Host State must have some capability of storage for fresh fuel.	Host State will acquire DU or RU outside the facility as a normal operation and, consequentially, the Host State must have some capability of storage for fresh fuel.
Host State will than prepare the target pins outside the NES. In particular, it will substitute two control rods for each FA with LEU material and irradiate them for one fuel cycle. To reach a SQ the same procedure must be repeated for 3 times.	Host State will than prepare the target pins outside the NES. In particular, it will substitute two fuel assemblies in the outer ring of the core with two assemblies like the blanket type. To reach a SQ they must be irradiated for one fuel cycle.

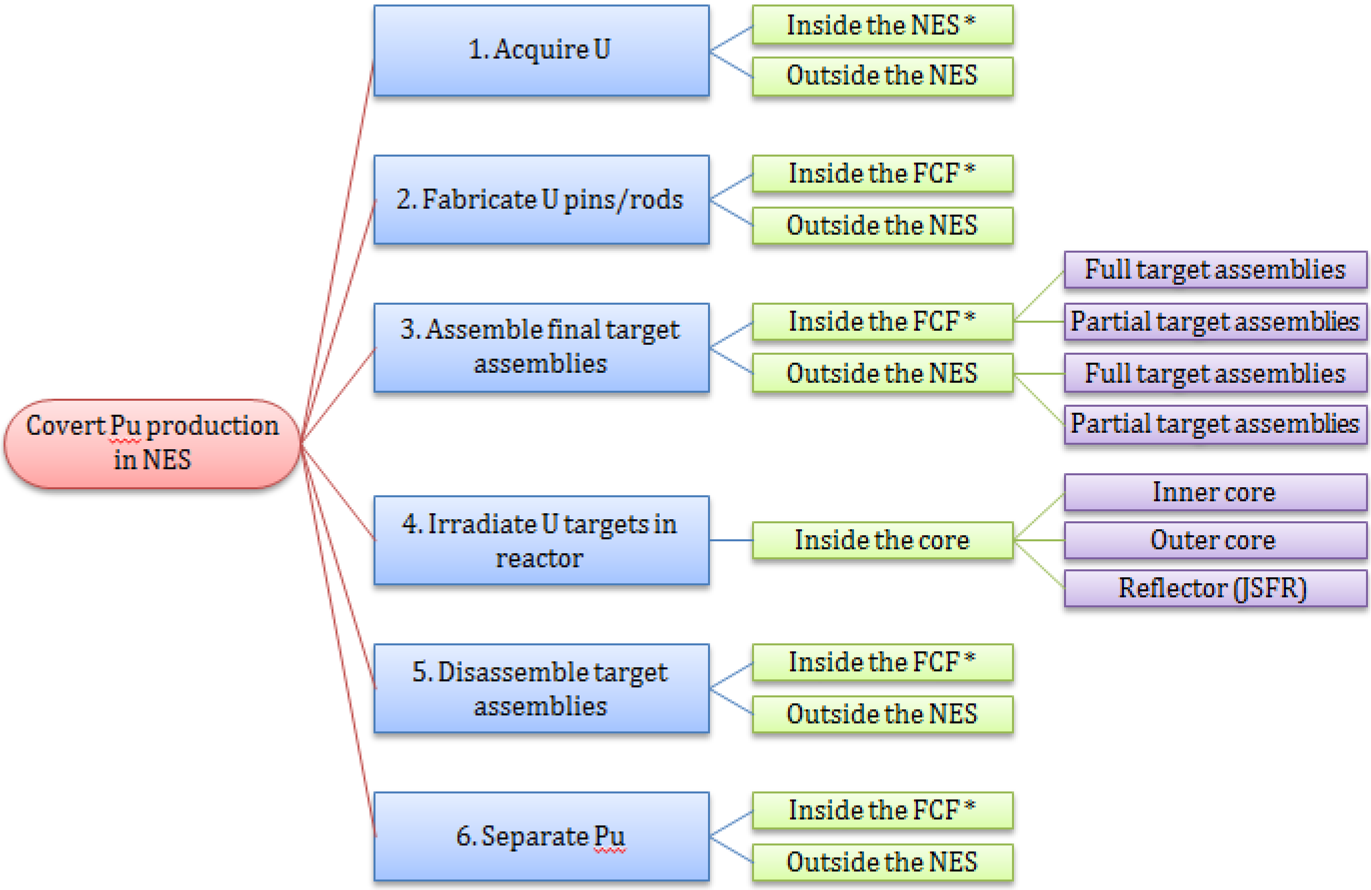


Fig. 8.1: Covert Pu production pathways identification.
* These possibilities are out of study.

The results of the evaluation will be present in section 9.2.

8.3 Breakout

The third PR threat is the breakout. Breakout does not exist unto itself but as a “strategy modifier”: ultimately every successful proliferant state necessarily breaks out if/when it decides to use or announce possession of a nuclear weapon. The nature of the breakout determines much of the nature of the threat (both the time available to the proliferant state – before and after breakout, and ultimately the complexity of weapon made possible). The interesting aspect of breakout is that its scenario, diversion and/or misuse, is the one that minimizes the time from breakout to weapons readiness, which is a subset of the PT measure. The goal of analyzing the breakout scenario is therefore to complement the concealed misuse/diversion scenarios by exploring the minimum post-breakout time to weapons readiness.

As described in the PR&PP Methodology and in the Case Study [93, 98], several strategies of breakout are possible. The strategy chosen by a proliferant state will affect both the time available and potential complexity for proliferation activities, as shown below and in Fig. 8.2.

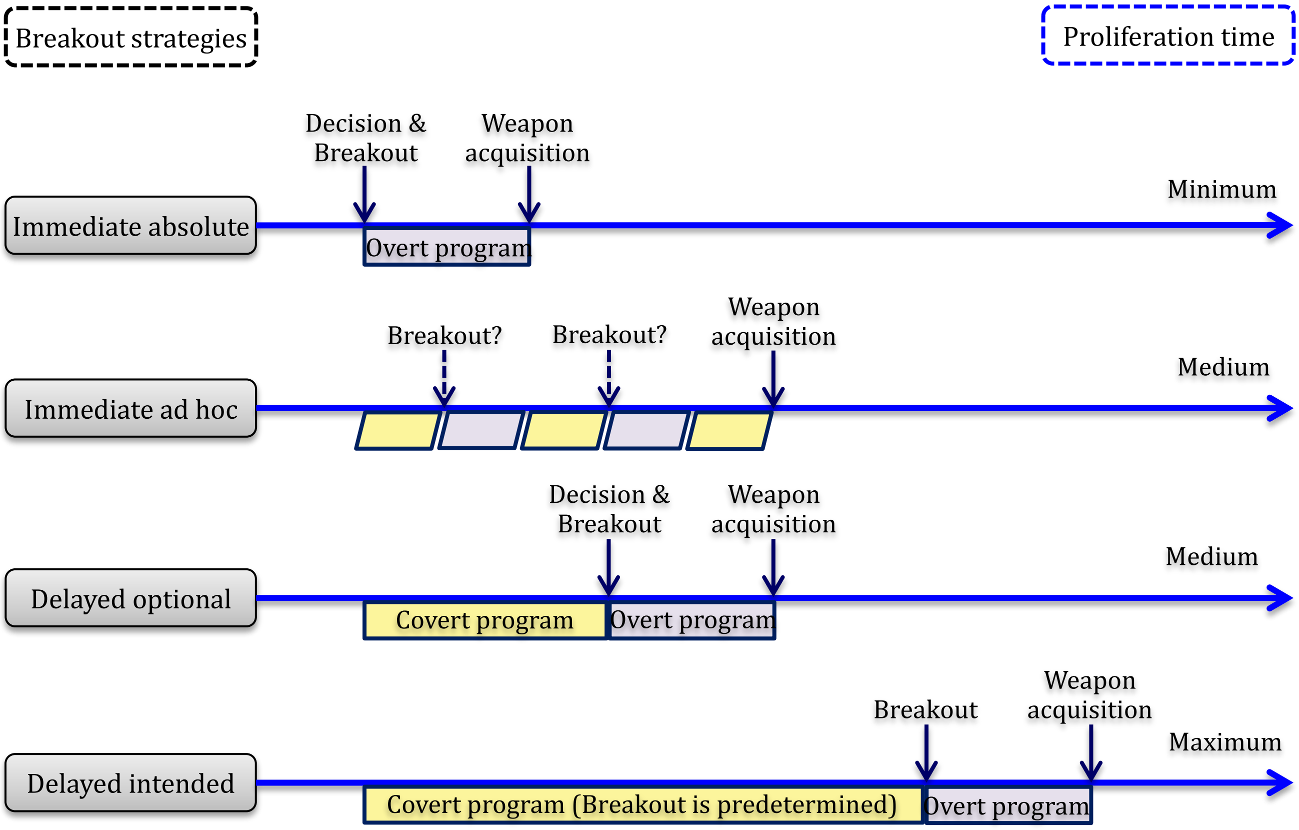


Fig. 8.2: Qualitative depiction of breakout strategies.

- *Immediate, absolute breakout*. Proliferant state decides to break out and immediately acts upon decision: minimum time, minimum complexity available to proliferation activities.
- *Immediate, ad hoc breakout*. Proliferant state "effectively" breaks out through actions, without explicitly breaking out): medium time, medium complexity available to proliferation activities.
- *Delayed, optional breakout*. Proliferant state covertly misuses or diverts, with acceptance of the detection risk and intention to break out if/when detection occurs: medium time, medium complexity available to proliferation activities.
- *Delayed, intended breakout*. Proliferant state covertly misuses or diverts, with acceptance of the detection risk and a predetermined schedule for breakout and overt activity – the "load the gun" scenario: maximum time, maximum complexity available to proliferation activities.

For this study only the immediate absolute and the delayed intended breakout scenario will be considered and the targets chosen were discussed as shown in Tab. 8.8 and Tab. 8.9 taking into account that the safeguards measures will be not applicable after the breakout declaration, while we will consider that the Host State will continue acting under the Safety regulations regime. The choice of the immediate absolute strategy and the delayed optional strategy is connected with the main advantages for the State: for the first strategy, in fact, the overall proliferation time is the minimum one; while for the second strategy the proliferation time during the overt program could be minimal and this could affect the response time.

Even if the breakout scenarios are based on diversion and misuse, some extra considerations are needed. Here we will consider that activities of reprocessing will be performed at the legal reprocessing plant present in the Host State territory. In particular, a small PUREX type reprocessing plant will be considered. Due to the fact that two different types of PUREX plants can be available, the co-conversion and the co-extraction, they will be discussed during the evaluation of measure and the results will be shown in section 9.3. To understand the difference between these two type of plants, it can be said that using the co-extraction U and Pu are always together so extra activities based on pH are needed for the extraction of Pu itself; using the co-conversion type, instead, U will be add to Pu after its extraction.

Tab. 8.8: Immediate absolute breakout scenarios for LWR and SFR.

LWR	**SFR**
Overt diversion scenario of spent fuel assemblies: The spent fuel assemblies in the spent fuel pool will be ship to the legal reprocessing plant where they will be reprocessed to extract Pu. This material will be used for the weapons fabrication.	Overt diversion scenario of irradiated blanket assemblies: After substituting the irradiated blanket assemblies in the spent fuel pool with the spent fuel elements, they will be shipped to the legal reprocessing plant where they will be reprocessing to extract Pu. This material will be used for the weapons fabrication.

Tab. 8.9: Delayed intended breakout scenarios for LWR and SFR.

LWR	**SFR**
Covert misuse of reactor for the production of Pu to reach a better quality of material: Host State will acquire LEU outside the facility and irradiate the fuel assemblies as a normal operation. However, the irradiation time will be lower of normal operations (about 54 days, Fig. 8.3 and Tab. 8.10). Preparation and shipment to the legal reprocessing plant. Overt program: reprocessing and Pu extraction. This material will be used for the weapons fabrication.	Covert diversion of irradiated blanket assemblies: After substituting the irradiated blanket assemblies in the spent fuel pool with the spent fuel elements, they will be shipped to the legal reprocessing plant. Preparation and shipment to the legal reprocessing plant Overt program: reprocessing and Pu extraction. This material will be used for the weapons fabrication.

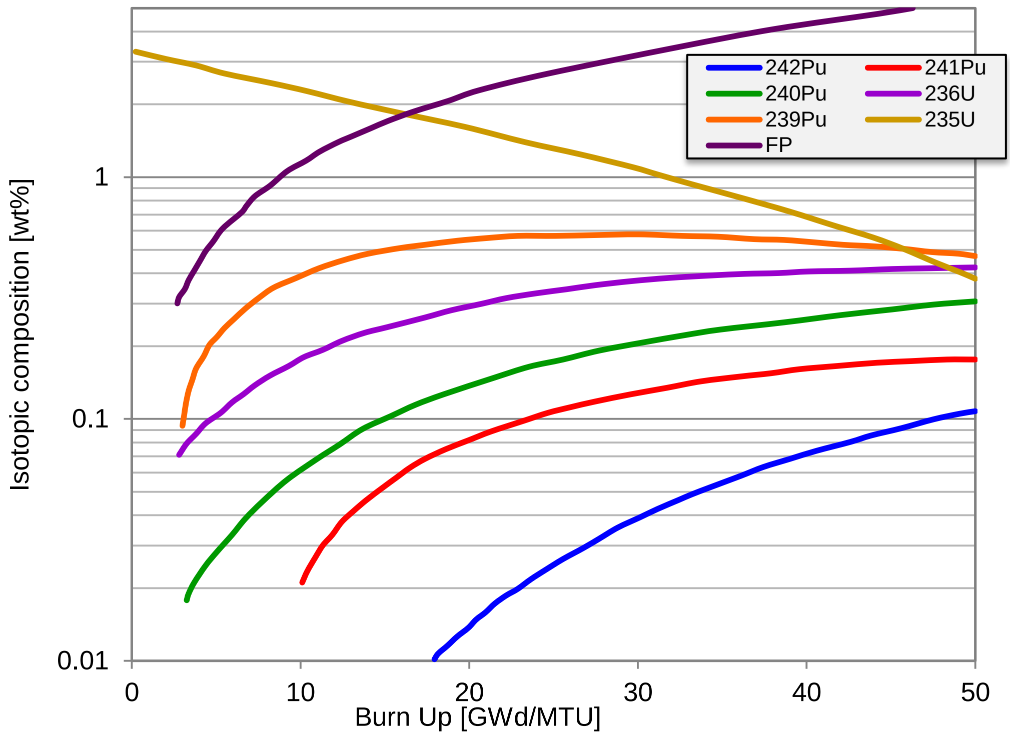


Fig. 8.3: Variation of the composition of heavy metal in LWR with Burn-up.

Tab. 8.10: Variation of the material type in LWR with Burn-up.

BU [Gwd/MTU]	Days	Pu240/Pu239	Material Type
2	54	0.06	Weapon Grade
20	540	0.25	Reactor Grade

The results of the evaluation will be present in section 9.3.

8.4 Theft and sabotage

In order to establish a baseline definition for physical protection areas within a facility the following diagram (Fig. 8.4) represents the generic site layout.

The outermost layer of the site layout is referred to as the *offsite* area. This is the surrounding area not owned by the host facility and it can be public or private lands.

The next layer is the *site area*. This area is the outermost boundary of the facility and, generally, a site fence is constructed around the entire perimeter providing the first layer of protection. Access to the site area is limited to access control points for personnel and vehicle. The first one (Access Control 1 in Fig. 8.4) is an access point for individuals on foot, whereas the second one (Access Control 2 in Fig. 8.4) represents all the areas that are designed to accommodate vehicles that must enter and exit the facility (for consistency, all even numbered ACs in Fig. 8.4 are access points for vehicles, and odd numbered ACs are access points for personnel) The site area is typically where office buildings, parking, and non-plant structures are located.

The next layer is the *protected area* (PA). A PA fence establishes the boundary between the protected area and the site area. The PA is traditionally where maintenance facilities are located, dry cask storage, plant auxiliary buildings and occasionally the cooling tower.

The next layer in the generic site layout is the *exclusion area*. The exclusion area is surrounded by PIDAS. The boundary around the exclusion area is no longer a simple chain link fence, but is now an enhanced barricade to delay, deter and detect an adversary. This area typically consists of non-safety related components and emergency backup equipment (i.e. emergency diesel generators).

The next layer is the *restricted area*. This area typically consists of safety related components.

Within the restricted area is the *vital area*; which with regards to most PP designs contains the primary target material. The entire PP system is designed to enhance protection around the target area. While access to the vital area is controlled by ACs, other means of entry are reflected on Fig. 8.4 as potential entry points for adversaries (wall, roof, windows…). In addition, Air Space is reflected on the diagram to indicate that all areas are accessible via air craft.

The layered site layout provides increased security, detection and deterrence factors as one moves from the outer to the inner most layer. However, it should be noted that although the PP system is designed to protect the primary target other target areas exist that are contained within the other areas of the facility.

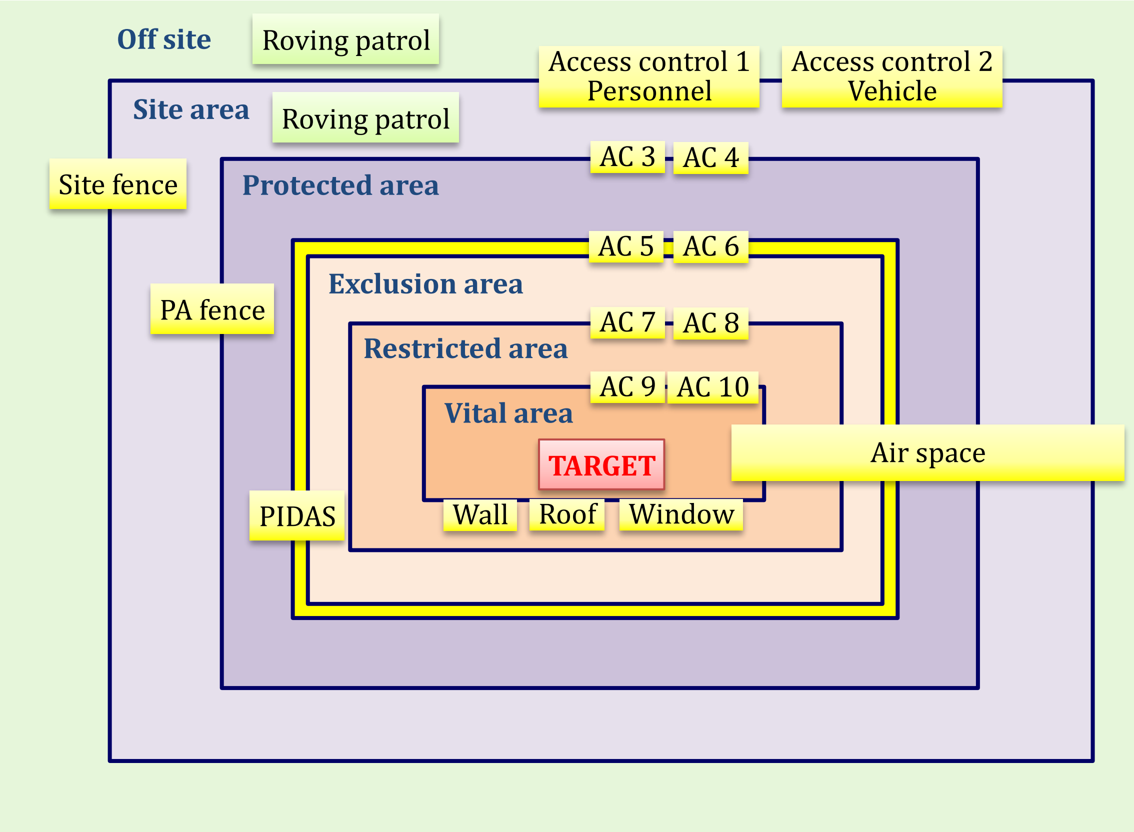


Fig. 8.4: Generic site layout.

Regarding the definition of a PP threat, there are two components to consider: type, objectives, and capabilities of the actor and the actor's strategy.

Three types of actors must be considered to define the PP threat space:

- Outsiders
- Outsiders in collusion with insiders
- Insiders alone.

Outsiders can include armed terrorist groups, agents of proliferant states, advocacy group, organized criminal gangs, and lone individuals. Insiders can be sympathetic with outsiders but may also include disaffected, anti-social, mentally unstable, or suborned employees or contract staff. The PP assessment should also consider a mixture of non-Host State and sub-national threats.

Five categories of actor capabilities must be considered to define the PP threat space:

- Knowledge (including outsider access to insider knowledge)
- Skills
- Weapons and tools (commercial, military, or improvised)
- Number of actors
- Commitment and dedication (risk tolerance up to self-sacrifice).

Five categories of actor objectives must be considered to define the PP threat space:

- Sabotage intended to disrupt normal operations
- Sabotage intended to cause radiological release
- Theft for production of nuclear explosives
- Theft for production of RDDs
- Theft of technical information.

A summary of all these factors is shown in Tab. 8.11.

Tab. 8.11: Summary of the PP threat dimensions.

Actor type	Actor capabilities	Objectives	Strategies
• Outsider • Outsider with insider • Insider alone • Above and non-Host State	• Knowledge • Skills • Weapons and tools • Number of actors • Dedication	• Disruption of operations • Radiological release • Nuclear explosives • Radiation Dispersal Device • Information theft	• Various modes of attack • Various tactics

For this study the following specific threat is defined:

1. Actor Type: Military trained assault force actor (outsider in collusion with insider);
   2. Capabilities:
      a. Knowledge: knowledge of plant layout and PP basic design, sufficient knowledge of plant processes to understand targets of opportunity;
      b. Skills: ability to design assault equipment to penetrate barriers, training in using assault weapons;
      c. Weapons and tools: assault weapons, specialized explosive ordinance, armored vehicles;
      d. Numbers of actors: 10 outsiders and 1 insider;
      e. Dedication: Military objective oriented;
   3. Objective: theft of nuclear material from the plant to produce at least one nuclear weapon device (1SQ), sabotage of the spent fuel pool for a radiological release outside the plant site;
   4. Strategy: Surprise assault on the facility.

The details of action performed by the intruder are shown in Tab. 8.12 for the theft scenarios and in Tab. 8.13 for the sabotage ones. More details will be presented in section 9.6.

Tab. 8.12: Theft scenarios for LWR and SFR.

LWR	**SFR**
Theft of spent fuel located in the fuel hall before the internal transport to the interim storage pool. Intruders need to cross the plant boundary and entering the protected area before to reach the target. Here they need to load the fuel into the vehicle and go out back to the plant boundary. It was assumed that a normal shipping cask will be present in the storage as shown in Fig. 8.5. [159]	Theft of spent fuel located in the interim storage pool after the internal transport from the reactor pool. Intruders need to cross the plant boundary and entering the protected area before to reach the storage. Here they need to load the fuel into the vehicle and go out back to the plant boundary. It was assumed that a shipping cask similar to the LWR ones will be present in the storage.

Tab. 8.13: Sabotage scenarios for LWR and SFR.

LWR	**SFR**
Sabotage will be performed using explosive in the spent fuel pool inside the fuel building. The intruders must cross plant boundary and the protected area before entering the fuel hall and the fuel building to reach the pool and place the explosive. The objective is the radiological release outside the	Sabotage will be performed using explosive in the spent fuel pool inside the reactor building in the auxiliary facility area. The intruders must cross plant boundary, the protected area and entered the reactor building before reach the pool and place the explosive. The objective is the radiological release outside the

plant site area.	plant site area.

Typical specifications for truck cask:
Gross Weight (including fuel): 25 tons
Cask Diameter: 1.2 m
Overall Diameter (including Impact Limiters): 1.8 m
Overall Length (including Impact Limiters): 6 m
Capacity: Up to 4 PWR fuel assemblies

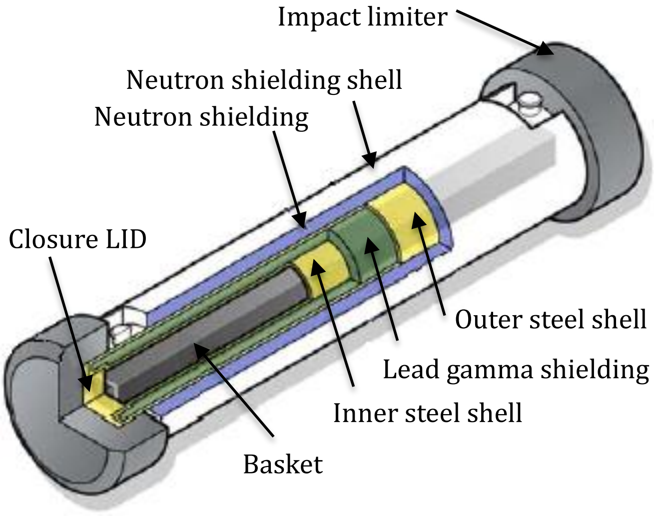


Fig. 8.5: Generic truck cask for spent fuel.

9 ANALYSIS OF PATHWAY APPLYING THE PR&PP EVALUATION METHODOLOGY

Having in mind that the PR&PP methodology can be applied to the entire fuel cycle or portions of a nuclear energy system, requires that for each family of threats (diversion, misuse, breakout, theft and sabotage) different pathway scenarios must be evaluated and that at least three experts must be present during the evaluation process, in this study the following limitation are fixed: it is focused only the reactor site; only one scenario for each threats is discussed during the evaluation process as a result from previous internal discussion meetings; six experts in the field of reactor design and fuel cycle, safeguards, physical protection and the methodology are present during the discussion.

However, due to time limits, only scenario from diversion and misuse will be discussed in the first evaluation meeting and the measure DE was not considered in this phase. In the following paragraphs, the results of the evaluation approach will be presented and discussed.

9.1 Diversion

Remembering that for the diversion scenario the spent fuel for LWR and the blanket for the SFR present in the spent fuel pool will be the target material (see Tab. 8.6), in Tab. 9.1 and Tab. 9.2 the results obtained respectively for LWR and SFR, from evaluation process are described for each measures, while in Fig. 9.2 and Fig. 9.3 a summary of these are shown.

It must be underline that one of the assumptions made for the Host State capabilities, was that it is an industrial nation with nuclear capabilities: not only the operating plant for energy production, but also reprocessing plants for both LWR and SFR fuels (see paragraph 8.1). This is a very strong assumption and means a very high capability of the Host State and it is reflected in a low PT value. Because the State has already the knowledge and the plants, it would be very easy and fast to assemble a clandestine extraction site: the State can use the hot-cell presents in the reprocessing plant and the only equipment needed for the clandestine laboratory are the cutting machine, the dissolution tank, the mixer and the acids for extraction. On the other hand, without these capabilities, the proliferation time will be enhanced to medium because the construction time would require at least 1 year.

Another important point to underline is hidden inside the technical difficulty measure. In fact, at least three different types of difficulties were enhanced during the discussion: the surveillance equipment falsification, the Pu extraction process and the weapon's assembly difficulties. Only the intrinsic difficulties of the Pu extraction process was considered in the evaluation process, however, it was assumed that the surveillance equipment falsification could be done easily, but the weapon construction is strongly connected with the material type and maybe some tests must be conduct after the weapon's assembly. It means that this parameter can enhanced both the TD and the PT in scenarios with MT between medium and very high.

The last important point to underline is hidden inside the DP measure. The DP, in fact, can be linked to instruments (camera, detector, seal …) or inspection activities. In this second case, the time needed to perform the verification is a key parameter that must be considered. An example of this is shown in Fig. 9.1.

Tab. 9.1: Measure evaluation for LWR diversion scenario.

Measure	Evaluation basis	Value	Assumptions
TD	Reprocessing will be the dominant segment. The State has already reprocessing plants like PUREX: it has the knowledge and the technology needed.	LOW (5-25%)	Difficulties for device falsification and weapon's assembly are not considered. Device falsification will be quite easy. Difficulty for weapon's assembly might be not so high due to the MT.
PC	A typical military budget for an advanced country is about 4x1010 euro. Comparing 1x109 euro with 4x1010 euro ⇒ 2.4%. For a clandestine facility the budget will be lower.	VERY LOW (0-5%)	Past experience in constructing reprocessing facilities show a budget of about 1x109 euro. The same value for the clandestine facility is chosen.
PT	Prepare a small clandestine reprocessing laboratory (dominant segment): cutting machine, dissolution tank, mixer settler for extraction, Nitrogen gas & TBP (2weeks). Falsify camera and ID reader (N.A.). Remove SF from the pool and replace it with dummy fuel in the pool (2h/2FA). Prepare the shipment (1day/2FA). Shipment to the clandestine reprocessing plant (1day/2FA). Separation of Pu (dominant segment) includes the retrieving assemblies from the casks, storage them to the pool (1day/2FA), reassemble to pins, cut, dissolve and extraction (16days/FA).	VERY LOW (0-3months) Total time is ≃ 50 days	State has a reprocessing facility; it has hot-cell, but needs to establish all other equipment for a pin by pin separation process. Without this, the PT will be at least 1 year (Medium). Dummy elements are present in the pool. Cask exists in the hall just next to the pool. Extraction process time comes from reference [160]. In a very efficient reprocessing plant as the Tokai one in Japan where 0.7tonU/day can be reprocessed, the time required is 2 days for both the two FAs. [161].
MT	Reactor Grade Pu	MEDIUM (RG-Pu)	The material type is spent fuel with high burnup, but it was converted in RG-Pu.
DP	The 1st detection point is the camera at the pool during the replacement of FAs. Re-verification has the 100% to detect the diversion but it takes time to be performed (see Fig. 9.1 for details). However, the time factor is not considered in the methodology.	HIGH (75-95%) MEDIUM (25-75%)	Camera is installed to monitor the SF pool but not for the ship out.

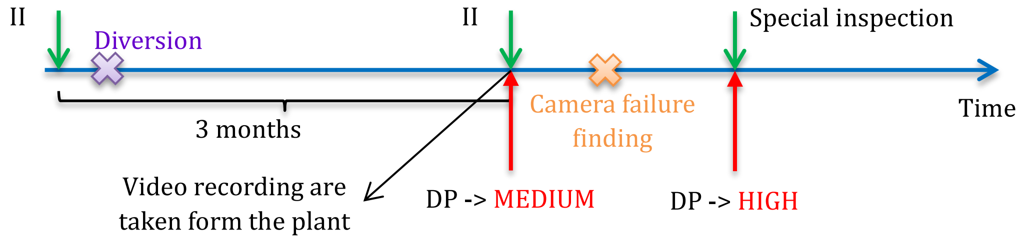
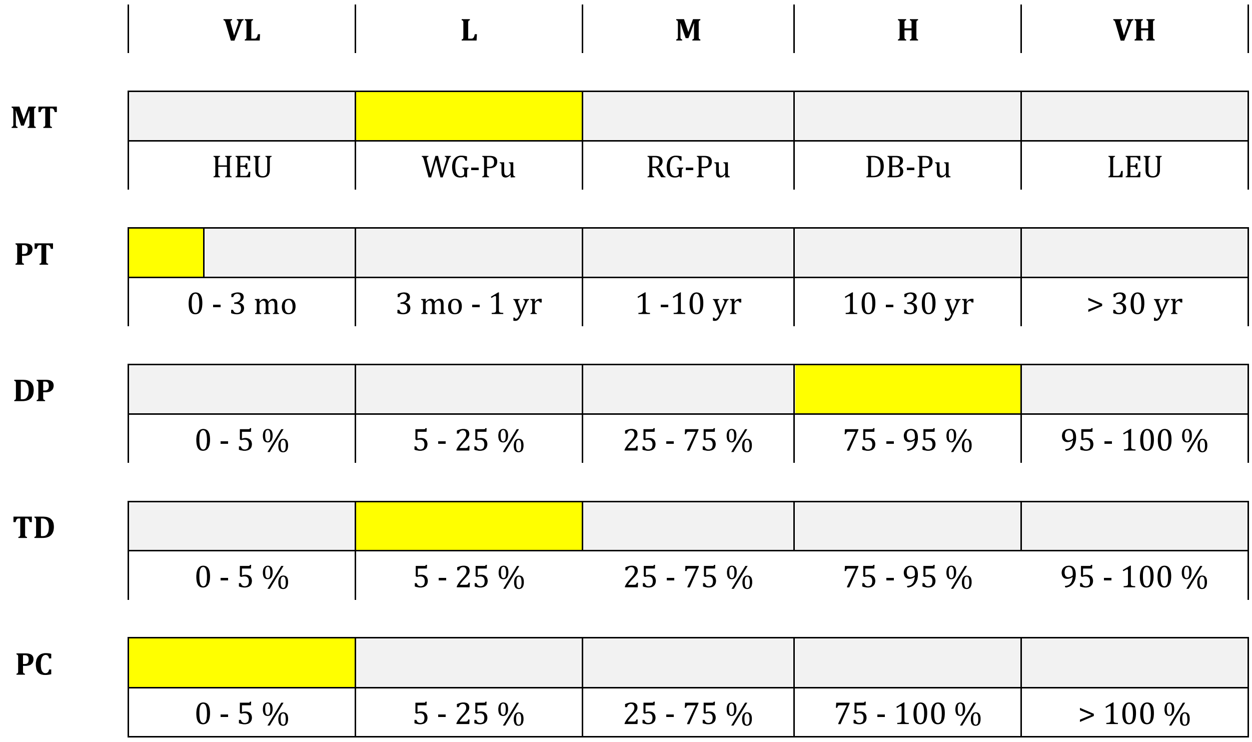


Fig. 9.1: Example of time line for re-verification.

Tab. 9.2: Measure evaluation for SFR diversion scenario.

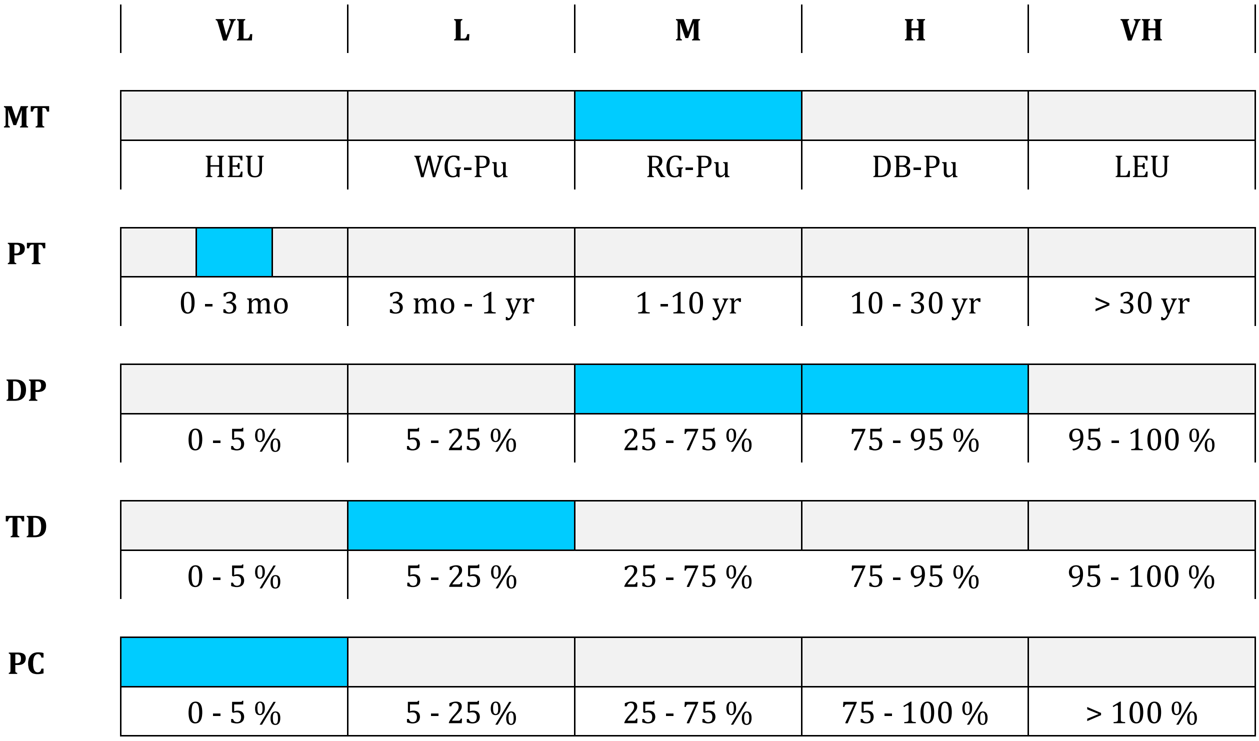
Measure	Evaluation basis	Value	Assumptions
TD	Reprocessing will be the dominant segment. The State has already reprocessing plants like PUREX: it has the knowledge and the technology needed. A laser must be used to schear the wrapper tube, but this fact was considered not increasing the TD.	LOW (5-25%)	Difficulties for device falsification and weapon's assembly are not considered. Device falsification will be quite easy. Difficulty for weapon's assembly might be not so high due to the MT.
PC	The Japanese military budget is about 5x10^{12} yen (about 4x10^{10} euro). Comparing 1.2x10^{11} yen with 5x10^{12} yen about 2.4%. Of course for a clandestine facility the budget will be even lower.	VERY LOW (0-5%)	The same budget associated to the construction of a full scale plant for reprocessing experiments (RETF) in Japan was taken as a reference: 1.2x10^{11} yen (about 1x10^{9} euro).
PT	Prepare a small clandestine reprocessing laboratory (dominant segment): cutting machine, dissolution tank, mixer settler for extraction, Nitrogen gas & TBP (2weeks). Falsify camera and ID reader (N.A.). Remove irradiated blanket from the pool and replace it with dummy element in the pool (1h/BF). Prepare the shipment (1day/BF). Shipment to the clandestine reprocessing plant (1day/BF). Separation of Pu (dominant segment) includes the retrieving assemblies from the casks, storage them to the pool (1day/2FA), reassemble to pins, cut, dissolve and extraction (16days/BF).	VERY LOW (0-3months) Total time is ≃ 33 days	State has a reprocessing facility ⇒ it has hot-cell, but needs to establish all other equipment for a pin by pin separation process. Without this, the PT will be at least 1 year (Medium). Dummy elements are present in the pool. Cask exists in the hall just next to the pool. It was considered that schearing the wrapper tube takes more time for the cutting phase compared with the LWR case, but the extraction process is faster even if the Pu content make a batch size smaller compared with the LWR case
MT	Weapon Grade Pu	LOW (WG-Pu)	
DP	The 1st detection point is the camera at the pool during the replacement of BF. Also seal are placed in the shipping door ⇒ the detection probability is increased.	HIGH (75-95%)	We based our description to Monju safeguards approach

For an easy reading of these results, the form of a bar chart is chosen and shown in Fig. 9.2 and Fig. 9.3. It must be noted that the order in which measures are presented in this chart is not the same as above. Here, the measures are shown in the order as they are discussed during the evaluation process: MT, PT, DP, TD and PC. It was noticed that following this sequence the evaluation discussion results to be easier.



	VL	L	M	H	VH
MT		🟨			
	HEU	WG-Pu	RG-Pu	DB-Pu	LEU
PT	🟨				
	0 - 3 mo	3 mo - 1 yr	1 -10 yr	10 - 30 yr	> 30 yr
DP				🟨	
	0 - 5 %	5 - 25 %	25 - 75 %	75 - 95 %	95 - 100 %
TD		🟨			
	0 - 5 %	5 - 25 %	25 - 75 %	75 - 95 %	95 - 100 %
PC	🟨				
	0 - 5 %	5 - 25 %	25 - 75 %	75 - 100 %	> 100 %

Fig. 9.2: SFR binned measure values for diversion pathway.



	VL	L	M	H	VH
MT			🟦		
	HEU	WG-Pu	RG-Pu	DB-Pu	LEU
PT	🟦				
	0 - 3 mo	3 mo - 1 yr	1 -10 yr	10 - 30 yr	> 30 yr
DP			🟦	🟦	
	0 - 5 %	5 - 25 %	25 - 75 %	75 - 95 %	95 - 100 %
TD		🟦			
	0 - 5 %	5 - 25 %	25 - 75 %	75 - 95 %	95 - 100 %
PC	🟦				
	0 - 5 %	5 - 25 %	25 - 75 %	75 - 100 %	> 100 %

Fig. 9.3: LWR binned measure values for diversion pathway.

9.2 Misuse

Remembering that for the misuse scenario the target material is obtained with irradiation of ad-hoc targets for the covert Pu production (see paragraph 0), in Tab. 9.3 and Tab. 9.4 the results obtained respectively for LWR and SFR, from evaluation process are described for each measures, while in Fig. 9.4 and Fig. 9.5 a summary of these are shown.

Again the Host State has nuclear capabilities that include the reprocessing plants for both LWR and SFR fuels and this influenced the value of TD.

Another important aspect to take into account for the determination of TD is the influence that the insertion of targets inside the reactor core can produce on the neutron flux and reactivity and, consequentially, on the reactor operations. It must be remembered that one of the extra assumptions made for the misuse scenario is that the Host State want to minimize disruption of normal facility operations. During the evaluation process it was considered that the targets insertion will not affected the reactor economy. However, this can be considered quite true for the SFR case where the target is inserted in the core outer ring (in proximity of the blanket area) and substitute one of the fuel elements, while for LWR, where more fuel elements are introduced in the reactor core using the CR space, a most carefully evaluation must be done. In this case the TD might be enhanced.

Moreover, it must be underline the value reached in the MT measure. Because the main objective for the misuse scenario is to produce at least one SQ of weapon-useable material, the LWR case it would be less attractive due to the fact that the material quality still remain RG-Pu even using an ad-hoc target. This result can be explained considering that the material used in the case of LWR is LEU: as it possible to see from Fig. 8.3 the only way to obtain a MT better than RG-Pu is to reach a BU less than 5÷10GWd/MTU, but it implies that the target must be in the reactor less than 1cycle (18 months) and it will increase to value of DP and influence negatively on the reactor operations due to the need of continuously shutdown. On the other hand, the choice of using LEU is done because we want to focus only on the reactor site. If the Host State will use at least NU, the MT quality will be increased but it will imply that the Host State needs to introduce surreptitiously in its boundary this material, but this is out of the scope of this study.

The last point to underline is the difference in the value of DP measure. For the LWR, the first assumption done during the evaluation process was that there are no detection measures checking the replacement of control rods. In this case the detection probability for the misuse will be Very Low. In this case, to enhance this value, an additional protocol will be required. An example proposed during the evaluation process is the introduction of detection monitor at the fabrication facility, but it is out of the scope of this study. However, looking back at the configuration of the MBA XE01 (in Fig. 6.3) is possible to see that some detection monitors are present in the transfer channel. Due to the fact that the only road to bring out the CRs from the reactor core is towards this channel, if the detection limit is enough to distinguish between fuel rods and activate materials, the DP can be enhanced to High.

Also for the SFR case study, relative to the DP measure, two different possibilities were examined during the evaluation discussion: the target materials sent to the clandestine facility or to the legal ones. Assumption under these two possibilities is that the irradiated targets for the misuse will be shipped out the reactor with the normal shipment. Under this constrain, if the material will be send to the clandestine facility, the detection probability is considered to be Very High because at the legal reprocessing facility two vacant elements will be found during inspection. On the other hand, if the materials will be sending to the regular reprocessing plant, the detection probability is considered to be High due to the presence of radiation monitor in the reactor site. For the following analysis and the scope of this study, only the possibility of using the clandestine reprocessing plant will be taken into account, so the DP measure has a value of Very High.

For an easy reading of these results, the form of a bar chart is chosen and shown in Fig. 9.4 and Fig. 9.5. It must be noted that the order in which measures are presented in this chart is not the same as above. Here, the measures are shown in the order as they are discussed during the evaluation process: MT, PT, DP, TD and PC. It was noticed that following this sequence the evaluation discussion results to be easier.

Tab. 9.3: Measure evaluation for LWR misuse scenario.

Measure	Evaluation basis	Value	Assumptions
TD	For this measure the difficulties for device falsification and for weapon's assembly are not considered. However, the device falsification will be quite easy but the difficulty for weapon's assembly might be high.	LOW (5-25%)	Spent fuel would require a reprocessing facility, but State has already a reprocessing plant (PUREX) so it has the knowledge about the process and technology needed. For the nature of the treat where some targets are introduced in the reactor core for burning, the impact on the reactor operation must be carefully considered. In this first step, however, it was assumed that the introduction of these targets don't create any problem.
PC	The Japanese military budget is about $5x10^{12}$ yen (about $4x10^{10}$ euro). Comparing $1.2x10^{11}$ yen with $5x10^{12}$ yen about 2.4%. Of course for a clandestine facility the budget will be even lower.	VERY LOW (0-5%)	The same budget associated to the construction of a full scale plant for reprocessing experiments (RETF) in Japan was taken as a reference: $1.2x10^{11}$ yen (about $1x10^{9}$ euro). The preparation of targets was considered to have a minimal impact on this measure.
PT	Preparation of targets (few days). Prepare a small clandestine reprocessing laboratory will require a cutting machine, dissolution tank, mixer settler for extraction, Nitrogen gas & TBP (2weeks). Irradiation of targets inside the reactor core is the dominant segment (18months x 3times ≃ 5years). Remove targets from the core and send them to the spent pool for cooling down (included in the irradiation time). Cooling down of targets (at least 1year). Prepare the shipment (1day). Shipment to the clandestine reprocessing plant (1day). Separation of Pu. It includes the retrieving assemblies from the casks, storage them to the pool (1day), reassemble to pins, cut, dissolve and extraction (16days).	MEDIUM (1-10years)	This measure is governed by the irradiation time, so, differently form the diversion scenario, if the State has no reprocessing facilities and consequently has not hot-cell, the value of proliferation time still remain in the Medium bin. The irradiation time includes also the maintenance period and refueling time. The cooling down period required for the targets was assumed using the data provided for the Tokai reprocessing plant [161]. For the time evaluation of extraction process the reference [160] was considered. However, in a very efficiency reprocessing plant as the Tokai one in Japan where 0.7tonU/day can be reprocessed, the time required is 2 days for both the two FAs [161].
MT	Reactor Grade Pu	MEDIUM (RG-Pu)	Even with ad-hoc targets it was assumed that the material can't reach the WG-Pu quality.

Table continues on the next page

Tab. 9.3 (continued): Measure evaluation for LWR misuse scenario.

Measure	Evaluation basis	Value	Assumptions
DP	For the evaluation of this measure different assumptions were done. If there are no detection measures checking the replacement of control rods, the detection probability for the misuse will be Very Low. In this case an additional protocol is required, but it is not considered in this study. However, the only road to bring out the CRs from the reactor core is towards the transfer channel and here a neutron detector is located. If the detection limit is enough to distinguish between fuel rods and activate materials, the DP of irradiated targets will be High.	VERY LOW (0-5%)) HIGH (75-95%)	An example of additional protocol proposed is a detection system at the fabrication facility.

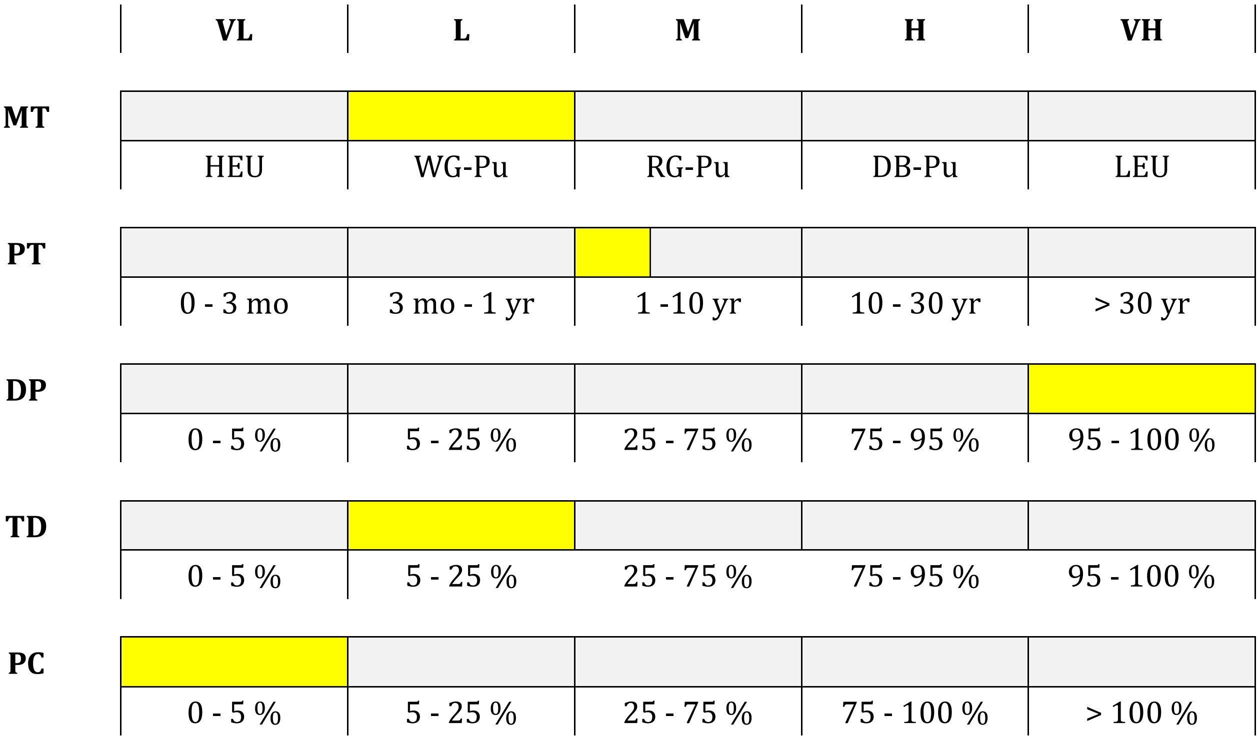
Tab. 9.4: Measure evaluation for SFR misuse scenario.

Measure	Evaluation basis	Value	Assumptions
TD	For this measure the difficulties for device falsification and for weapon's assembly are not considered. However, the device falsification will be quite easy but the difficulty for weapon's assembly might be high.	LOW (5-25%)	Spent fuel would require a reprocessing facility, but State has already a reprocessing plant (PUREX) so it has the knowledge about the process and technology needed. In this case, for the nature of targets material and their irradiation position inside the core (in the external ring) it was assumed that their introduction doesn't create any problem.
PC	The Japanese military budget is about $5x10^{12}$ yen (about $4x10^{10}$ euro). Comparing $1.2x10^{11}$ yen with $5x10^{12}$ yen about 2.4%. Of course for a clandestine facility the budget will be even lower.	VERY LOW (0-5%)	The same budget associated to the construction of a full scale plant for reprocessing experiments (RETF) in Japan was taken as a reference: $1.2x10^{11}$ yen (about $1x10^{9}$ euro). The preparation of targets was considered to have a minimal impact on this measure.

Table continues on the next page

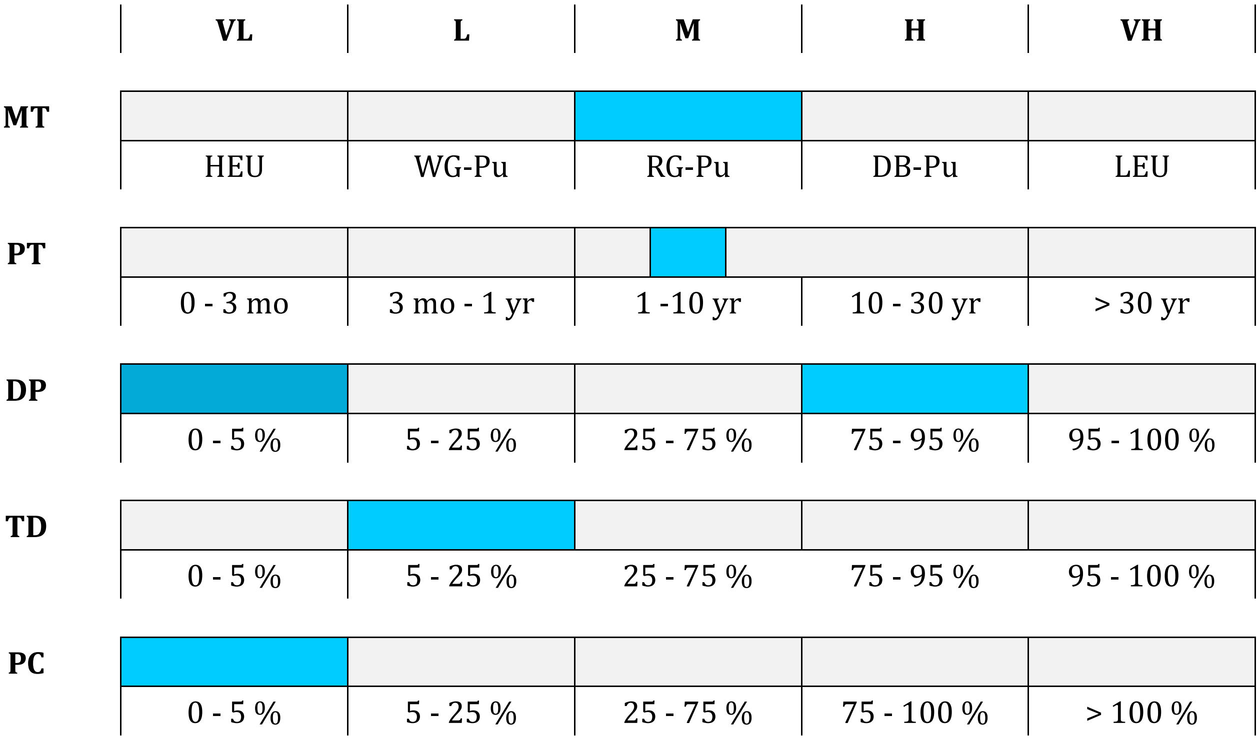
Tab. 9.4 (continued): Measure evaluation for SFR misuse scenario.

Measure	Comments	Value	Assumptions
PT	Preparation of targets (few days). Prepare a small clandestine reprocessing laboratory will require a cutting machine, dissolution tank, mixer settler for extraction, Nitrogen gas & TBP (2weeks). Irradiation of targets inside the reactor core is the dominant segment (21months). Remove targets from the core and send them to the spent pool for cooling down (few days). Cooling down of targets (at least 1year). Prepare the shipment (1day). Shipment to the clandestine reprocessing plant (1day). Separation of Pu. It includes the retrieving assemblies from the casks, storage them to the pool (1day), reassemble to pins, cut, dissolve and extraction (16days).	MEDIUM (1-10years)	This measure is governed by the irradiation time, so, differently form the diversion scenario, if the State has no reprocessing facilities and consequently has not hot-cell, the value of proliferation time still remain in the Medium bin. For the time evaluation of extraction process the reference [160] was considered. However, in a very efficiency reprocessing plant as the Tokai one in Japan where 0.7tonU/day can be reprocessed, the time required is 2 days for both the two FAs [161]. It was considered that shipment is carried out at the same time with the declared casks.
MT	Weapon Grade Pu	LOW (WG-Pu)	Also with ad-hoc targets the quality obtained is WG-Pu quality.
DP	For the evaluation of this measure two different possibilities were examined during the evaluation discussion: the target materials sent to the clandestine facility or to the legal ones. In the first case, the detection probability is considered to be Very High because at the legal reprocessing facility two vacant elements will be found during inspection. In the second case, instead, the detection probability is considered to be High due to the presence of radiation monitor in the reactor site.	HIGH (75-95%) VERY HIGH (95-100%)	For the following analysis only the possibility of using the clandestine reprocessing plant will be taken into account, so the DP is Very High because detected at the end of transportation due to the missing 2 assemblies.



	VL	L	M	H	VH
MT	HEU	🟨 WG-Pu	RG-Pu	DB-Pu	LEU
PT	0 - 3 mo	3 mo - 1 yr	🟨 1 -10 yr	10 - 30 yr	> 30 yr
DP	0 - 5 %	5 - 25 %	25 - 75 %	75 - 95 %	🟨 95 - 100 %
TD	0 - 5 %	🟨 5 - 25 %	25 - 75 %	75 - 95 %	95 - 100 %
PC	🟨 0 - 5 %	5 - 25 %	25 - 75 %	75 - 100 %	> 100 %

Fig. 9.4: SFR binned measure values for misuse pathway.



	VL	L	M	H	VH
MT	HEU	WG-Pu	🟦 RG-Pu	DB-Pu	LEU
PT	0 - 3 mo	3 mo - 1 yr	🟦 1 -10 yr	10 - 30 yr	> 30 yr
DP	🟦 0 - 5 %	5 - 25 %	25 - 75 %	🟦 75 - 95 %	95 - 100 %
TD	0 - 5 %	🟦 5 - 25 %	25 - 75 %	75 - 95 %	95 - 100 %
PC	🟦 0 - 5 %	5 - 25 %	25 - 75 %	75 - 100 %	> 100 %

Fig. 9.5: LWR binned measure values for misuse pathway.

9.3 Breakout

As already said, due to the fact that breakout does not exist unto itself but as a “strategy modifier”, during the evaluation process not all the measures are need to be discussed. As presented in Tab. 8.8 for the immediate absolute strategy, the scenario proposed recreate the diversion pathway (already discussed in section 9.1) with the only difference that the State will use the already present reprocessing plant (further defined as the legal reprocessing plant). Under these assumptions, only the proliferation time measure is needed to be discussed. It must be underline, however, that the detection probability for the immediate absolute strategy is not a usable measure because the intention of breakout is already declared by the State.

The result of the discussion for the PT measure is presented in Tab. 9.5 for the LWR and in Tab. 9.6 for the SFR, while for the other measures refer to Tab. 9.1 and Tab. 9.2.

Regarding the delayed intended strategy, as presented in Tab. 8.9, instead, a distinction must be done between the case of SFR and LWR.

For the SFR, in fact, the scenario proposed still recreates the diversion pathway (already discussed in section 9.1) with the use of the legal reprocessing plant, but during the covert program (taking the irradiated blanket and shipping to the reprocessing plant) the measure DP as well as PT must be taking into account during the evaluation process. During the overt program, instead, the DP measure is no more usable.

For the case of the LWR, the scenario proposed is different form the diversion one and it is more similar to the misuse pathway. The difference with the misuse pathway (described in section 8.2) is the irradiation time that in this case is about 2 months (each LWR cycle is 18 months) for obtaining a higher level in the material type. Under these considerations, for the covert program, not only the proliferation time and the detection probability measures are needed to be discussed, but also the material type. For the overt program, instead, also the PT measure is to taken into account.

The result of the discussion is presented in Tab. 9.7 for the LWR and in Tab. 9.8 for the SFR, while for the other measures refer to Tab. 9.3 and Tab. 9.2.

Tab. 9.5: PT measure evaluation for LWR immediate absolute breakout scenario.

Measure	Evaluation basis	Value	Assumptions
PT	Remove SF from the pool (1h/FA). Prepare the shipment (1day/FA). Shipment to the legal reprocessing plant (1day). Separation of Pu (dominant segment) considering that the all process include also the chopping and the enrichment for reach a very high purity Pu (5days/FA).	VERY LOW (0-3months) Total time is ≃ 2 weeks (for 2 FA)	State has a small reprocessing facility, like PUREX type. Two types of reprocessing plan was discussed, the co-conversion and the co-extraction, but there is only a small different in time that not affect the evaluation results. Cask exists in the hall just next to the pool. Data are taken from a facility like the Tokai reprocessing plant where 0.7tonU/day can be reprocessed. [161].

Tab. 9.6: PT measure evaluation for SFR immediate absolute breakout scenario.

Measure	Evaluation basis	Value	Assumptions
PT	Remove blanket from the pool (1h/BF). Prepare the shipment (1day/BF). Shipment to the legal reprocessing plant (1day). Separation of Pu (dominant segment) considering that the all process include also the chopping and the enrichment for reach a very high purity Pu (5days/BF).	VERY LOW (0-3months) Total time is ≃ 1 week (for 1 BF)	State has a small reprocessing facility, like PUREX type. Two types of reprocessing plan was discussed, the co-conversion and the co-extraction, but there is only a small different in time that not affect the evaluation results. Cask exists in the hall just next to the pool. Data are taken from a facility like the Tokai reprocessing plant where 0.7tonU/day can be reprocessed. [161].

Tab. 9.7: PT, DP and MT measures evaluation for LWR delayed intended breakout scenario.

Measure	Evaluation basis	Value	Assumptions
PT	Covert program: Irradiate fuel (54days). Prepare the shipment (1day/FA). Shipment to the legal reprocessing plant (1day). Overt program: Separation of Pu considering that the all process include also the chopping and the enrichment for reach a very high purity Pu (5days/FA).	VERY LOW (0-3months) LOW (3-12months) Total time is ≃ 2 months (for 2 FAs) Total time is ≃ 4 months (for 10 FAs)	The number of FAs to be treated to reach 1SQ is to better investigate; however, the limit number of FA to remain in the VL bin is between 5 and 6. Using data about the Pu production of a LWR of 400MWe the amount of Pu (kg) per ton of U is 1.6 (about 10 FA). [162] Cask exists in the hall just next to the pool. Data are taken from a facility like the Tokai reprocessing plant where 0.7tonU/day can be reprocessed. [161].
DP	Effective only during the covert program	HIGH (75-95%)	Shut down the NPP after 54 days and shipping fuel outside is not a normal operation.
MT	Weapon Grade Pu	LOW (WG-Pu)	

Tab. 9.8: PT and DP measures evaluation for SFR delayed intended breakout scenario.

Measure	Evaluation basis	Value	Assumptions
PT	Covert program: Remove blanket from the pool (1h/BF). Prepare the shipment (1day/BF). Shipment to the legal reprocessing plant (1day). Overt program: Separation of Pu (dominant segment) considering that the all process include also the chopping and the enrichment for reach a very high purity Pu (5days/BF).	VERY LOW (0-3months) Total time is ≃ 1 week (for 1 BF)	State has a small reprocessing facility, like PUREX type. Two types of reprocessing plan was discussed, the co-conversion and the co-extraction, but there is only a small different in time that not affect the evaluation results. Cask exists in the hall just next to the pool. Data are taken from a facility like the Tokai reprocessing plant where 0.7tonU/day can be reprocessed. [161].
DP	Effective only during the covert program.	MEDIUM (25-75%) HIGH (75-95%)	The seal in the shipping door is no more effective because it is a normal shipment from the facility to the reprocessing plant. More layer of safeguards are required.

In Fig. 9.6 and Fig. 9.7 the summary of the complete results for the breakout scenario, in the form of the bar chart, are presented.

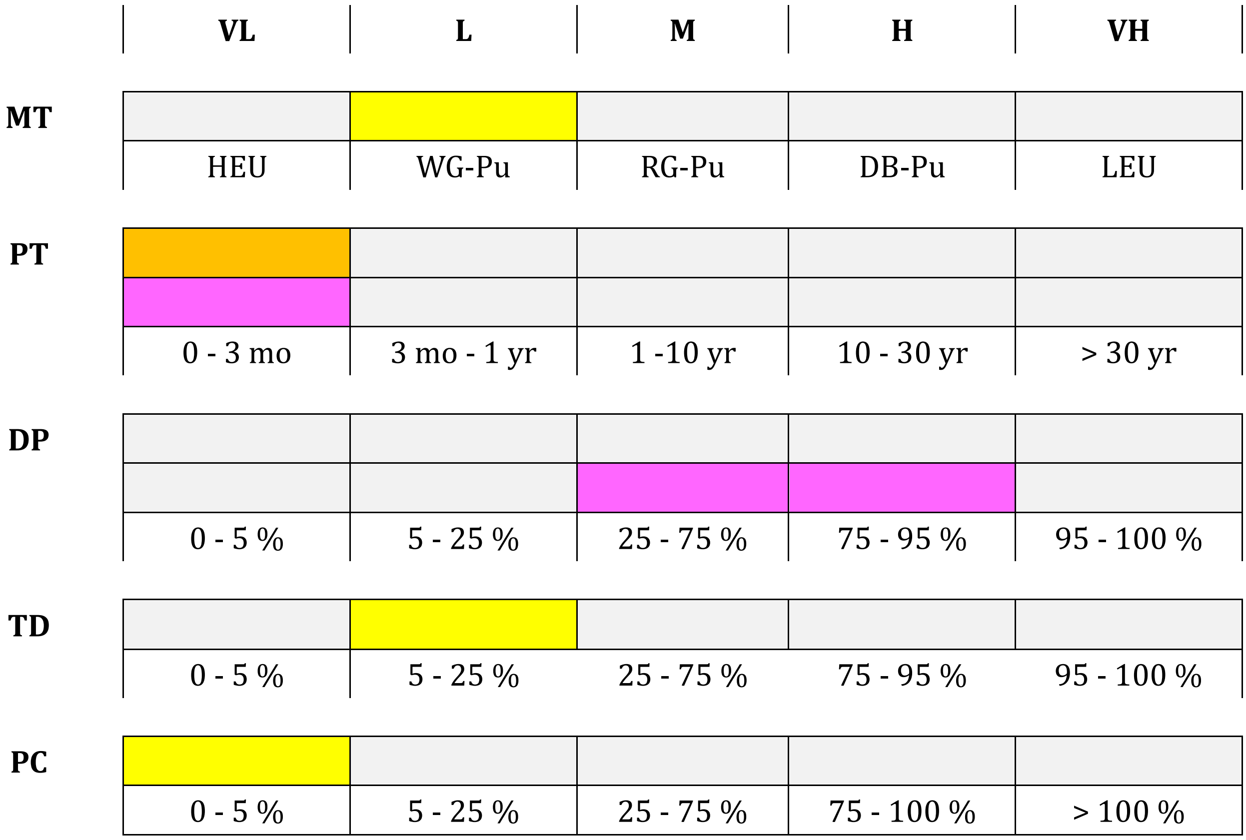


Fig. 9.6: SFR binned measure values for breakout pathway (orange and purple are referred to the immediate absolute and delayed intended strategy respectively for the measures discussed in the evaluation process; yellow is referred to measures derived from the previous pathways).

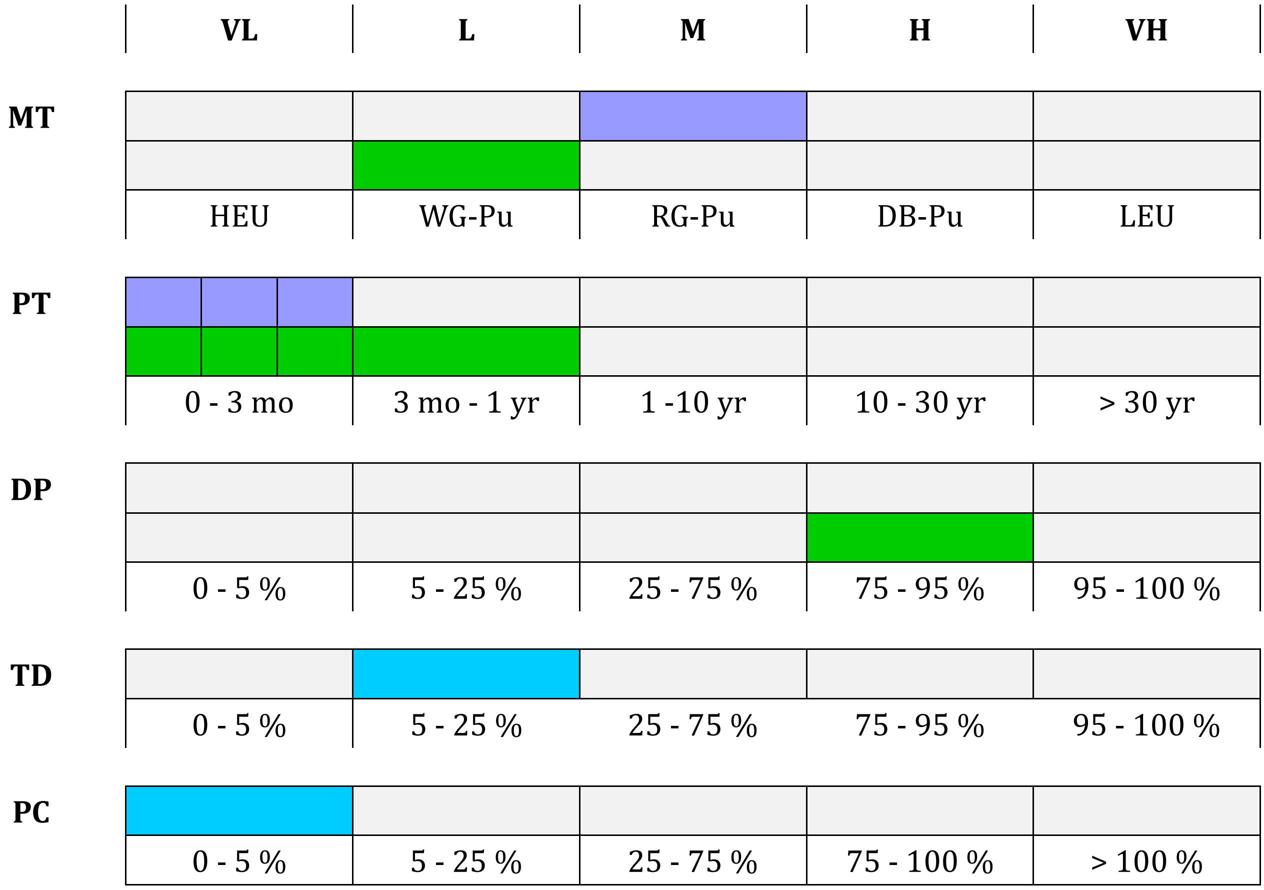


Fig. 9.7: LWR binned measure values for breakout pathway (violet and green are referred to the immediate absolute and delayed intended strategy respectively for the measure discussed in the evaluation process; blue is referred to measures derived from the previous pathways).

9.4 GIF Goal results

The GIF Goal for the Generation IV nuclear energy systems says that a GEN-IV NES is to be the least desirable route to proliferation by hindering the diversion of nuclear material from the system and hindering the misuse of the NES and its technology in the production of nuclear weapons or other nuclear explosive devices.

To see if the system analyzed satisfies the GIF Goal it is important to set, for each measure, the limit for unacceptable proliferation risk. In particular, each State need to decide under which level a system can be considered nonproliferation enough. It means that these limits are strongly dependent by the State background, and because each State maybe needs to set its own levels, there is not a unique possibility. A suggestion to set this limits is that policy makers can evaluate them together with the system designers. Once the limits are set, it is important to compare the results obtained with the evaluation of the system: when a measure is below the limit it means that a possible ways to upgrade the measures need to be identified.

In Fig. 9.8 and Fig. 9.9 an example of this limits and the following comparison with the SFR system for both diversion and misuse scenario is shown.

To set the limits the following considerations are done:

- For MT, the limit is set to be at least medium considering the material suitability for explosive device;

- For PT, the limit is set to low considering that IAEA inspection frequency for the systems analyzed is every 3 month;
- For DP and TD, the limits are set to be at least 50% of probability;
- For PC, the limit is set to be at least medium considering an acceptable reduction of the military budget.

It must be remembered that the limits for unacceptable proliferation risk are strongly dependent by the State background so even with the same values obtained by the evaluation methodology, the following comparison and suggestions could be different depending on the set up of limits.

A possibility to set up this limits, could be a working team formed both from policy makers and system designers.

In our example, comparing these limits with the evaluation results for the SFR system, it is possible to see that, for the diversion scenario, the only measure up the limit is the Detection Probability, while, for the misuse scenario, also the Proliferation Time is over the limit.

The application of the methodology shows that TD and PC are strongly dependent on the State background more than the scenario considered, so designers can't act on this measure to enhance its value. MT is instead an important point for FBR. Designers can increase its value avoiding the use of blanket, but this decision must be done in accordance with the State energy policy. However, to compensate this measure, system designers can act on the DP taking present that this value can influence the DE measure (not considered for now during the evaluation).

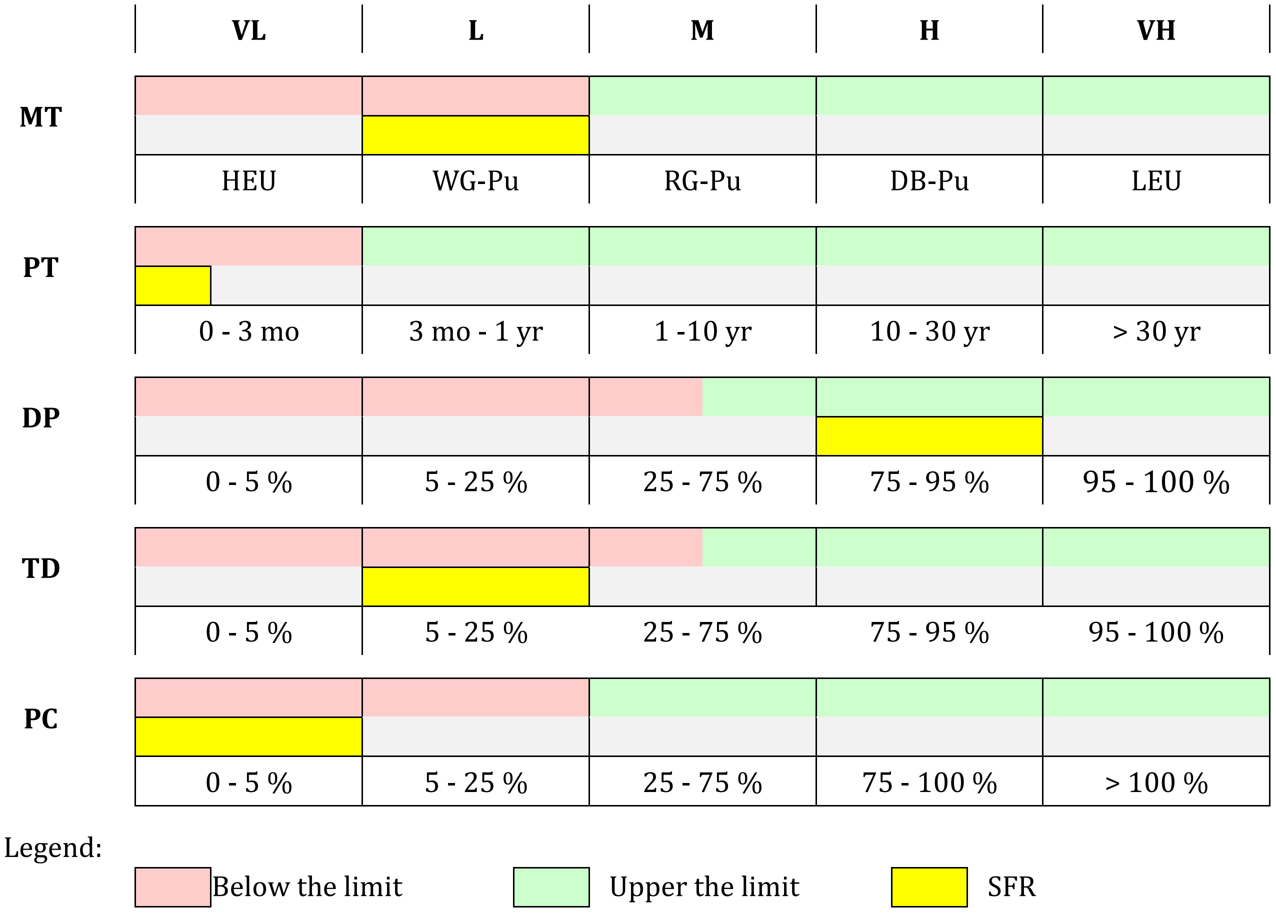


Fig. 9.8: Example of SFR diversion results for the GIF goal.

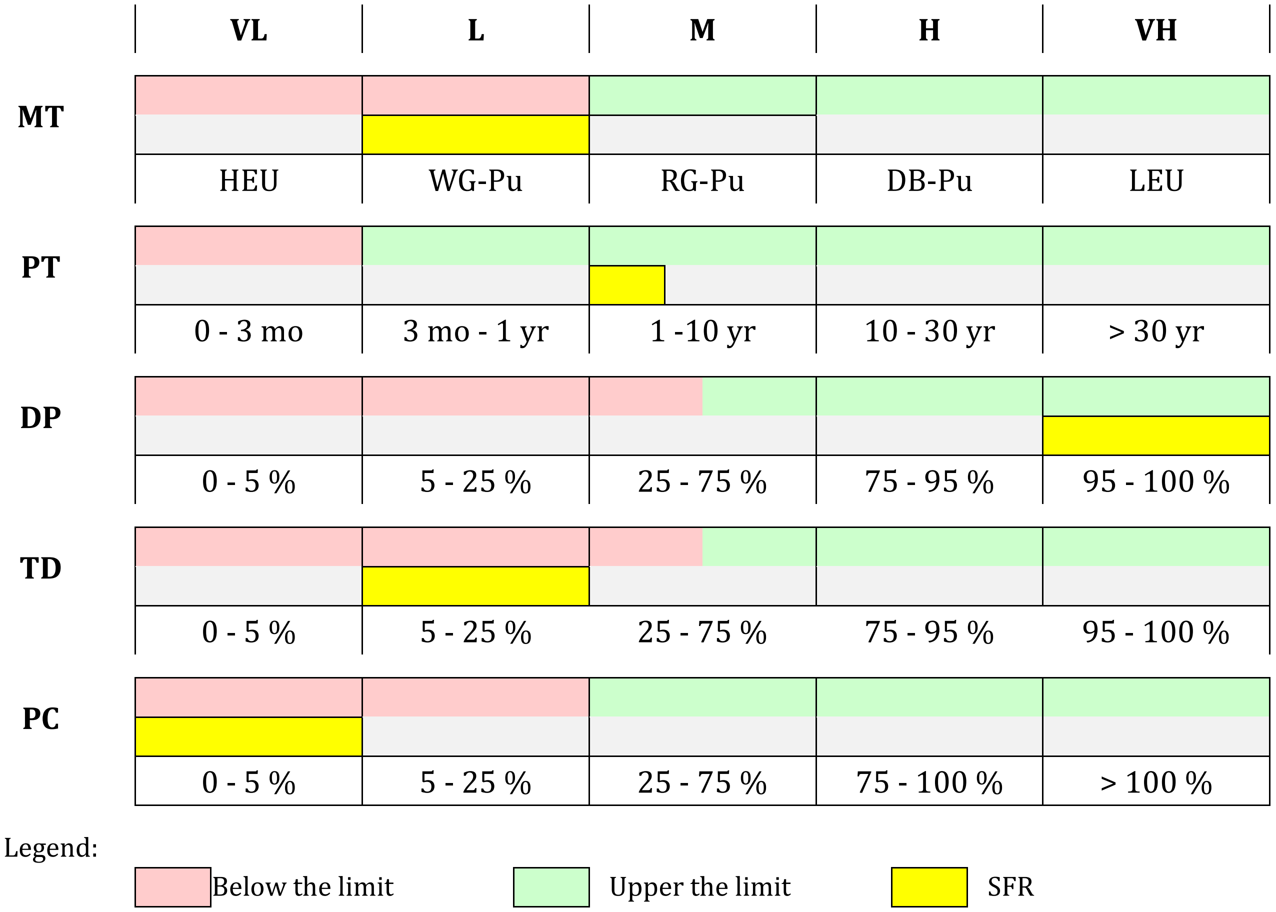


Fig. 9.9: Example of SFR misuse results for the GIF goal.

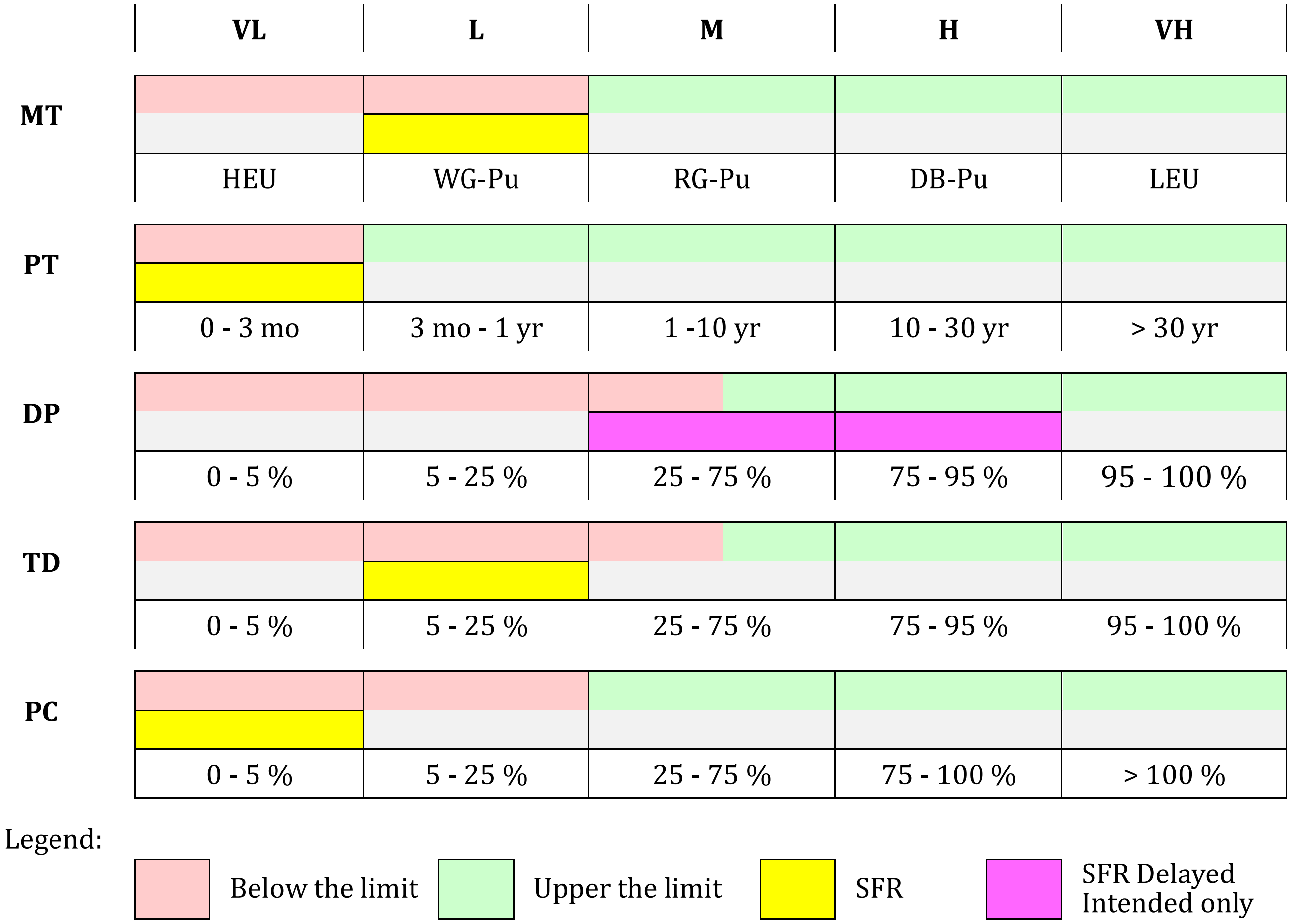
Considering now the breakout scenario based on the diversion pathway of the SFR, we need to make different considerations depending on the type of strategy: immediate absolute or delayed intended. In Fig. 9.10 the comparison between the limits and the SFR system for both the strategy is presented.

For the breakout scenario only the Proliferation Time and the Detection Probability are subject to change and, in particular, for the immediate absolute strategy the Detection Probability has no meaning because the State has already declared its intention to breakout. Under this considerations and because in the diversion scenario, with the present limits, the only measure that is in the acceptable region is the Detection Probability, it means that in the case of the immediate absolute strategy, because the Proliferation Time still remain in the very low bin, there are no measure that are over the set limits.

According to the findings of the diversion scenario, since the measures on which designers can act are mainly the Material Type and the Detection Probability, in the case of the immediate absolute strategy a key role is played by the response time after the State declaration of breakout. If this time is lower than the Proliferation Time, limiting actions can be done effectively. However, the response time could be affected by some State characteristics such as its transparency and international framework.

For the delayed intended, instead, the Detection Probability has a meaning only during the covert program but, following the evaluation results, the bin of interest is from medium to high. It means that, according to the situation, it could be results to be in the borderline with the set limit.

Also the Proliferation Time, presented here as the total time for both the covert and overt program, still remain in the very low bin so under the acceptable limit. However, differently form the immediate absolute strategy, here it is also important to consider the Proliferation Time before and after the declaration of breakout. Under this aspect, in fact, if the State actions are not detected during the covert program, the response time after the declaration is even shorter than the previous case. As already underline, this is one of the big advantages for the State in choosing the delayed intended strategy.



	VL	L	M	H	VH
MT	🟥	🟥	🟩	🟩	🟩
		🟨			
	HEU	WG-Pu	RG-Pu	DB-Pu	LEU
PT	🟥	🟩	🟩	🟩	🟩
	🟨				
	0 - 3 mo	3 mo - 1 yr	1 -10 yr	10 - 30 yr	> 30 yr
DP	🟥	🟥	🟥🟩	🟩	🟩
			🟪	🟪	
	0 - 5 %	5 - 25 %	25 - 75 %	75 - 95 %	95 - 100 %
TD	🟥	🟥	🟥🟩	🟩	🟩
		🟨			
	0 - 5 %	5 - 25 %	25 - 75 %	75 - 95 %	95 - 100 %
PC	🟥	🟥	🟩	🟩	🟩
	🟨				
	0 - 5 %	5 - 25 %	25 - 75 %	75 - 100 %	> 100 %

Legend:

🟥 Below the limit 🟩 Upper the limit 🟨 SFR 🟪 SFR Delayed Intended only

Fig. 9.10: Example of SFR breakout results for the GIF goal.

9.5 Development target results

The development target considered in this study says that a FBR cycle system that can be internationally accepted by achieving proliferation resistant to material diversion and facility misuse similar or superior to domestic and international advanced LWR cycle and next generation nuclear system.

To satisfy this target, the results from the evaluation of SFR, must be compared with the results obtained for the LWR reference system. Looking at this comparison, when a SFR measure is below the LWR one it would be important to identify the possible ways to upgrade it. In Fig. 9.11 and in Fig. 9.12, the comparison between SFR and LWR for diversion and misuse respectively are shown.

It is possible to see as TD and PC are strongly dependent on the State background more than the system analyzed, so the value for LWR and SFR is the same.

MT is an important point for SFR. Design can increase its value avoiding the use of blanket, but this decision must be done in accordance with the State energy policy.

DP is strongly connected with the safeguards approached used. Designers can increase its value to compensate MT, but it can influence other measures as DE (not considered for now during the evaluation).

PT is strongly connected with the reprocessing activities and depends on the State capabilities. The small difference between LWR and SFR is connected with the number of FA to be needed to obtain 1 SQ.

For misuse, again we can see that TD and PC are strongly dependent on the State background so the value for LWR and SFR is the same.

MT is an important point for SFR. Design can increase its value avoiding the use of blanket, but this decision must be done in accordance with the State energy policy.

DP is influenced by the scenario and by the safeguards approached used. In our case, the SFR DP is higher than the LWR ones, but more misuse scenario are needed to judge this measure.

PT is influenced by the irradiation time for targets. Designers can't act on this parameter.

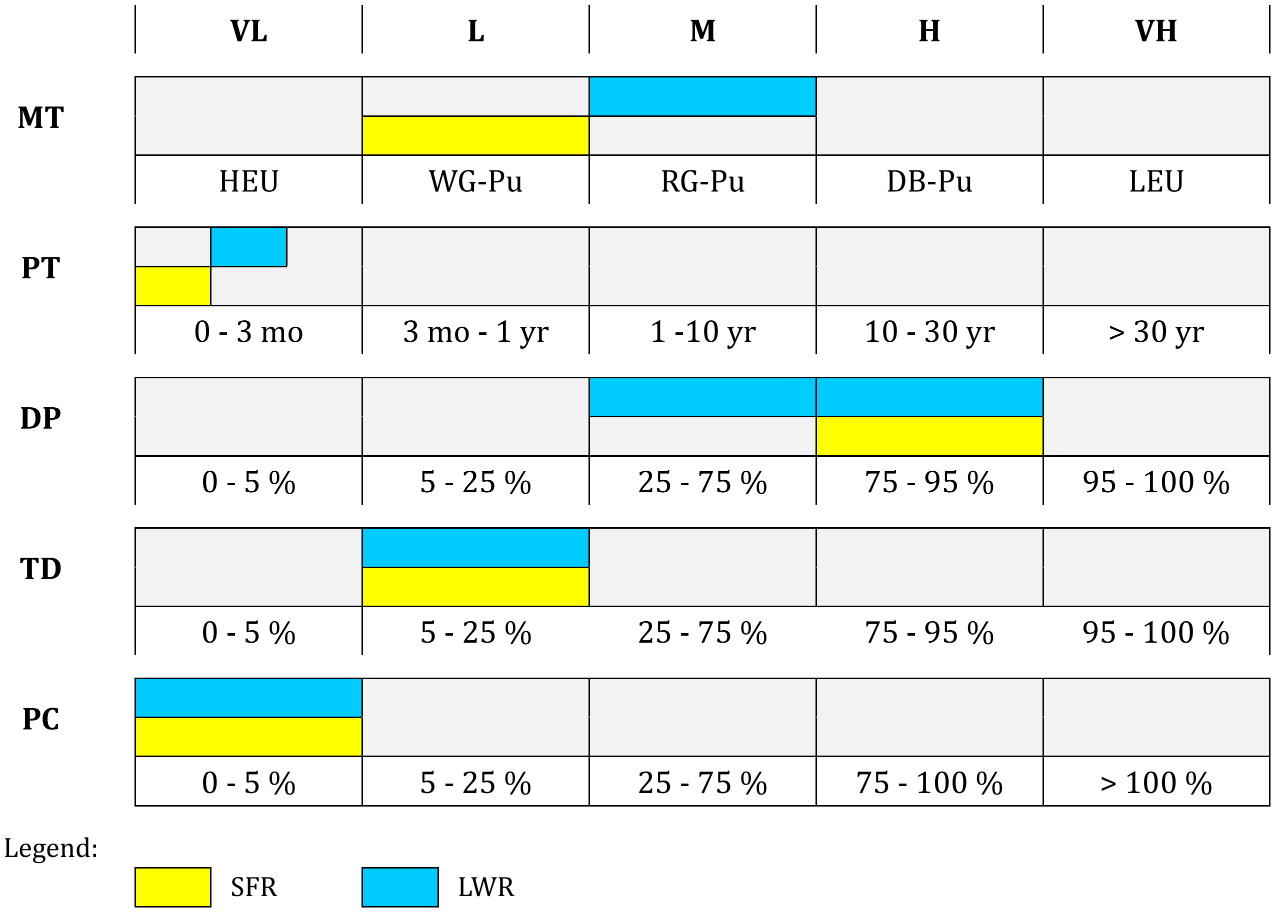


Fig. 9.11: Comparison of binned measure values for diversion pathways.

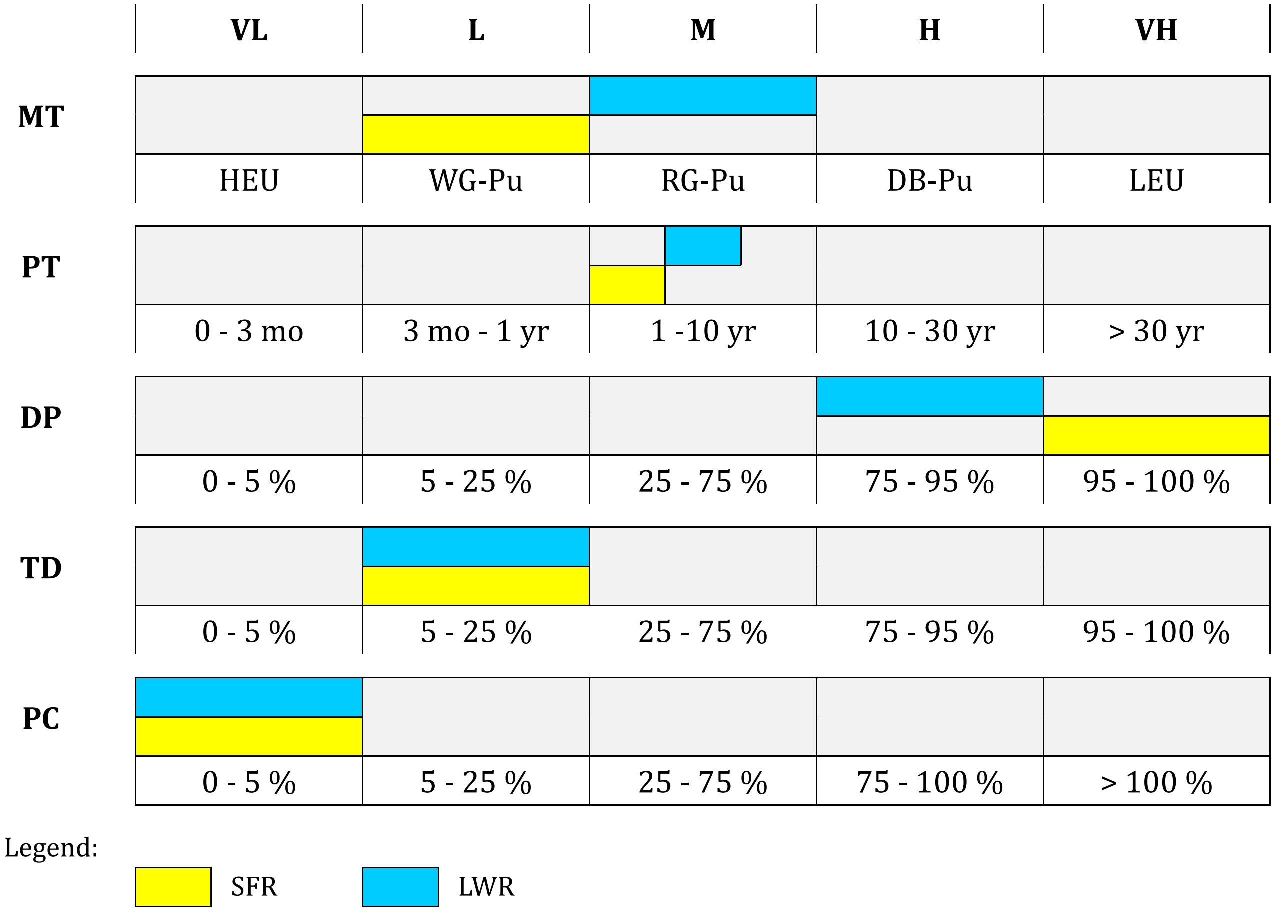
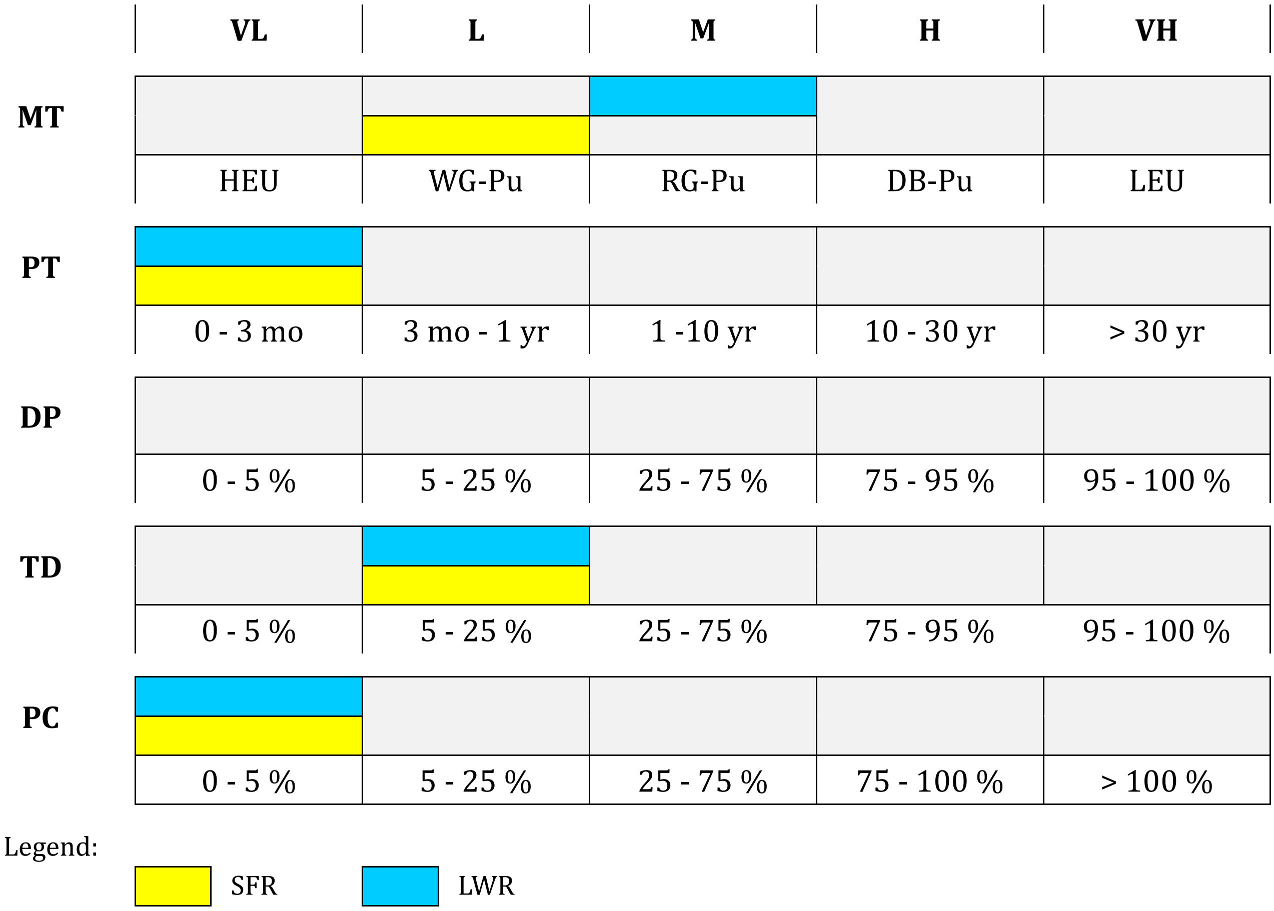


Fig. 9.12: Comparison of binned measure values for misuse pathways.

Considering now the breakout scenario with the immediate absolute strategy for both SFR and LWR (see Fig. 9.13), based on the diversion pathway of these plants, it is easy to notice that, due to the fact that the Detection Probability is not available for this case, the only remained difference between theme is the Material Type. However, as for the previous scenario, it must be remembered that design can increase the value of MT avoiding the use of blanket, but this decision must be done in accordance with the State energy policy.

It is instead different the situation of the delayed intended strategy as presented in Fig. 9.14. In this case, in fact, while the scenario for the SFR is still based on the diversion ones, the scenario assumed for the LWR is based on the misuse pathway to reach a better quality of material. The irradiation time for this case is reduced from 1 cycle to about 2 months and under this condition it is possible to reach weapon grade plutonium even with a light water reactor. Using these pathways the Material Type difference between the SFR and the LWR is deleted, but still remain some difference in the Proliferation Time and in the Detection Probability. However, the PT is different only in relation with the number of FAs that are needed to be treated in the LWR for reaching 1 SQ. As briefly described in Tab. 9.7, even if the number of FAs to be treated to reach 1SQ is to better investigate, the PT measure can be analyzed as a fix term plus a variable one. The fix amount of time is connected with the irradiation time, while the variable one is linked with

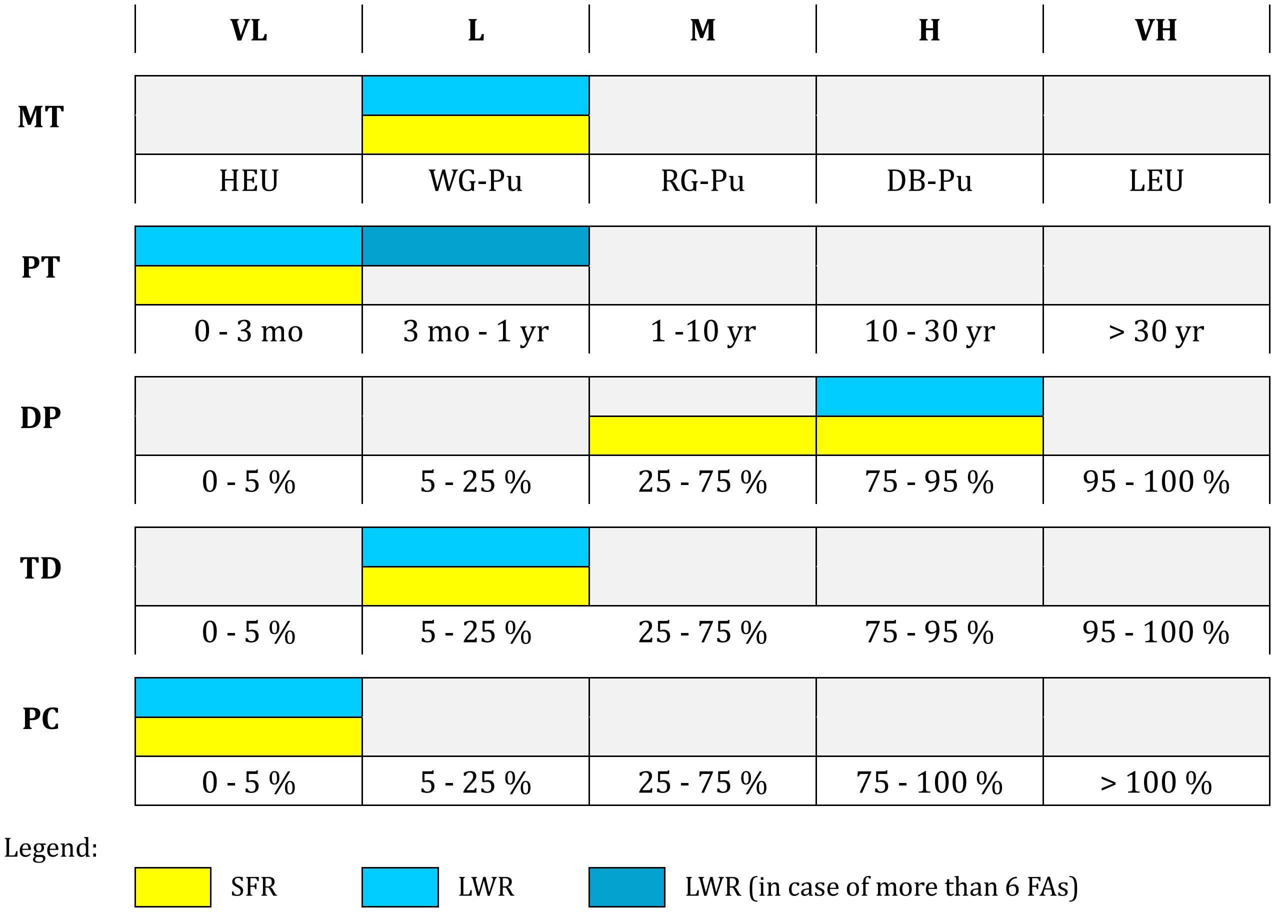
the time for the shipment and for the Pu extraction and purification. Using a very simple parametric analysis, if the number of FAs is below six, the PT still remain in the VL bin without any sensible difference with the case of the SFR; however, if the number of FAs is equal or exceed the number of six, the PT measure for the LWR is moved from the very low to the low bin. In a first approximation, with the availability of data of abnormal Pu production of a 400MWe light water reactor, considering a scale factor of 4 (the LWR power is 1600MWe), the production of Pu, in first approximation, could be considered to be about 6.4 kg of Pu per ton of U. Using this value, the number of FA needed could be estimated to be three that means that the PT measure for the LWR is still remain in the very low bin without any difference with the SFR case. Moreover, the same consideration done before regarding the response time are still available for these cases.
The last point of a possible difference between the case of the SFR and the LWR is the Detection Probability. In the case of the LWR, the shutdown of the NPP after about two months and the consequent shipment of fuel outside the facility is not a normal operation so the probability of be detected is high. Instead, for the SFR, the presence of the extra seal in the shipping door is no more effective because it is assumed that the State will wait the programmed shipment from the facility to the reprocessing plant. As underlined during the evaluation process, this is an important results and designer could working on it creating more layers of safeguards for the detection of illicit trafficking.



	VL	L	M	H	VH
MT		🟨	🟦		
	HEU	WG-Pu	RG-Pu	DB-Pu	LEU
PT	🟦 🟨				
	0 - 3 mo	3 mo - 1 yr	1 -10 yr	10 - 30 yr	> 30 yr
DP					
	0 - 5 %	5 - 25 %	25 - 75 %	75 - 95 %	95 - 100 %
TD		🟦 🟨			
	0 - 5 %	5 - 25 %	25 - 75 %	75 - 95 %	95 - 100 %
PC	🟦 🟨				
	0 - 5 %	5 - 25 %	25 - 75 %	75 - 100 %	> 100 %

Legend:
🟨 SFR 🟦 LWR

Fig. 9.13: Comparison of binned measure values for breakout pathways (immediate absolute).



	VL	L	M	H	VH
MT		🟦 🟨			
	HEU	WG-Pu	RG-Pu	DB-Pu	LEU
PT	🟦 🟨	▨			
	0 - 3 mo	3 mo - 1 yr	1 -10 yr	10 - 30 yr	> 30 yr
DP			🟨	🟦 🟨	
	0 - 5 %	5 - 25 %	25 - 75 %	75 - 95 %	95 - 100 %
TD		🟦 🟨			
	0 - 5 %	5 - 25 %	25 - 75 %	75 - 95 %	95 - 100 %
PC	🟦 🟨				
	0 - 5 %	5 - 25 %	25 - 75 %	75 - 100 %	> 100 %

Legend:

🟨 SFR 🟦 LWR ▨ LWR (in case of more than 6 FAs)

Fig. 9.14: Comparison of binned measure values for breakout pathways (delayed intended).

9.6 Theft and sabotage

The PP theft threat considered in this study has the objective of the single theft of fissile material from the plant in sufficient quantity to obtain 1 SQ of nuclear weapon material; the PP sabotage threat, instead, has the objective of a radiological release outside the plant site.

Theft

Because fuel inside the core is not accessible, without very time-consuming actions compared to that in other facility locations and is not transportable for any distance without a shielded vehicle, item storage areas were considered more attractive than the reactor core itself due to the mobility of the materials inside. In Fig. 9.15, the scenario presented briefly in Tab. 8.12 will be outlined in terms of an Adversary Sequence Diagram (ASD).
Using the PR&PP methodology, an ASD can be analyzed either quantitatively or qualitatively. For the qualitatively analysis, the binned metrics showed in Tab. 9.9 is used as presented in the PRPP methodology. It could be useful when analyzing plant designs in a conceptual phase where the exact design of the plant is not yet completed. It is also advantageous to perform the first PP analysis prior to developing a PP design in order to identify areas of interest, potential pathways, and targets. Following the binned metrics, the qualitative analysis of each steps presented in the theft path is summarized in Tab. 9.11. According to this qualitative description, the relative probability of interruption is calculated considering three different response force times (see Tab. 9.10) as shown in Fig. 9.16, Fig. 9.17 and Fig. 9.18.

Tab. 9.9: Physical Protection Qualitative Metrics for the evaluation of conceptual nuclear facility designs.

Metrics	**Range / Value**			
	High	**Medium**	**Low**	**No**
Probability of Detection: P_d	$1 > P_d \geq 0.9$	$0.9 > P_d \geq 0.8$	$0.8 > P_d \geq 0.2$	$0.2 > P_d = 0$
	0.95	0.85	0.5	0.1
Delay Time: t_d	$60m \geq t_d > 30m$	$30m \geq t_d > 10m$	$10m \geq t_d > 1m$	$1m \geq t_d = 0$
	45m	20m	5.5m	0.5m
Response Time: t_r	$1m \geq t_r = 0$	$10m \geq t_r > 1m$	$30m \geq t_r > 10m$	$60m \geq t_r > 30m$
	0.5m	5.5m	20m	45m

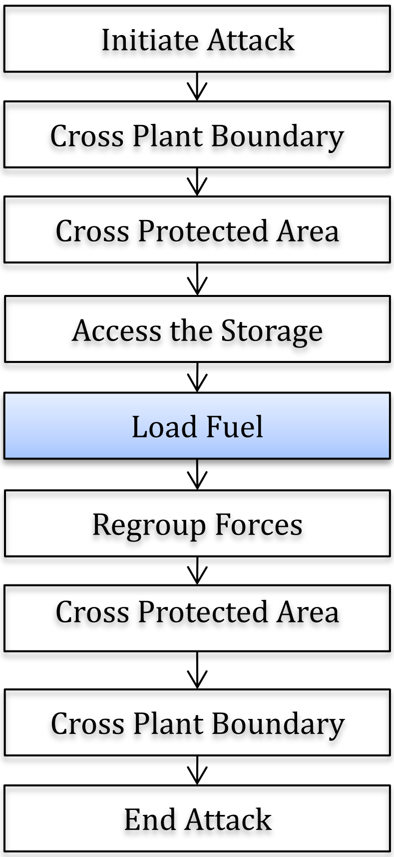


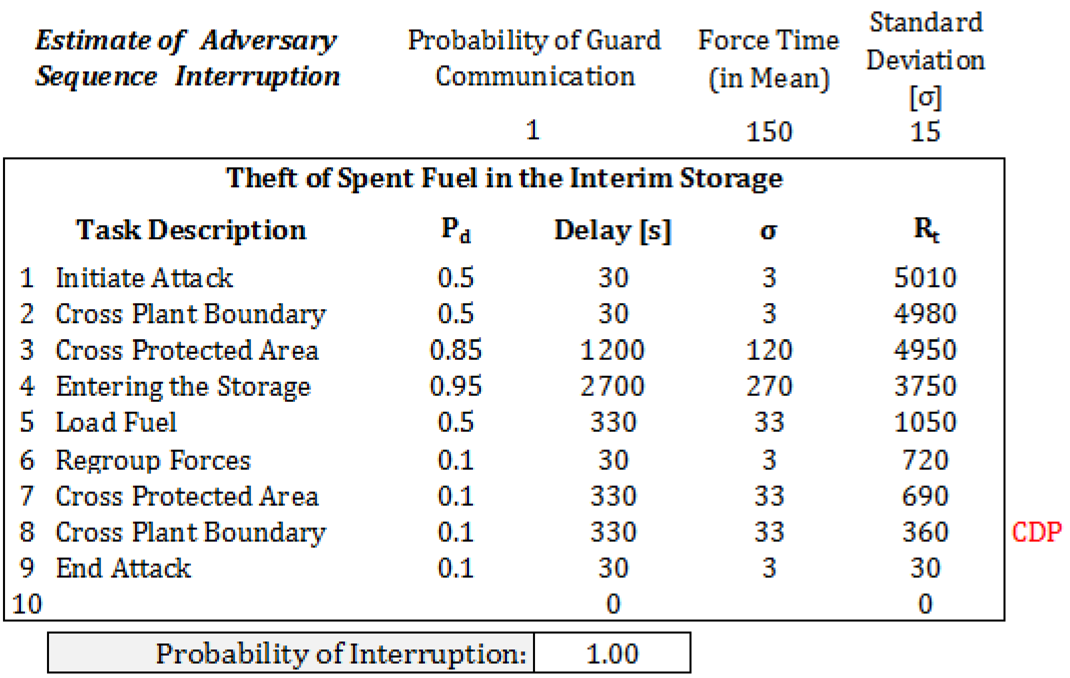
Fig. 9.15: Adversary Sequence Diagram for theft of spent fuel in the interim storage pool.

Tab. 9.10: Response force time options.

Option	**Response Force Time [s]**
A	150
B	300
C	600

Tab. 9.11: Qualitative analysis of each step along the theft pathway.

	Task	P_d	Delay	Assessment description
1	Initiate Attack	Low	No	The militarily trained force is assumed to achieve both strategic and tactical surprise.
2	Cross Plant Boundary	Low	No	The outer boundary is typically a simple fence with at least one sensor on it.
3	Cross Protected Area	Medium	Medium	The PIDAS boundary is a set of fences, vehicle barriers, and sensors. A trained group will readily be able to cross this, but not without detection. At this point, defensive forces are moving in and engaging the adversary.
4	Access the Storage	High	High	When the sensors alarm, the building will be locked down. The adversary will have to force (via explosives) their way in. This step must be performed while under fire.
5	Load Fuel	Low	Low	Any adversary that is loading fuel is not available to engage the defensive forces.
6	Regroup Forces	No	No	Regrouping must occur under fire, through known access points and in a known location.
7	Driving Vehicle, Cross Protected Area	No	Low	Complete defensive force response will have arrived by this point. Vehicles will be placed under heavy fire to disable them as an avenue of escape. Dismounted adversaries have to cross the PIDAS while under fire.
8	Driving Vehicle, Cross Plant Boundary	No	Low	Since the defensive forces will be converging on the adversaries, it is assumed that it will be easy to the adversaries continue on through the plant boundary.
9	End Attack	No	No	Only adversaries get to decide when to quit.



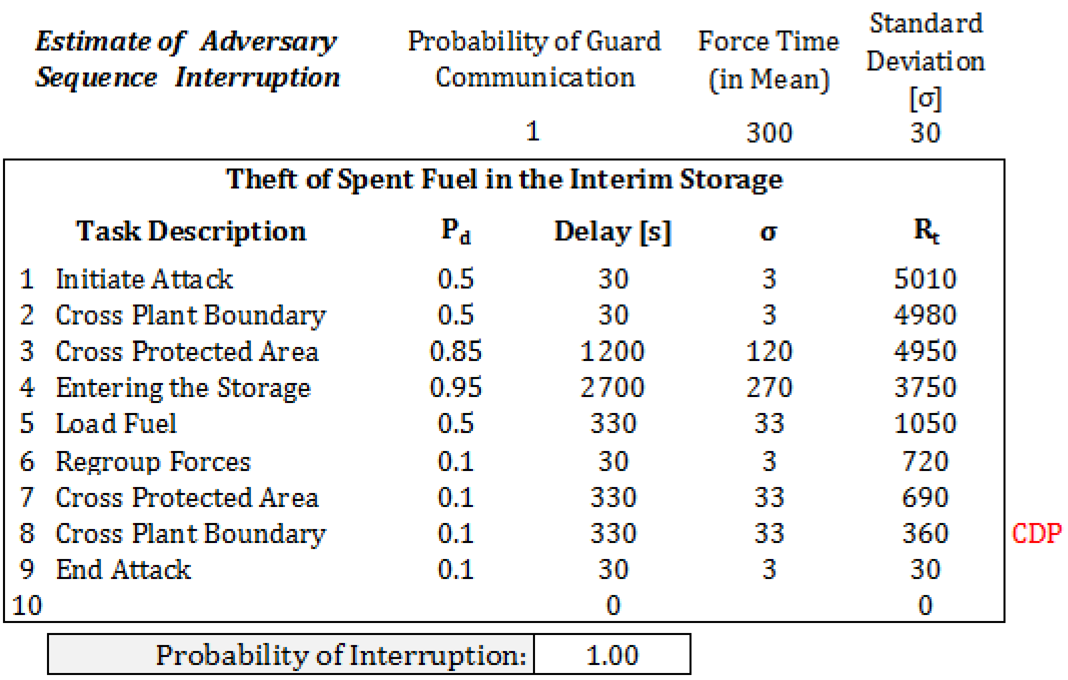
Estimate of Adversary Sequence Interruption	Probability of Guard Communication	Force Time (in Mean)	Standard Deviation [σ]
	1	150	15

Theft of Spent Fuel in the Interim Storage

	Task Description	P_d	Delay [s]	σ	R_t	
1	Initiate Attack	0.5	30	3	5010	
2	Cross Plant Boundary	0.5	30	3	4980	
3	Cross Protected Area	0.85	1200	120	4950	
4	Entering the Storage	0.95	2700	270	3750	
5	Load Fuel	0.5	330	33	1050	
6	Regroup Forces	0.1	30	3	720	
7	Cross Protected Area	0.1	330	33	690	
8	Cross Plant Boundary	0.1	330	33	360	CDP
9	End Attack	0.1	30	3	30	
10			0		0	

Probability of Interruption:	1.00

Fig. 9.16: Probability of interruption with PPS option A, theft.



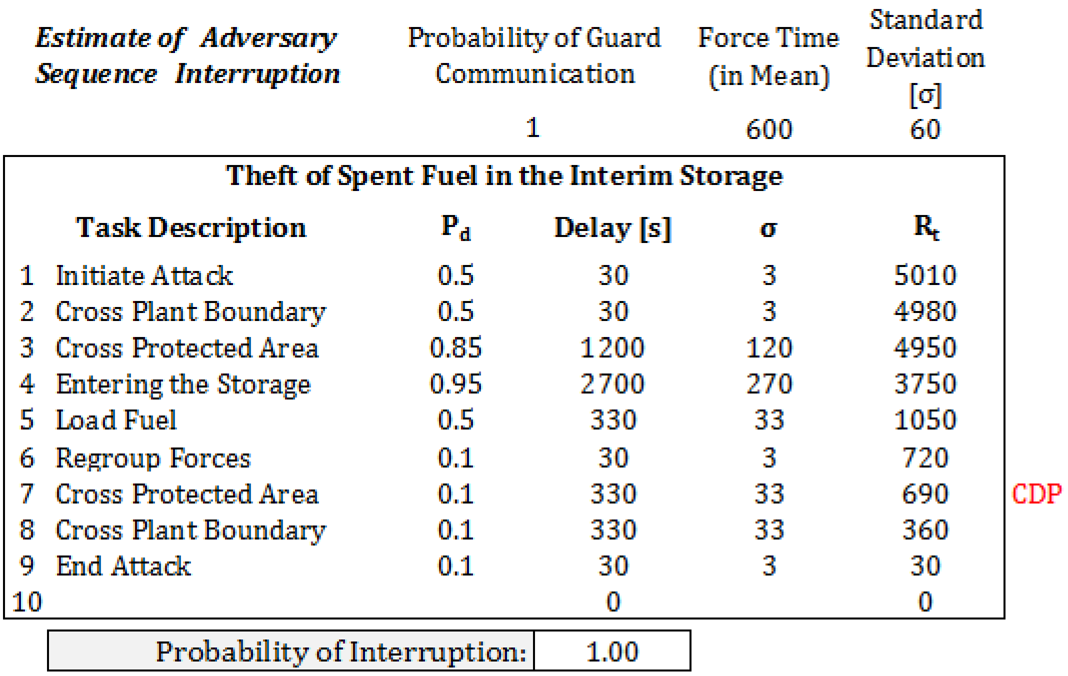
Estimate of Adversary Sequence Interruption	Probability of Guard Communication	Force Time (in Mean)	Standard Deviation [σ]
	1	300	30

Theft of Spent Fuel in the Interim Storage

	Task Description	P_d	**Delay [s]**	**σ**	R_t	
1	Initiate Attack	0.5	30	3	5010	
2	Cross Plant Boundary	0.5	30	3	4980	
3	Cross Protected Area	0.85	1200	120	4950	
4	Entering the Storage	0.95	2700	270	3750	
5	Load Fuel	0.5	330	33	1050	
6	Regroup Forces	0.1	30	3	720	
7	Cross Protected Area	0.1	330	33	690	
8	Cross Plant Boundary	0.1	330	33	360	CDP
9	End Attack	0.1	30	3	30	
10			0		0	

Probability of Interruption:	1.00

Fig. 9.17: Probability of interruption with PPS option B, theft.



Estimate of Adversary Sequence Interruption	Probability of Guard Communication	Force Time (in Mean)	Standard Deviation [σ]
	1	600	60

Theft of Spent Fuel in the Interim Storage

	Task Description	P_d	**Delay [s]**	**σ**	R_t	
1	Initiate Attack	0.5	30	3	5010	
2	Cross Plant Boundary	0.5	30	3	4980	
3	Cross Protected Area	0.85	1200	120	4950	
4	Entering the Storage	0.95	2700	270	3750	
5	Load Fuel	0.5	330	33	1050	
6	Regroup Forces	0.1	30	3	720	
7	Cross Protected Area	0.1	330	33	690	CDP
8	Cross Plant Boundary	0.1	330	33	360	
9	End Attack	0.1	30	3	30	
10			0		0	

Probability of Interruption:	1.00

Fig. 9.18: Probability of interruption with PPS option C, theft.

The same evaluation was also done quantitatively using a hypothetical PP system description. In Fig. 9.19 the assumptions done and the value for the P_d and delay is shown for each steps of the path. Values are taken form data provided during the Regional Training Course on Physical Protection of Nuclear Material and Facilities [163] and elaborated using the Multipath very-Simplified Estimate of Adversary Sequence Interruption (MP VEASI) version 1.02, April 11, 2009 developed by the Sandia national Laboratories. An example for the path in consideration under the option A for the response time is shown in Fig. 9.20, while in Tab. 9.12 a summary of the probability of adversary success (complement to one of probability of interruption) for the different options used.

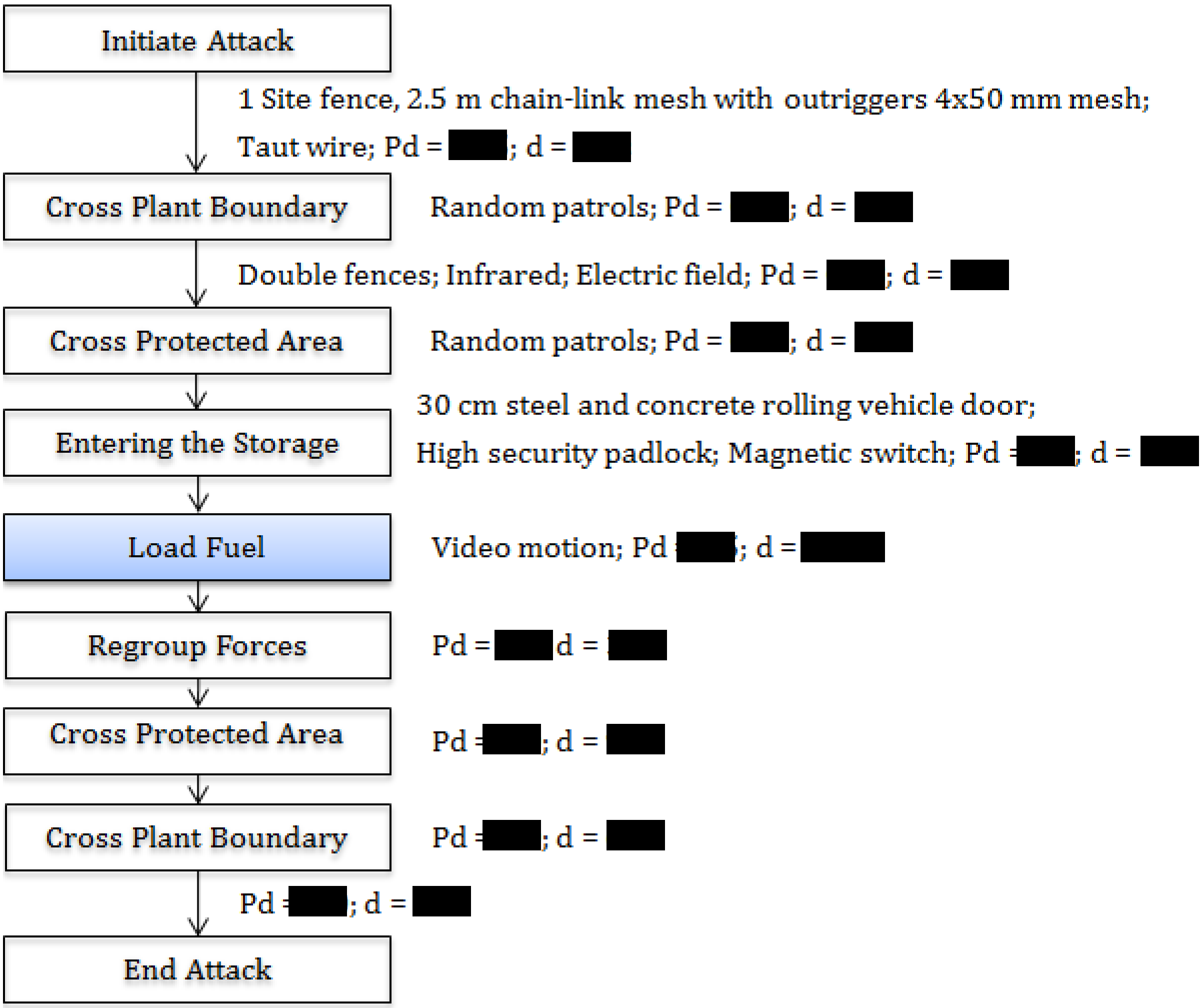


Fig. 9.19: Annotated ASD for theft of SF in the SFR.

P(Interruption), P$_I$ 0.970

Delay:(After CDP) 180

Response Strategy Denial

PPS Response Time(sec) 150

Total Path Delay 523 (sec)

Path Complete

T(sec)	Adversary Task Time Remaining After First Sensing(sec)	Timely Detection	Element #		1	2	3	4
				O	Offsite			
12	511	0.25	1		Fence PD T(sec) JUMP [redacted]			
18	493	0.02		A	PD [redacted]	T(sec) [redacted]	Plant boundary	
24	469	0.58	1		Fences PD T(sec) JUMP [redacted]			
25	444	0.02		B	PD [redacted]	T(sec) [redacted]	Protected Area	
54	390	0.8	2		Door + switch PD T(sec) JUMP [redacted]	Door explosive PD T(sec) JUMP [redacted]		
180	210	0.5		C	PD [redacted]	T(sec) [redacted]	Load Fuel	
30	180 CDP	0 CDP	1		Regroup Forces PD T(sec) JUMP [redacted]			
90	90	0		D	PD [redacted]	T(sec) [redacted]	Cross PA	
60	30	0	1		PB PD T(sec) JUMP [redacted]			
30	0	0		E	PD [redacted]	T(sec) [redacted]	End	

Fig. 9.20: Probability of interruption with PPS option A using a hypothetical PP layout in the SFR.

The same approach was used also to evaluate the LWR theft pathway. In Fig. 9.21 the annotated ASD for theft of SF in the spent pool is shown for each steps of the path. The summary of the probability of adversary success for the different options used is presented in Tab. 9.12.

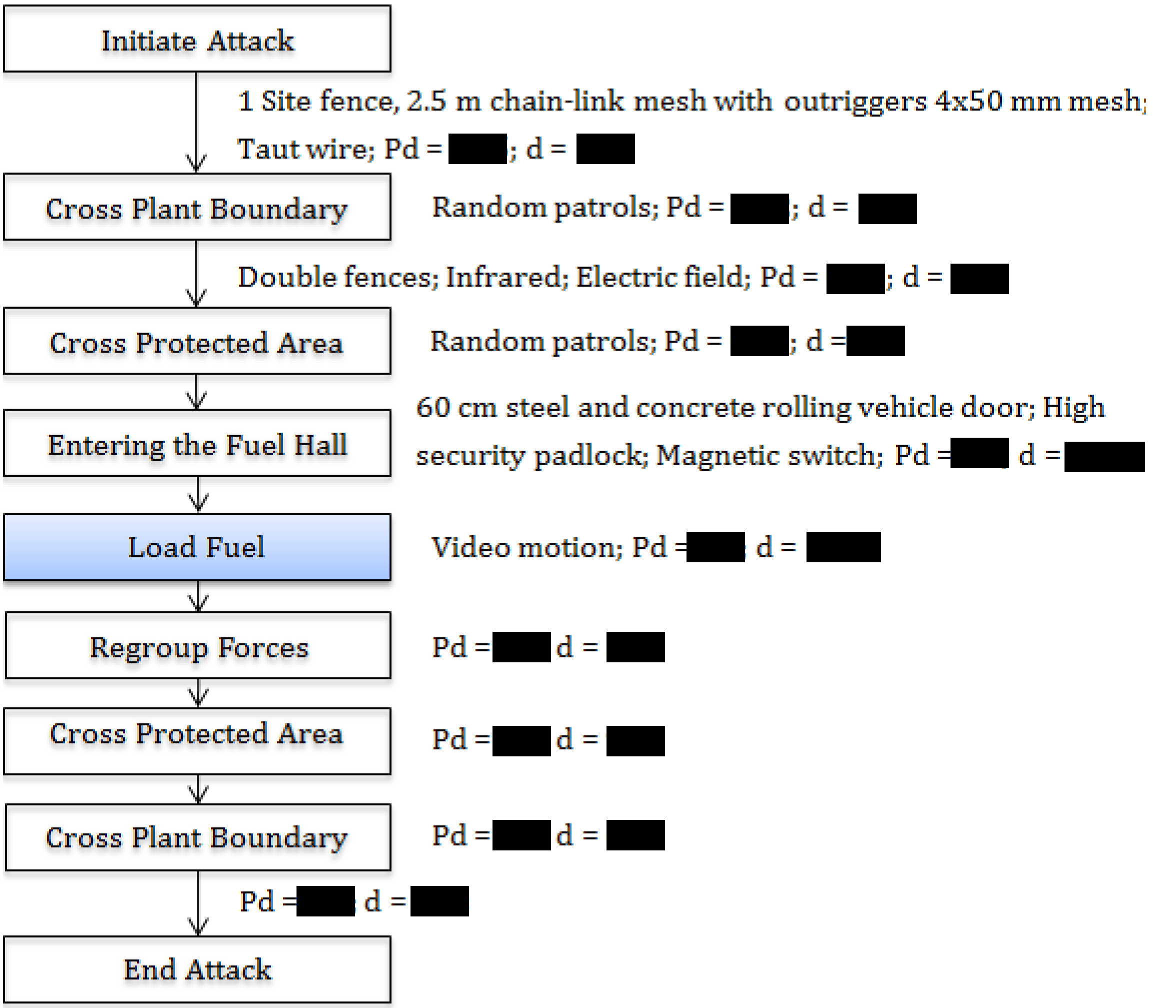


Fig. 9.21: Annotated ASD for theft of SF in the LWR.

Tab. 9.12: Summary of probability of adversary success for theft.

Target	Option A	Option B	Option C
Theft of SF in the Interim Storage (SFR)	0.03	0.06	1.00
Theft of SF in the Spent Pool (LWR)	0.03	0.06	0.74

Following the path analysis, the obtained probability of adversary success and the possible consequences in case of adversary success was discussed during the evaluation meeting according to the PP measure (see Tab. 1.2). The results of the evaluation will be presented in the further section “

Evaluation results’ from page 186.

Sabotage

The sabotage event to be analyzed, as presented in Tab. 8.13, is the damage of the reactor spent pool using explosive. This event could cause an immediate release only if the explosive could reach the spent fuel elements causing the breaking of the cladding and the release of radioactive gases. However, this such of event, could cause irreparable damage to the facility and if the cooling water level will be critical, a criticality event could happen in the pool with consequential release of a big amount of radioactive material outside the plant. Of course the amount of radioactive material will be consistent with the number of spent fuel present in the pool, but the presence of an insider could help the adversary to attack in the most convenient time.
In Fig. 9.22 and Fig. 9.26, the scenario presented briefly in Tab. 8.13 is outlined in terms of an annotated ASD for both the SFR and the LWR. However, also in this case, before the quantitative analysis a qualitative one is done. Assumptions for each steps of the sabotage pathways are summarized in Tab. 9.13, while the results are shown in Fig. 9.23, Fig. 9.24 and Fig. 9.25, considering the same response force times used for the theft scenario (see Tab. 9.10).
The results of the quantified analysis are shown in Tab. 9.14, while the results of the PP evaluation discussion will be presented in the further section Evaluation results from page 186.

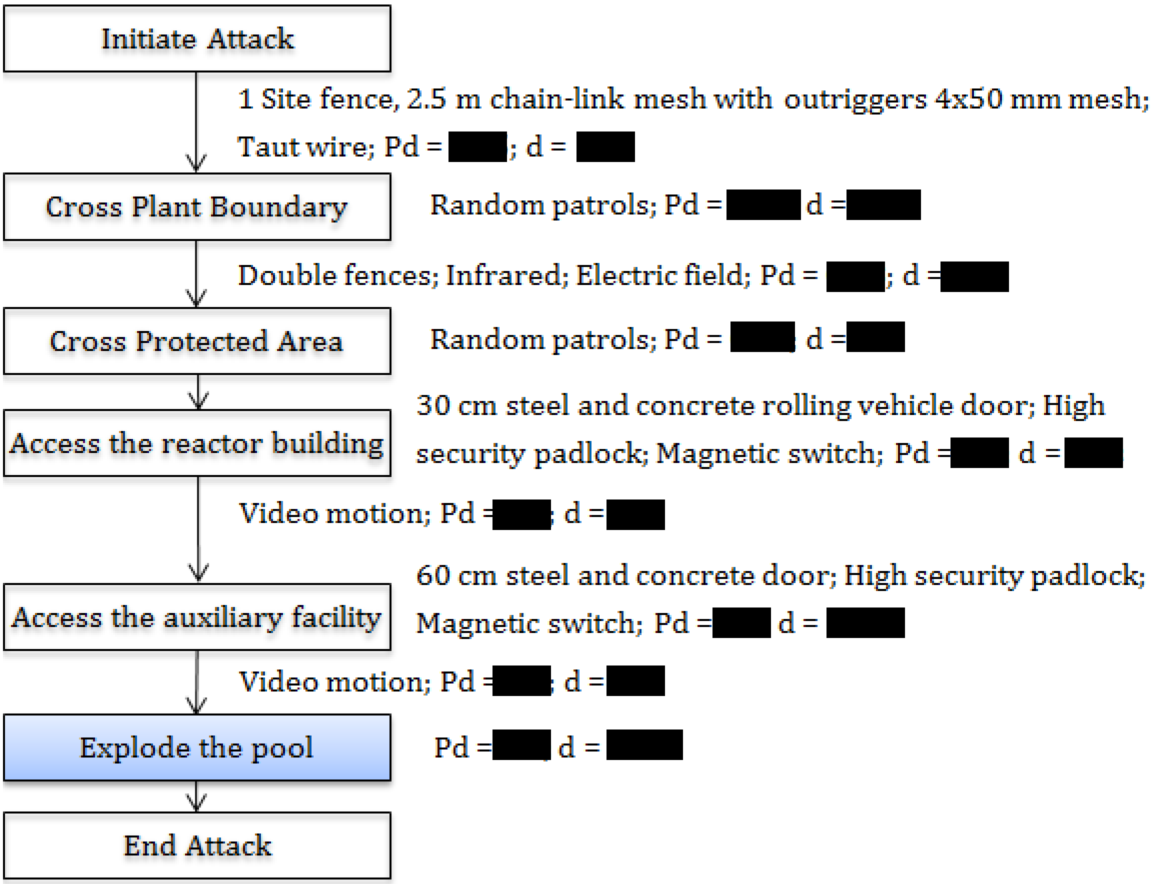
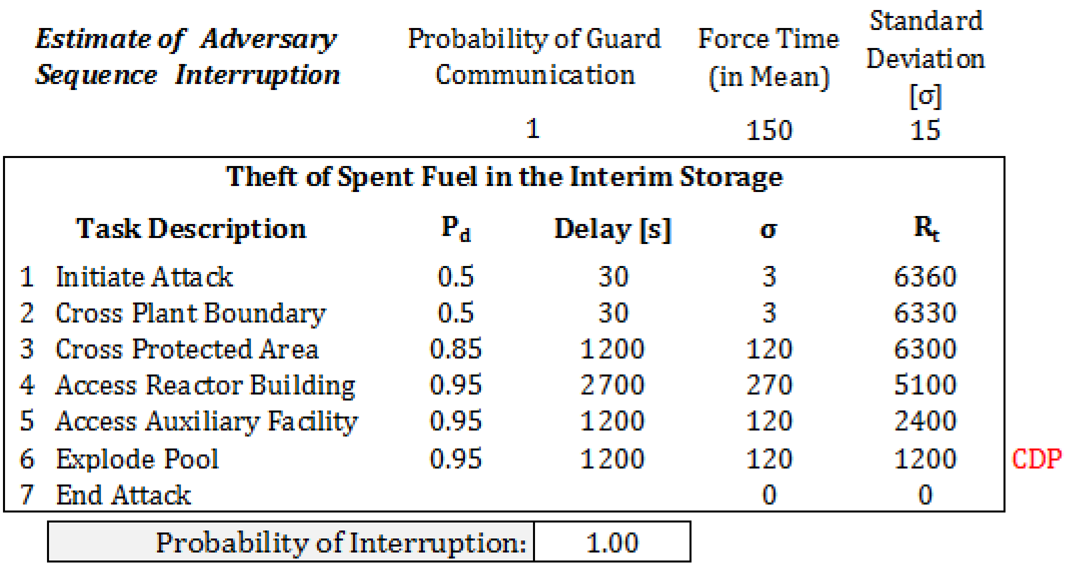


Fig. 9.22: Annotated ASD for sabotage of SF pool in the SFR.

Tab. 9.13: Qualitative analysis of each step along the sabotage pathway.

	Task	**P_d**	**Delay**	**Assessment description**
1	Initiate Attack	Low	No	The militarily trained force is assumed to achieve both strategic and tactical surprise.
2	Cross Plant Boundary	Low	No	The outer boundary is typically a simple fence with at least one sensor on it.
3	Cross Protected Area	Medium	Medium	The PIDAS boundary is a set of fences, vehicle barriers, and sensors. A trained group will readily be able to cross this, but not without detection. At this point, defensive forces are moving in and engaging the adversary.
4	Access the Reactor Building	High	High	When the sensors alarm, the building will be locked down. The adversary will have to force (via explosives) their way in. This step must be performed while under fire.
5	Access the Auxiliary Facility	High	Medium	Once inside the Reactor Building, the interior sensors could detect the adversaries' position, but not difficult to reach the auxiliary facility located inside. However, complete defensive force response will have arrived by this point.
6	Explode the Pool	High	Medium	The placing of the explosives and their detonation will require a sufficient amount of time. Detection at this point is extremely likely once the explosion occurs.
7	End Attack			



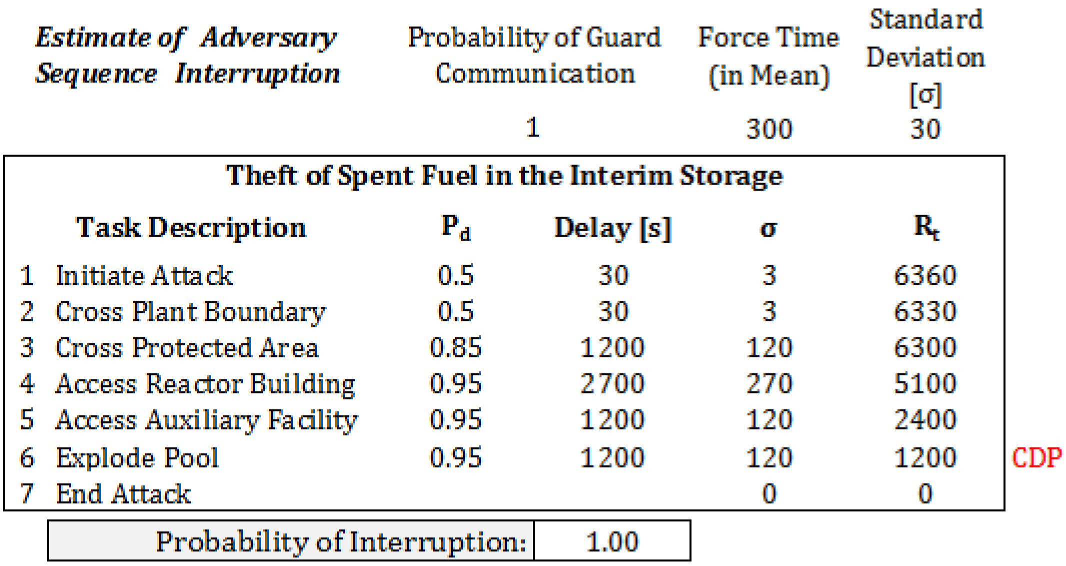
Estimate of Adversary Sequence Interruption	Probability of Guard Communication	Force Time (in Mean)	Standard Deviation [σ]
	1	150	15

Theft of Spent Fuel in the Interim Storage

	Task Description	**P_d**	**Delay [s]**	**σ**	**R_t**	
1	Initiate Attack	0.5	30	3	6360	
2	Cross Plant Boundary	0.5	30	3	6330	
3	Cross Protected Area	0.85	1200	120	6300	
4	Access Reactor Building	0.95	2700	270	5100	
5	Access Auxiliary Facility	0.95	1200	120	2400	
6	Explode Pool	0.95	1200	120	1200	CDP
7	End Attack			0	0	

Probability of Interruption:	1.00

Fig. 9.23: Probability of interruption with PPS option A, sabotage SFR.



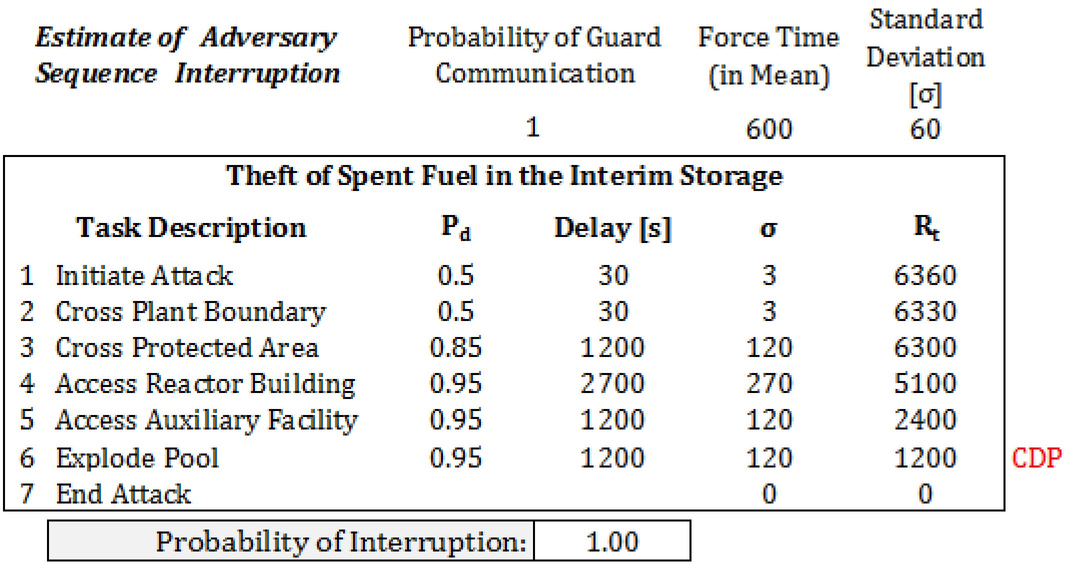
Estimate of Adversary Sequence Interruption	Probability of Guard Communication	Force Time (in Mean)	Standard Deviation [σ]
	1	300	30

Theft of Spent Fuel in the Interim Storage

	Task Description	P_d	Delay [s]	σ	R_t	
1	Initiate Attack	0.5	30	3	6360	
2	Cross Plant Boundary	0.5	30	3	6330	
3	Cross Protected Area	0.85	1200	120	6300	
4	Access Reactor Building	0.95	2700	270	5100	
5	Access Auxiliary Facility	0.95	1200	120	2400	
6	Explode Pool	0.95	1200	120	1200	CDP
7	End Attack			0	0	

Probability of Interruption:	1.00

Fig. 9.24: Probability of interruption with PPS option B, sabotage SFR.



Estimate of Adversary Sequence Interruption	Probability of Guard Communication	Force Time (in Mean)	Standard Deviation [σ]
	1	600	60

Theft of Spent Fuel in the Interim Storage

	Task Description	P_d	Delay [s]	σ	R_t	
1	Initiate Attack	0.5	30	3	6360	
2	Cross Plant Boundary	0.5	30	3	6330	
3	Cross Protected Area	0.85	1200	120	6300	
4	Access Reactor Building	0.95	2700	270	5100	
5	Access Auxiliary Facility	0.95	1200	120	2400	
6	Explode Pool	0.95	1200	120	1200	CDP
7	End Attack			0	0	

Probability of Interruption:	1.00

Fig. 9.25: Probability of interruption with PPS option C, sabotage SFR.

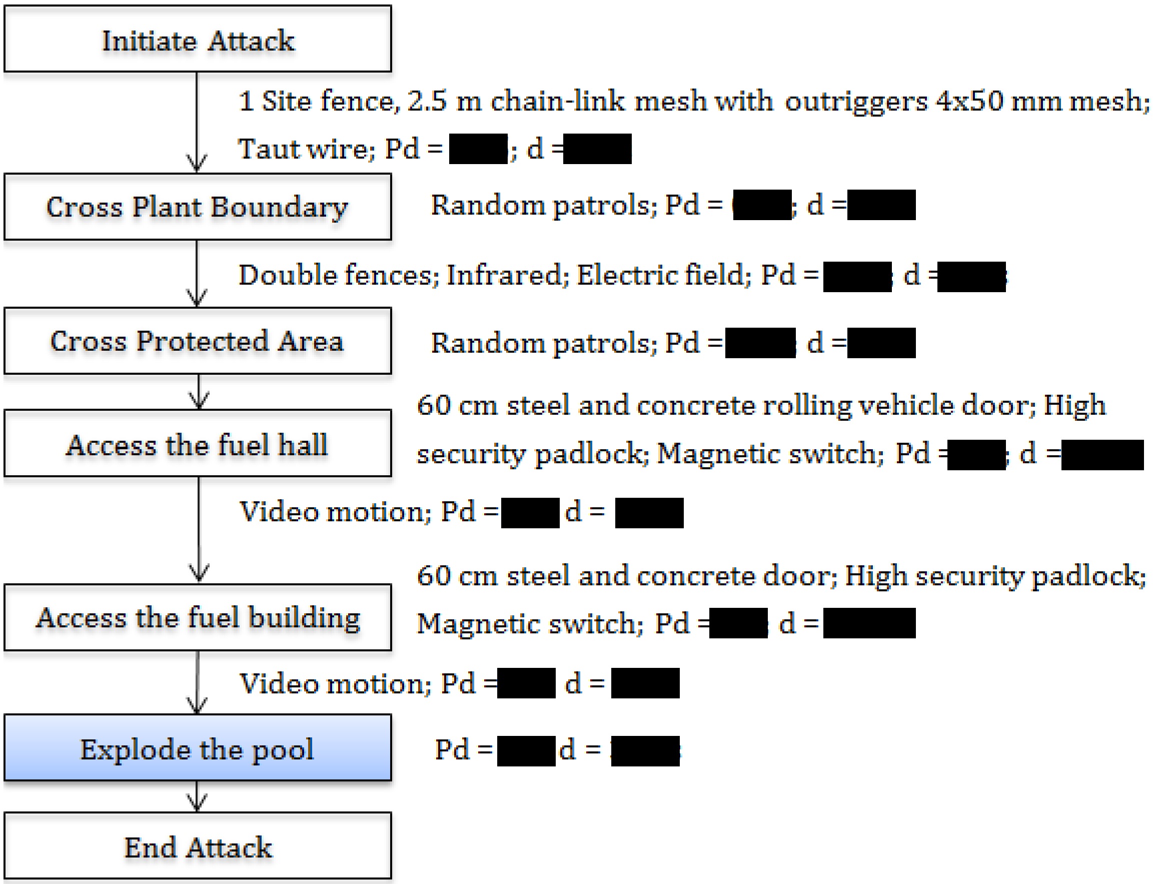


Fig. 9.26: Annotated ASD for sabotage of SF pool in the LWR.

Tab. 9.14: Summary of probability of adversary success for sabotage.

Target	Option A	Option B	Option C
Sabotage of the SF pool in SFR	0.00	0.01	0.75
Sabotage of the SF pool in LWR	0.00	0.01	0.30

Evaluation results

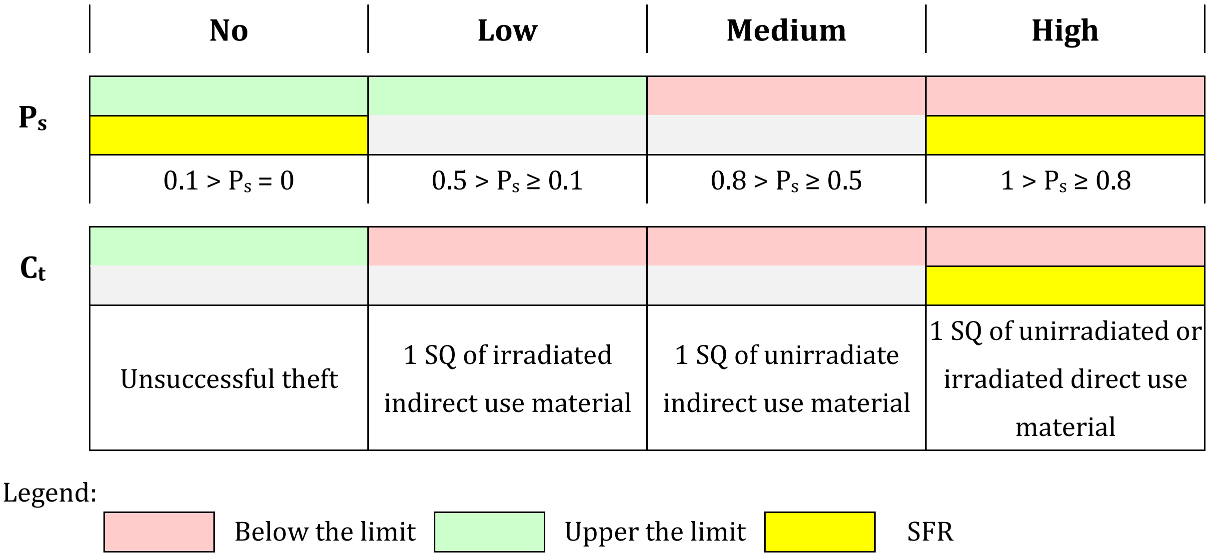
Also for the case of theft and sabotage, as show in section 1.3, the results obtained could be analyzed in term of GIF goals or development targets. In particular, for the GIF goal, a Generation IV NES is to provide enhanced protection against theft of materials suitable for nuclear explosives or RDDs and enhanced protection against sabotage of facilities and transportation; for the development target, instead, a FBR cycle system that can be internationally accepted by adopting physical protection system consistent with IAEA guideline and law/rule and with FBR system concept, with a level similar or superior to domestic and international advanced LWR cycle and next generation nuclear system.

As done for the case of PR paths, first the limits for the different measures will be set and the SFR results will be compared with them for both theft and sabotage (Fig. 9.27 and Fig. 9.28), and after the SFR and LWR results will be compared between them (Fig. 9.29 and Fig. 9.30)

To set the limits the following considerations are done:

- For P_S, the limits are set to be less than 50% of probability;
- For C_t, the limit is set to No considering as an unacceptable risk the theft of any kind of material even if the theft of an indirect use material type will give to the response more time to find and recover it;
- For C_R the limit is set to No considering as an unacceptable risk any radioactive release.

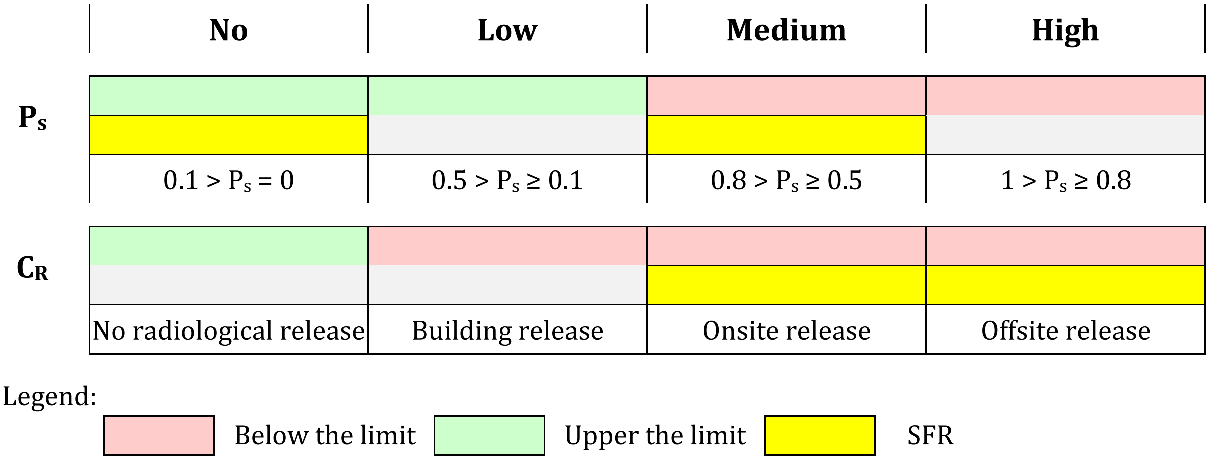
In this step, we exclude from the evaluation the PPR and the C_E measures because too difficult to evaluate at this stage and the C_D measure because the theft target of the terrorist is not considered being a radioactive material, but nuclear material.
From Fig. 9.27 and Fig. 9.28, it is easy to see that the probability of success in both theft and sabotage case could be really different and this id strongly connected with the response team time. Regarding the theft consequences, instead, the presence of blanket in the plant is the main cause of such high value in the C_t measure. For the sabotage consequences, instead, it must be remembered that the value of medium and high are considered being the worst scenario possible without any mitigation activity after the sabotage success.



	No	Low	Medium	High
P_s	🟩 🟨	🟩	🟥	🟥 🟨
	$0.1 > P_s = 0$	$0.5 > P_s \geq 0.1$	$0.8 > P_s \geq 0.5$	$1 > P_s \geq 0.8$
C_t	🟩	🟥	🟥	🟥 🟨
	Unsuccessful theft	1 SQ of irradiated indirect use material	1 SQ of unirradiate indirect use material	1 SQ of unirradiated or irradiated direct use material

Legend:
🟥 Below the limit 🟩 Upper the limit 🟨 SFR

Fig. 9.27: Example of SFR theft results for the GIF goal.



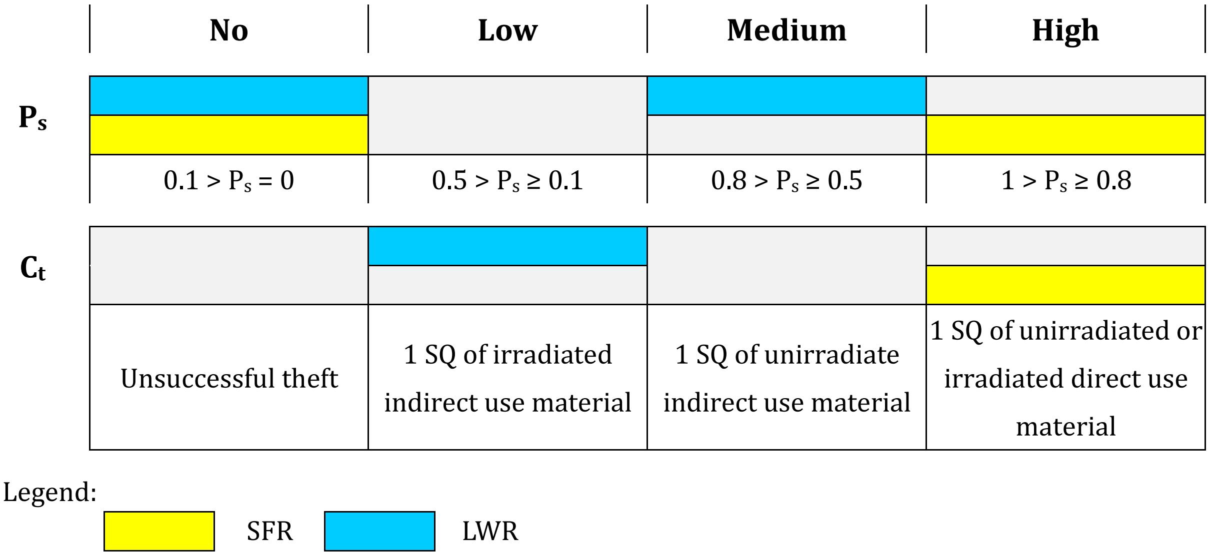
	No	Low	Medium	High
P_s	🟩 🟨	🟩	🟥 🟨	🟥
	$0.1 > P_s = 0$	$0.5 > P_s \geq 0.1$	$0.8 > P_s \geq 0.5$	$1 > P_s \geq 0.8$
C_R	🟩	🟥	🟥 🟨	🟥 🟨
	No radiological release	Building release	Onsite release	Offsite release

Legend:
🟥 Below the limit 🟩 Upper the limit 🟨 SFR

Fig. 9.28: Example of SFR sabotage results for the GIF goal.

Comparing now the SFR evaluation result with the LWR ones, it is possible to see how the different kind of material present in the plant could drastically change the value for the C_t measure in case of theft. However, it must be underline that if the theft of material to perform a RDD will be taken into account the situation could change.

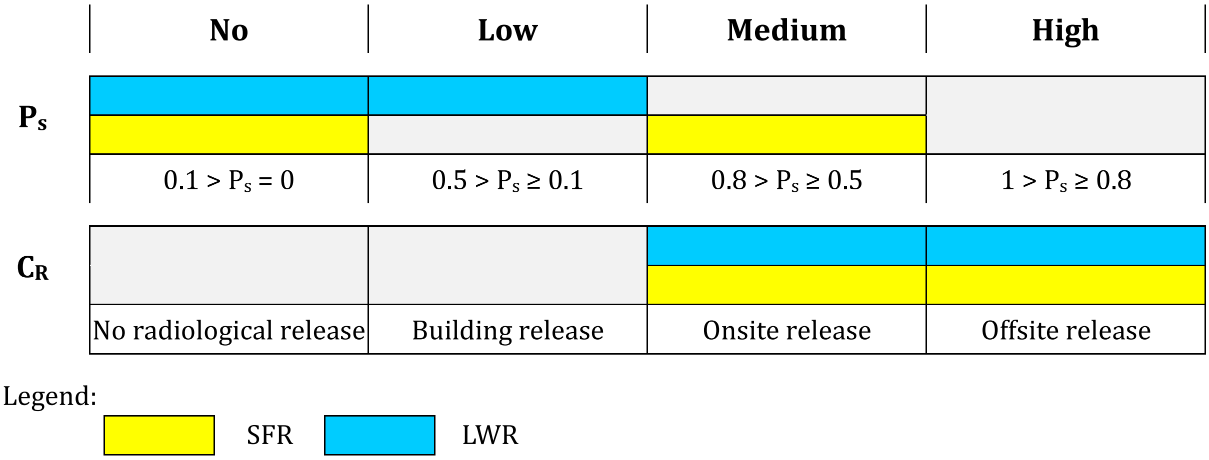
It must also underline that the difference in the P_s is mainly cause by the different layout of the plants and by the choice of PP systems. Changing the layout and the PP systems in used could be results in a change in the evaluation results.



	No	**Low**	**Medium**	**High**
P_s	🟦 🟨		🟦	🟨
	$0.1 > P_s = 0$	$0.5 > P_s \geq 0.1$	$0.8 > P_s \geq 0.5$	$1 > P_s \geq 0.8$
C_t		🟦		🟨
	Unsuccessful theft	1 SQ of irradiated indirect use material	1 SQ of unirradiate indirect use material	1 SQ of unirradiated or irradiated direct use material

Legend:
🟨 SFR 🟦 LWR

Fig. 9.29: Comparison of binned measure values for theft pathways.



	No	**Low**	**Medium**	**High**
P_s	🟦 🟨	🟦	🟨	
	$0.1 > P_s = 0$	$0.5 > P_s \geq 0.1$	$0.8 > P_s \geq 0.5$	$1 > P_s \geq 0.8$
C_R			🟦 🟨	🟦 🟨
	No radiological release	Building release	Onsite release	Offsite release

Legend:
🟨 SFR 🟦 LWR

Fig. 9.30: Comparison of binned measure values for sabotage pathways.

10 CONCLUSION

Two objectives are identified for the Generation IV NES: the GIF Goal and the Development target. The GIF Goal suggest that new GEN IV NES are to be the least desirable route to proliferation and are to provide enhanced protection against theft and sabotage; the development target considered in this study, instead, suggest that new GEN IV NES need to achieve PR and PP similar or superior to advanced LWR NES.

To verify if a GEN IV NES meets these objectives, the PR&PP methodology could be used.

In this study this methodology is applied to a hypothetical commercial sodium fast reactor based on the layout of the JSFR. The entire possible threat categories are considered: diversion, misuse, breakout, for PR, and theft and sabotage for PP.

To meet the GIF Goal, it is needed to set some limits for the PR and PP. In this study these limits are identified considering the material suitability for explosive device, the IAEA inspection frequency and considering an acceptable reduction of the military budget, however, it must be remembered that there are no standards values and the limits for unacceptable proliferation risk are strongly dependent by the State background. A possibility to set up these limits could be a working team formed both from policy makers and system designers.

To satisfy the development target considered, the methodology is also applied to an ALWR based on the layout of the EPR. In this case both values coming from the methodology evaluation for SFR and LWR are compared one by one.

From these two comparisons, as show in section 1, it is possible to underline some suggestions for designers.

For both the GIF goal and the development target results, in the case of the State as actor, the application of the methodology shows that the measures Proliferation Technical Difficulty and Proliferation Cost are more strongly dependent on the State's background than on the type of NES considered. This is reflected by the fact that the value of these measures for both the LWR and the SFR is the same. That means that designers cannot directly act on this measure to enhance its value, but it is responsibility of the State itself.

Moreover, for the Proliferation Time, the methodology shows that it is strongly connected to the reprocessing activities and depends more on the State's capabilities. There is a small difference between the LWR and SFR cases, but this is not relevant for the methodology and the comparison; it is mainly caused by the different number of fuel assemblies needed to obtain 1 SQ in the two systems.

The measure Fissile Material Type is instead an important point for the SFR. Both the two comparison shows that the presence of blanket in a FBR is the main reason of the low value of Fissile Material Type measure in the evaluation results. Designers can act directly on this measure in different ways. For example, they can increase its value avoiding the use of blanket or change the type of core material, its composition and configuration, but this decision must be done in accordance with the State energy policy. In an indirect way, moreover, to compensate for the Fissile Material Type measure, system designers can act on other measures such as the Detection Probability. This measure is strongly connected with the safeguards approach used, so designers can increase its value adding different safeguards layers, but taking into account that this can affect the measure Detection Resource Efficiency. Even if, in general, for FBR the value of the Fissile Material Type measure is lower, the comparison of the binned measure values for the breakout delayed intended pathway show that even in an ALWR it is possible to reach a low value of the Fissile Material Type measure. This suggests that it is really important to analyze all the possible pathway for each threats.

The detection probability is another measure that could be modified by designers and its value is strongly influenced by the safeguards approach used in the design of the NES. Moreover, the comparison shows that the same configuration could be enough for some scenario but could results insufficient for other ones depending on the pathway strategy. Designers can increase the detection probability measure using, for example, additional seals and neutron detectors, but it must be said that this can influence also the value of the detection efficiency measure in the opposite direction.

Other important points highlighted from the application of the methodology are regarding the methodology itself. In particular, during the discussion phase it is noticed that analyzes measure in the order MT – PT – DP – TD – PC helps the evaluation process.

Moreover, for the Detection Probability measure, it must be important to take into account the time to perform actions if this measure is connect with inspection activities. In case of inspection activities, in fact, there is the possibility to have a high or a very high value of the Detection Probability measure that is connected to the time gap between the inspection and the time in which the proliferation action is performed. This can affect the real value of the Detection Probability measure. However, this last point is not considered in the methodology. Even if in this study the Additional Protocols are considered to be out of the scope, during the evaluation process the importance to introduce additional protocols in the methodology is underlined. It will be a challenge for next studies to find a way in which Additional Protocols could be integrate in the Detection Probability measure.

As last one, the Technical Difficulty measure can be also influenced by the difficulties to assembly a nuclear device, but due to the classified information required in this case, this point is not part of this measure, but it is integrate in the classification of material.

APPENDIX

Conferences

- Symposium on International Safeguards: Linking Strategy, Implementation and People, Application of the GIF PR&PP methodology to a fast reactor system for a diversion scenario (oral presentation), 20 – 24 October 2014, Vienna
- 第 34 回核物質管理学会(INMM)日本支部年次大会, 34th annual meeting of the Institute of Nuclear Materials Management (INMM) – The Japanese chapter, Comparison between penalties coming from malevolent act against nuclear materials and facilities in Japan, US, Italy and France (oral presentation), 24 – 25 October 2013, Tokyo
- PRPP WG Meeting, Application of the PR&PP Methodology to a FR system (oral presentation), 17 – 18 October 2013, Vienna
- IAEA Workshop on the Interface between Safety and Security of Research Reactors, Safety and Security of Research Reactors in Italy: Impact of a Security Event at a Triga Reactor (oral presentation), 7 – 11 October 2013, Vienna
- International Conference on Nuclear Security: Enhancing Global Efforts, Impact of a security event on a TRIGA reactor (poster presentation), 1–5 July 2013, Vienna
- The European Forum to discuss Nuclear Technology Issues, Opportunities & Challenges, AP 1000 severe accident calculation with ASTEC Code (oral presentation), 9 -12 December 2012, Manchester

Publications

- F. Rossi, Application of the GIF PR&PP methodology to a commercial sodium fast reactor for a preliminary analysis of PR scenarios (under review at the ESARDA Bullettin).
- F. Rossi, A. Guglielmelli, F. Rocchi, Impact of a security event at a TRIGA reactor, Annals of Nuclear Energy, Volume 76, February 2015, Pages 125-136.
- F. Rossi, Application of the GIF PR&PP methodology to a fast reactor system for a diversion scenario, Proceedings of the Symposium on International Safeguards: Linking Strategy, Implementation and People, Vienna, 20-24 October 2014, Conference ID: 46090
- F. Rossi, Comparison between penalties coming from malevolent act against nuclear materials and facilities in Japan, US, Italy and France, Proceedings of the 34th annual meeting of the Institute of Nuclear Materials Management
- M. di Giuli, F. Rossi, M. Sumini, F. De Rosa, In Vessel Retention Analysis with Astec code, Proceedings of the European nuclear conference, 2012, Pages 5-5

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