IAEA Nuclear Energy Series

No. NF-0

Nuclear Fuel Cycle Objectives

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IAEA NUCLEAR ENERGY SERIES PUBLICATIONS

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Under the terms of Articles III.A and VIII.C of its Statute, the IAEA is authorized to foster the exchange of scientific and technical information on the peaceful uses of atomic energy. The publications in the **IAEA Nuclear Energy Series** provide information in the areas of nuclear power, nuclear fuel cycle, radioactive waste management and decommissioning, and on general issues that are relevant to all of the above mentioned areas. The structure of the IAEA Nuclear Energy Series comprises three levels: **1 — Basic Principles and Objectives; 2 — Guides; and 3 — Technical Reports.**

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NUCLEAR FUEL CYCLE OBJECTIVES

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

IAEA NUCLEAR ENERGY SERIES No. NF-O

NUCLEAR FUEL CYCLE OBJECTIVES

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FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

The Nuclear Energy Basic Principles is the highest level publication in the IAEA Nuclear Energy Series, and describes the rationale and vision for the peaceful uses of nuclear energy. It presents eight Basic Principles on which nuclear energy systems should be based to fulfil nuclear energy's potential to help meet growing global energy needs.

The Nuclear Energy Series Objectives are the second level publications. They describe what needs to be considered and the specific goals to be achieved at different stages of implementation, all of which are consistent with the Basic Principles. The four Objectives publications include Nuclear General Objectives, Nuclear Power Objectives, Nuclear Fuel Cycle Objectives, and Radioactive Waste Management and Decommissioning Objectives. This publication sets out the objectives that need to be achieved in the area of the nuclear fuel cycle to ensure that the Nuclear Energy Basic Principles are satisfied. Within each of these four Objectives publications, the individual topics that make up each area are addressed. The five topics included in this publication are: resources; fuel engineering and performance; spent fuel management and reprocessing; fuel cycles; and the research reactor nuclear fuel cycle.

The IAEA expresses its gratitude to all the experts who contributed to the drafting of this publication. The IAEA officers responsible for this publication were G.R. Dyck and V. Inozemtsev of the Department of Nuclear Energy.

EDITORIAL NOTE

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1. INTRODUCTION

1.1. BACKGROUND

The IAEA's Nuclear Energy Basic Principles publication [1] presents the basic principles on which nuclear energy systems should be based, to fulfil nuclear energy's potential to help meet growing global energy needs. These principles are intended to provide a broad and holistic approach to the use of nuclear energy and to be equally applicable in all essential elements of the nuclear energy systems, including human, technical, management and economic aspects, with due regard to protection of people and the environment, non-proliferation and security.

The following paragraphs present an overview of the Basic Principles.

Beneficial use

- **Benefits.** The use of nuclear energy should provide benefits that outweigh the associated costs and risks.
- **Transparency.** The use of nuclear energy should be based on open and transparent communication of all its facets, as applicable.

Responsible use

- **Protection of people and the environment.** The use of nuclear energy should be such that people and the environment are protected in compliance with the IAEA safety standards, IAEA Nuclear Security Series guidance, and other nationally and internationally recognized standards.
- **Security.** The use of nuclear energy should take due account of the risk of the malicious use of nuclear and other radioactive material, as well as the act of sabotage against the facilities.
- **Non-proliferation.** The use of nuclear energy should take due account of the risk of the proliferation of nuclear weapons.
- **Long term commitment.** The use of nuclear energy should be based on a long term commitment.

Sustainable use

- **Resource efficiency.** The use of nuclear energy should be efficient in using resources.

- **Continual improvement.** The use of nuclear energy should be such that it pursues advances in technology and engineering to continually improve safety, security, proliferation resistance, protection of the environment and economics.

1.2. PURPOSE AND SCOPE

This publication establishes the criteria that need to be fulfilled in order to satisfy the Nuclear Energy Basic Principles in the area of the nuclear fuel cycle for each of the following topics:

- Resources;
- Fuel engineering and performance;
- Spent fuel management and reprocessing;
- Fuel cycles;
- Research reactors: Nuclear fuel cycle.

These five sets of criteria are known collectively as ‘nuclear fuel cycle objectives’.

1.3. DERIVATION OF THE NUCLEAR FUEL CYCLE OBJECTIVES

The nuclear fuel cycle objectives are drawn from many sources, including the conclusions of major international conferences on different stages and aspects of nuclear fuel cycles, many of which are held in cooperation with the IAEA. Experts from various Member States provided advice to the IAEA through a number of consultants meetings and Technical Working Groups (TWGs), such as the TWGs on Nuclear Fuel Performance and Technology, on Nuclear Fuel Cycle Options and Spent Fuel Management, and on Research Reactors, and through the OECD/NEA–IAEA Uranium Group. The IAEA’s International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) is another important source of guidance.

2. DESCRIPTION OF THE NUCLEAR FUEL CYCLE OBJECTIVES

The objectives for each topic within the area of the nuclear fuel cycle are described in accordance with the sequence in the Basic Principles publication [1]. A number of important considerations should be noted at the onset. While the subject area ‘nuclear fuel cycle’ is organized into five topics, the fuel cycle must be considered on a holistic basis and should not be compartmentalized. Moreover, the nuclear fuel cycle needs to be considered in the context of the reactor and/or system of reactors currently operating or those that might operate in the future. The impact of the fuel cycle needs to be assessed over thousands of years. Hence, the nuclear fuel cycle objectives identified for each of the topics in this publication should be considered together, rather than individually, as well as in the broader context of the objectives for the other three subject areas of the IAEA Nuclear Energy Series: Nuclear General, Nuclear Power, and Radioactive Waste Management.

2.1. OBJECTIVES FOR RESOURCES[1]

Basic Principle: Benefits

Objective: Uranium resources are characterized utilizing best practices that contribute to long term management of the uranium production cycle.

An understanding of the availability of nuclear fuel resources is essential for the planning and development of all aspects of the utilization of the nuclear fuel cycle. This involves the following activities:

- Classifying uranium deposits, based on other factors in the geological setting;

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[1] Natural uranium and thorium are the basic raw materials for fuels for nuclear reactors. The present generation of nuclear reactors uses mostly uranium raw material for fuel fabrication. The statements in this section on uranium raw materials and resources are generally also applicable to thorium. The uranium production cycle covers mining and milling, including mine and mill remediation. It should be noted that, while zirconium is an important material in nuclear fuel, its supply is not considered in the context of this publication.

- Updating databases on world uranium deposits;
- Analysing uranium supply and demand for postulated nuclear power growth scenarios.

For the long term sustainability of the uranium production cycle, it is essential to ensure safe, efficient and sound practices in uranium exploration, mining and milling (including mine and mill remediation and reclamation), and to monitor and regulate these activities. It is also important to limit environmental impact, ensure economic use of natural resources, take into account community expectations and avoid undesirable legacies.

Basic Principle: Transparency

Objective: Information on natural uranium technologies, good practices across the uranium production cycle, and on the associated risks and benefits is distributed and discussed, engaging stakeholders and the general public.

Lessons learned from the history of uranium production show the importance of transparency and public consultation for uranium production. The safe and environmentally responsible operation of mines is essential for public acceptance. The exchange of information, knowledge and experience, as well as peer reviews, provide assurance to the public that the development of the uranium resource is safe, efficient and environmentally sound. However, the exchange of information has to take into account nuclear security requirements for the protection of sensitive information. Transparency of programmes on regulation and monitoring, security, waste disposal and mine and mill remediation will facilitate the acceptance of uranium production facilities in countries considering developing uranium production. Transparency of programmes, ownership and budgets for exploration activities can also have positive effects in earning public trust.

Basic Principle: Protection of People and the Environment

Objective: Effective legislation, regulation, monitoring and technological provisions are developed and implemented for the protection of people and the environment at all stages of the uranium production cycle.

Applying good practices and technologies for current and future uranium production facilities aims to protect workers, the public and the environment, as well as future generations from radiological and non-radiological hazards.

The protection of people and the environment should follow well established practices, including:

- Minimizing and avoiding the generation of legacy hazards, is an important criterion for future developments;
- Taking appropriate precautions for ventilation in mines and mills, for protection against fine dust particles containing uranium, and its daughter products, and radon gas;
- Minimizing waste or tailings volumes and areas of disturbance that arise from the uranium production cycle while mining and mine planning, including remediation.

Basic Principle: Security

Objective: Nuclear security measures are addressed and implemented during all stages of the uranium production cycle.

Uranium is a dual use strategic material. Appropriate measures should be put in place to ensure that nuclear security requirements are met so that uranium cannot be removed for unauthorized purposes. These measures should also cover failure of the prevention measures to detect and respond to criminal or unauthorized acts with nuclear security implications. Mining, processing facilities, transport and shipping must be isolated from uncontrolled public access; this precaution is also valid for waste, residue and tailings management facilities. All such nuclear security measures should be in full compliance with the relevant guidance in the IAEA Nuclear Security Series publications [2, 3], some of which are currently under revision.

Basic Principle: Non-Proliferation

Objective: Non-proliferation requirements and procedures regarding mining and milling operations are implemented as required by the additional protocol in IAEA Member States, where applicable.

Safeguards on uranium mining and milling facilities consist of verifying the activities declared by the State and the absence of undeclared activities through the implementation of an additional protocol (AP) [4]. Detailed nuclear material accountancy at such facilities is not required by an AP nor by a comprehensive safeguards agreement [5], unless the source material has reached “a composition and purity suitable for fuel fabrication or for being isotopically enriched”[2]. Allowing safeguards verification under an AP at mining and milling facilities would help to ensure that all mining and milling operations comply with IAEA safeguards requirements.

Basic Principle: Long Term Commitment

Objective: Evaluation of the supply of uranium includes assessments of long term supply and availability.

Nuclear power plants are capital intensive, with relatively low fuel costs. Plants are amortized over a long time frame to recover costs, and so must have a long term assurance of fuel supply. However, uranium mining is driven by supply and demand, and uranium mines and processing plants take a long time to put in place. Hence, a long term forecast of demand and strategic planning for uranium production or supply should be prepared to ensure its continuous availability. Mine and mill remediation also represent long term commitments.

Basic Principle: Resource Efficiency

Objective: Uranium recovery processes continue to develop in ways that are increasingly efficient, effective and economic.

Uranium recovery involves mining and milling. It is important to implement mining and milling techniques that recover as much of the uranium from the deposit as is economically viable. The cost of uranium production will depend on the grade, nature and location of the deposit. Hence, good practices in resource definition and in planning and operation of mines and mills are essential to maximize the production efficiency of resources. R&D should be undertaken to develop economic, innovative processes for recovering uranium.

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[2] Source material: “The term “source material” means uranium containing the mixture of isotopes occurring in nature... in the form of metal, alloy, chemical compound, or concentrate” (Article XX.3 of the IAEA Statute). Source material, as defined by the IAEA Statute, is nuclear material, although it may not have reached the purity and composition that triggers implementation of the whole range of safeguards measures, in particular nuclear material accountancy.

Basic Principle: Continual Improvement

Objective: The uranium production industry continually benefits from and incorporates changes through lessons learned and information exchange.

The effectiveness of processing and monitoring systems should be reviewed periodically with respect to safety and security, environment and health. Continuous improvement will be facilitated by sharing good practices, experience and information on technical, institutional and regulatory improvements in mining and milling technology.

2.2. OBJECTIVES FOR FUEL ENGINEERING AND PERFORMANCE

Basic Principle: Benefits

Objective: Fuel materials and designs are developed, and fabrication technologies are implemented to provide nuclear energy with benefits that outweigh the associated costs and risks, to achieve reliable and economical power generation, improved safety and reduced environmental impact.

Customers require nuclear power to be economically attractive. For the area of fuel engineering and performance, the challenges to the economics of nuclear power come from fuel reliability and performance. Poor fuel reliability can lead to fuel failures, increased discharges to the environment or waste generation, with high associated costs for remedial actions. Poor performance of fuel can lead to uncompetitive operation of a nuclear power plant, especially if flexible operational conditions have to be restricted, or fuel discharged before its optimal burnup or in-core residence time has been reached. A prerequisite for high performance and reliable fuel is the availability of radiation resistant materials able to withstand aggressive corrosive and high temperature operational conditions. Such fuel, when spent, should also keep its integrity during a planned period of storage and, depending on the fuel cycle selected, be able to be reprocessed. Since the improvement and development of nuclear fuels are time consuming and expensive processes, operators must also optimize their operational practices to match the properties of the fuel.

Basic Principle: Transparency

Objective: Information on fuel design and engineering is made available to stakeholders while respecting the proprietary nature of commercial data.

Operational environments and fuel behaviour, including fuel failures in different irradiation conditions, should be adequately documented and reported to ensure feedback that helps improve fuel performance. Open discussion of theoretical models and experimental methodologies, including advances in post-irradiation examination and poolside inspection techniques and capabilities, as well as in fuel design and manufacturing technologies, would bring about mutual benefits for the nuclear R&D community. Open exchange of information would stimulate interdisciplinary discussion with beneficial, synergistic effects.

This exchange of information should be balanced against the need to protect commercial interests. Confidentiality measures must be ‘reasonable under the circumstances’ and trade secret holders should provide users with remedies and necessary knowledge to ensure best practices, though under no circumstances should the nuclear security measures for the protection of sensitive information be compromised. Exchange of information has to take proprietary issues into account. Availability of information about performance and reliability of fuel is also important for public acceptance of nuclear power.

Basic Principle: Protection of People and the Environment

Objective: All stages of fuel design, manufacturing, handling and operation include provisions for the protection of people and the environment.

Radioactive material in nuclear fuel can present a significant hazard for people and the environment, and should be treated in accordance with IAEA safety standards [6, 7], IAEA Nuclear Security Series guidance [2, 3, 8], and other international and national relevant standards. Other materials used in fuel fabrication may also pose a threat to people and the environment. Appropriate technological and organizational measures should be taken to control radiation risks, hazardous materials and radioactive waste on the basis of the ‘optimization principle’ (also known as the ALARA[3] principle). Consideration should be given

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[3] ALARA is an acronym for an important principle in radiation exposure and other occupational health risks. It stands for ‘as low as reasonably achievable’. The aim is to minimize the risk of radioactive exposure or other hazards while keeping in mind that some exposure may be acceptable in order to further the task at hand.

to the implementation of remote and automated fuel fabrication and handling processes.

The fuel and its cladding provide an important barrier for the protection of people and the environment by containing harmful radioactive material. Fuel integrity should be assured in normal transient operational conditions and in most accident conditions in the reactor, as well as at later stages of spent fuel handling, transport and storage. Coolant chemistry and operational practice should be designed to avoid adverse effects on fuel materials and to reduce hazards arising from the transport of activity in the coolant. Where appropriate, consideration should also be given to fuel performance issues associated with reprocessing and transmutation.

Basic Principle: Security

Objective: Nuclear security measures are implemented at all stages of fuel design, manufacturing, handling, operation and decommissioning.

Some types of power reactors (e.g. fast reactors) have fresh fuel that can be enriched substantially or may contain plutonium. Also, irradiated fuel poses a direct threat of misuse due to its very high radioactivity. Appropriate nuclear security measures should be undertaken for both fresh and irradiated nuclear fuel in accordance with the guidance in IAEA Nuclear Security Series publications [2, 3, 8].

Basic Principle: Non-Proliferation

Objective: Fuel design features and production technologies are developed and implemented that strengthen their non-proliferation characteristics and facilitate IAEA safeguards.

All operations with nuclear material should be conducted in accordance with international safeguards obligations. Fuel engineering should consider proliferation resistant technologies of fuel fabrication and utilization. Use of irradiated or denaturated fuel materials and remote fuel fabrication are examples of fuel design features and production technologies which could potentially provide non-proliferation benefits.

Basic Principle: Long Term Commitment

Objective: Adequate R&D tools and educational and training opportunities that facilitate the availability of fuel options for sustainability of nuclear power are developed and implemented on a long term basis.

Fuel options for optimization of future fuel cycles should comply with non-proliferation and safeguards principles and should be based particularly on resource sustainability, cost efficiency, sound scientific and technological foundations and environmental protection. Test irradiation facilities and instrumentation for direct measurements of fuel properties and radiation behaviour should be used, as well as computer codes and theoretical models for the simulation of radiation effects. The correct use of these tools and the interpretation of the results require that an appropriate research and educational infrastructure is in place to establish and facilitate access to long term skills and capabilities. These capabilities should include a fundamental understanding of radiation effects, degradation of fuel and in-core structural materials, effects and processes in advanced coolants, and challenging irradiation environments.

Basic Principle: Resource Efficiency

Objective: New fuels, designs and fabrication technologies are developed for continued effective use of nuclear fissile and fertile materials.

Ensuring fuel availability is an obvious prerequisite of nuclear power sustainability. The existing technologies and operational practice have been developed during a period of relatively high availability of raw materials for fuel production, but the long term vision and market tendencies require less wasteful and more resource efficient fuel technologies and cycles. Such options, based on the principle ‘reduce, reuse and recycle’, exist and are being implemented partly through the use of reprocessed uranium (RepU) and plutonium in mixed oxide (MOX) reactor fuel. Other options include fuel breeding using fertile material (uranium-238 and thorium-232) and utilization of minor actinides (neptunium (Np), americium (Am) and curium (Cm)).

Basic Principle: Continual Improvement

Objective: Continual improvement of fuel safety and efficiency is ensured through implementation of adequate management and quality systems.

Sustained improvement is driven by safety, security and economic considerations. The necessary organizational and technical prerequisites are formalized in management and quality standards, human performance and quality assurance/quality control (QA/QC) requirements. The benefits of continual advancements may be realized in many technical areas, including:

- Optimization of core designs;
- Improvement of core materials for better fuel performance;
- Development and validation of physical models and computational codes for evaluation and prediction of fuel behaviour;
- Understanding of fuel failure root causes and implementation of prevention and remediation measures;
- Improvement of coolant chemistry and technology, particularly with respect to corrosion and hydride resistance of cladding alloys.

Nuclear fuel industries should progressively incorporate advanced concepts, ideas, technologies, materials, methodologies, and management practices from the nuclear community and other sectors of the economy.

2.3. OBJECTIVES FOR SPENT FUEL MANAGEMENT AND REPROCESSING[4]

Basic Principle: Benefits

Objective: Safe, secure and robust spent fuel storage or reprocessing systems are developed and implemented, that minimize fuel degradation while preserving future fuel cycle options, and the benefits of reprocessing are assessed to ultimately outweigh the associated risks and costs.

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[4] Note that, for the purpose of this publication, the scope of this area includes spent fuel storage and reprocessing. (‘Irradiated’ fuel may be a more appropriate term than ‘spent’, since the fuel contains residual fissile and fertile material which could be recycled.) Conventional reprocessing (the current PUREX technology) is addressed in this subject area, while advanced recycling technologies are covered in Section 2.4.

Delays in the ultimate disposition of spent fuel, whether direct disposal or reprocessing, may result in spent fuel being stored for a hundred years or longer. In order to store a variety of spent fuels safely and without degradation, R&D should be conducted to understand fuel properties and behaviour in wet and dry storage conditions. The condition of the fuel at the end of the storage or reprocessing period would be the starting point for the permanent repository. Ensuring excellent mechanical integrity of the spent fuel during storage would benefit both transportation and repository performance. Spent fuel storage systems should be designed to be safe; in particular, they should be robust and tolerant to external and internal hazards, as well as to failures of cooling or changes in chemistry. Regional or multilateral spent fuel storage facilities should also be considered, taking into account applicable laws and regulations for such storage [9].

Reprocessing and recycling used nuclear fuel improves fuel utilization by extracting additional energy from the recycled uranium and plutonium. Recycling into existing thermal reactors provides a modest improvement in fuel utilization. Recycling the plutonium into future fast reactors or high conversion thermal reactors could achieve a significant improvement in resource utilization. Reprocessing also reduces the radiological hazard from spent fuel, resulting in an improvement in repository performance in scenarios in which the repository may be disturbed. Reprocessing plants need to operate safely with minimum environmental impact and at a high level of safety [10].

Basic Principle: Transparency

Objective: Open communication regarding the operation of spent fuel storage and reprocessing facilities, and provision of necessary information to stakeholders and the public is implemented and maintained.

Past experience shows the importance of factual, timely and transparent communication with the public, regulators and other stakeholders with respect to fuel cycle facilities, particularly for unplanned events. Such events need to be put into a context that can be understood by the public. Information on the benefits and costs of the total fuel cycle (whether direct disposal, conventional reprocessing or advanced fuel recycling) needs to be open and balanced, to facilitate informed decision making.

Transparency is particularly important for the facilities associated with reprocessing or storage, to provide assurance in the areas of safety, environment, health and the security of sensitive nuclear material. However, the exchange of information has to take into account the nuclear security requirements for the protection of sensitive information. In addition, the exchange of information on technologies that could be used in the proliferation of nuclear weapons needs to be strictly controlled.

Basic Principle: Protection of People and the Environment

Objective: Radiological emissions from spent fuel storage facilities and reprocessing plants are minimized, which should minimize the dose to workers and the public consistent with the 'optimization principle' (also known as the ALARA principle), and protect the environment.

The handling, transportation, storage and reprocessing of spent nuclear fuel must be done safely, with minimal environmental impact in the short and long term, and within regulatory limits. A high level of safety, security and environmental protection is necessary. The capture and immobilization of problematic radionuclides is preferred over their release and environmental dilution. The release of hazardous chemicals from facilities associated with reprocessing should be minimized. The design of spent fuel storage and reprocessing facilities should facilitate operation over the entire period of operation of the facilities (which for spent fuel storage facilities could extend to a hundred years or longer), to ensure the ongoing long term protection of people and the environment. This should also include the prevention of sabotage against such facilities.

The protection of people and the environment is a cornerstone of sustainable development, as articulated by the 'Brundtland Report' of the United Nations World Commission on Environment and Development [11], reiterated during the first United Nations Conference on Environment and Development (the UNCED 'Earth Summit'), held in Rio de Janeiro in 1992, and adopted by the Kyoto Protocol in 1997, an international agreement linked to the United Nations Framework Convention on Climate Change, which commits its Parties by setting internationally binding emission reduction targets. One of the key elements of sustainability is to minimize the production of non-degradable waste. This element of sustainability is a key factor in evaluating spent fuel management, reprocessing strategies and technologies.

Basic Principle: Security

Objective: Appropriate nuclear security measures are applied for spent fuel storage facilities and reprocessing plants.

The presence of nuclear material and highly active radioactive material in fuel cycle facilities and processes associated with irradiated fuel necessitates the highest level of nuclear security measures in the design and operation of such facilities [2, 3]. In addition, nuclear security measures may need to be strengthened during the transport of such material.

Basic Principle: Non-Proliferation

Objective: Strict compliance with non-proliferation and safeguards system requirements and policies in spent fuel storage systems and reprocessing facilities.

The ability to separate out plutonium in fuel cycle facilities and processes associated with reprocessing presents a significant proliferation risk which must be mitigated through effective safeguards systems. Any separated plutonium material must also be carefully safeguarded. Spent fuel storage facilities must maintain a high standard of proliferation resistance and meet IAEA safeguards measures [12].

Basic Principle: Long Term Commitment

Objective: The long term management of spent fuel storage and reprocessing facilities is ensured by establishing appropriate institutional, funding and legal structures.

The responsibility for managing spent fuel will pass to generations that may not necessarily have directly benefited from the use of those facilities. Moreover, institutions and organizations change over time, and the organization that produced the spent fuel may not be present in the long term to assume responsibility for those liabilities. The plants themselves that produced the spent fuel may be shut down or decommissioned. Safety and security should be ensured for the long term, in particular with adequate resources and funding. While the long time frame for this responsibility is in one sense a burden, it may also be an opportunity to benefit from new technologies that may be developed in the future.

Basic Principle: Resource Efficiency

Objective: Safe, efficient, cost effective spent fuel storage systems are implemented that provide for the option of reprocessing or recycling to extend fuel resources.

Spent nuclear fuel can be considered either as a waste liability or as a future fuel resource. The view taken depends on many factors, such as the amount of residual fissile material in the spent fuel; the complexity, efficiency and expense of recycling that material into new fuel compared to fresh fuel; the reactor system in which that fuel is used; the management of the wastes from the recycling process; the composition of the used recycled fuel and its disposition; and the proliferation aspects of the entire system. While the reprocessing and recycling of plutonium and uranium in existing thermal reactors achieves a modest extension of uranium resources, the use of plutonium (and possibly minor actinides) in future fast reactors or in high conversion thermal reactors has the potential of achieving a significant extension of fuel resources, while improving the long term environmental impact of the fuel cycle. Providing for integrity and safe long term management of spent fuel from current reactors thus preserves the option of recycling that material, using either existing reprocessing technology or future more advanced fuel cycle options.

Basic Principle: Continual Improvement

Objective: R&D and technology development, as well as shared experience from operational lessons learned in spent fuel management and reprocessing, are supported.

In order to safely store spent fuel for very long periods without degradation, the results from R&D programmes and experience from operating facilities on the behaviour of spent fuel under storage conditions should be shared. As advanced fuels and fuel cycles are considered, their impact on spent fuel management should be addressed. Similarly, lessons learned from the operation of reprocessing facilities should be captured and used in the upgrade of existing facilities, and in the design of new recycling processes and facilities. Information can be shared through databases, workshops and conferences.

2.4. OBJECTIVES FOR FUEL CYCLES

Basic Principle: Benefits

Objective: Fuel cycle technologies are developed to provide the benefits of improved performance in the areas of safety, proliferation resistance, sustainability and economics, which will ultimately outweigh the associated risks and costs.

The long term availability of nuclear resources and the management of spent fuel and radioactive waste are critically important factors in the long term viability and acceptability of nuclear power. Additionally, the fuel cycle must contribute to the safe, secure and economical production of power, and address concerns about security and non-proliferation (referring to both fuel cycle facilities and the use of advanced fuels in reactor). One example of an advanced fuel cycle with the potential of contributing to these objectives is a closed fuel cycle involving multiple recycling of used fuel material in a fast reactor. The sustainability of the nuclear fuel cycle can clearly be improved by designing fuel cycles that reduce our use of natural resources and minimize the impact on the environment.

The impact and benefits of fuel cycle facilities must be assessed over the entire fuel cycle (front end, fuel fabrication, in-reactor use, spent fuel storage, recycling (if done), waste management and disposal), over long time frames, and address several aspects. These include economics, fuel resource availability, environmental impact, safety, security, and proliferation resistance for normal operation and accident conditions for the reactor and the fuel cycle facilities.

Scenarios should be studied for a variety of reactor types and systems of reactors, including transition scenarios from open to closed fuel cycles. Regional or multilateral fuel cycle facilities may also be considered.

Basic Principle: Transparency

Objective: Decision making on the implementation of fuel cycles is based on open communication and facilitated by providing sufficient and accurate information on a range of fuel cycle options to a variety of stakeholders.

Transparency is particularly important in the nuclear fuel cycle to ensure that the public, decision makers and other stakeholders have all the information needed to make informed decisions that will have an impact over a very long time frame. Transparency is also necessary to gain the collective, local and international trust and confidence that nuclear fuel cycle material and facilities will not be used for harmful intent and that they are environmentally acceptable. However, the exchange of information has to take into account the nuclear security requirements for the protection of sensitive information. Given the expense and complexity of fuel cycle research and the need for specialized facilities, the sharing of R&D results in the technical community is encouraged.

Basic Principle: Protection of People and the Environment

Objective: Fuel cycles are developed that protect people and the environment by minimizing the radiological impact over the entire fuel cycle.

When assessing the impact of the fuel cycle on people and the environment, the entire fuel cycle must be considered, from the front end, through in-reactor performance, spent fuel or isotope storage, fuel recycling and fabrication, to disposal of spent fuel and nuclear waste. Minor actinide destruction in fast reactors, in systems of fast and thermal reactors, or in accelerator driven systems (ADSs) will reduce the radiotoxicity of the nuclear fuel waste.

The use of fuel cycles, from design through disposal, must meet the IAEA's safety standards and nuclear security guidance relating to the protection of people and the environment [10, 13, 14], and their appropriate implementation as national laws and regulations.

Basic Principle: Security

Objective: Nuclear security measures are considered during the design and implemented during the operation of nuclear fuel cycle facilities.

Fuel cycles will need to ensure that the nuclear security requirements are implemented for nuclear and other radioactive material, associated facilities and activities at all stages of the fuel cycle, from separation technology to fuel fabrication, fresh and used fuel storage, in-reactor use, radioactive waste management and spent fuel management. Nuclear security measures, based on an appropriate legislative and regulatory framework and including guidance in IAEA Nuclear Security Series publications [2, 3, 8], must be considered in the design and operation of all facets of the fuel cycle.

Basic Principle: Non-Proliferation

Objective: Technologies and design features which strengthen proliferation resistance characteristics of nuclear systems are developed, which also facilitate IAEA safeguards.

All operations should have the provisions for proper nuclear material accounting and should be made in accordance with international safeguard obligations. The design of nuclear fuel cycle facilities should include from the beginning non-proliferation and safeguards objectives. In general, emphasis should be on the development of fuel cycles having a high degree of inherent proliferation resistance and for which safeguards can be readily applied. The use of separated plutonium should be avoided. Advanced nuclear fuel cycles could reduce or eliminate the proliferation risk of a growing stockpile of plutonium in the spent fuel.

Basic Principle: Long Term Commitment

Objective: Adequate R&D and industrial infrastructure, as well as an educational and institutional framework, and strategies for long term management and stewardship of the nuclear fuel cycle are established.

Nuclear power in general and the fuel cycle in particular will require the long term availability of qualified and trained people, R&D facilities (including both fuel cycle and irradiation facilities), complex industrial infrastructure and funding. For instance, the use of partitioning and transmutation to achieve a significant reduction in the long term radiotoxicity of high level waste will require a commitment to a reactor and fuel cycle strategy for centuries. This also implies a commitment to knowledge management and continuous learning, and the need to establish processes and systems for these objectives within nuclear institutions, countries and globally.

With regard to nuclear security, the long term commitment should take into account the sustainability of nuclear security measures during the life cycle of all nuclear fuel cycle facilities.

Basic Principle: Resource Efficiency

Objective: Fuel cycles and strategies are developed that ensure availability of economical fuel resources for centuries.

A key objective of nuclear fuel cycles is to maximize the use of both fissile and fertile resources, including thorium. Economic resource availability is essential to ensure the long term availability (over centuries) and viability of nuclear power. Fuel cycles are inextricably tied to innovative reactor designs, both thermal and fast, and reactor systems.

While the current, once-through fuel cycle uses approximately 0.5% of the uranium resource required in making the fuel (including losses in the enrichment process), a closed fast reactor fuel cycle could provide an improvement of a factor of 100, transforming 100 years of energy reserves into 10 000 years of energy reserves at the same level of energy production. The use of thorium fuel in a resource efficient thermal reactor is another example of a fuel cycle having long term resource sustainability. Synergistic systems of different reactor types should be considered in optimizing fuel cycles.

Basic Principle: Continual Improvement

Objective: Nuclear fuel cycle systems, processes and components are designed to be able to respond to changes in external factors, societal values and advances in technology over a long time frame, and to ensure improved safety and economic strategies.

Decisions on the development and implementation of fuel cycles take into account projections of external factors (such as the availability and cost of various energy sources and societal values), as well as the behaviour of nuclear material under demanding conditions (both in reactor and in storage and disposal) over periods ranging from decades to millennia. These decisions are made more difficult by the complexity and expense of advanced fuel cycle technology, where we are sometimes working at the boundaries of our understanding and knowledge, and where decisions are often made with incomplete knowledge. Yet the implications of fuel cycle decisions impact future generations for hundreds of thousands of years. Therefore, in order to be able to respond to changes in societal values or advances in technology, fuel cycle systems, processes and components should benefit from efficiency and safety improvements, be designed to be flexible and replaceable to the extent possible, either at the end of their lifetime or when superseded by better technology. There is also clearly a need to learn from past experience in the application of advanced reactors and fuel cycles.

Continuous improvement will be facilitated by sharing good practices, experience and information on technical, institutional and regulatory improvements and innovations in the fuel cycle. International cooperation and collaboration provide efficient means for this purpose.

2.5. OBJECTIVES FOR RESEARCH REACTORS: NUCLEAR FUEL CYCLE

The overarching nuclear fuel cycle objectives will, in general, also apply to research reactors. Those listed below have been developed to highlight specific differences or unique requirements relevant to the global research reactor community.

Basic Principle: Benefits

Objective: Fuel materials, designs and fuel cycle technologies are developed and implemented to achieve reliable and economical reactor operation, and safe, environmentally benign and proliferation resistant fuel cycles.

A prerequisite for high performance reliable fuel is the availability of radiation resistant material able to withstand the unique operational conditions relevant to the different reactor designs in the very diverse research reactor community.

In order to store a variety of spent fuels safely and without degradation, research needs to be carried out to understand fuel properties and behaviour in wet and dry storage conditions. This should include failed and degraded fuel, as well as high burnup fuel, and should also provide flexibility to accommodate innovative fuel designs in the future. Spent fuel storage systems should be designed to be robust and tolerant to failures of cooling or changes in chemistry. Since research reactors may be the only nuclear facility in a State — at least initially — regional or multilateral spent fuel repatriation, reprocessing, and/or storage services and facilities should be considered.

Research reactors are often critical contributors to nuclear R&D efforts through the provision of testing and demonstration facilities and services. In addition to supporting the nuclear fuel cycle of energy producing reactors, research reactor tests and demonstrations are also critical to the development of research reactor fuel cycles.

Basic Principle: Transparency

Objective: Effective communication and shared technical information, to the extent possible, with all stakeholders to ensure transparency, confidence and trust.

While some fuel cycle details are strictly confidential, open and transparent communication is critical to effective facility operation and regulation, taking into account the required nuclear security measures for the protection of sensitive information. Communication between stakeholders must be a conversation — not simply one party conveying information to others. Information that is presented must be clear and factual, and all parties should have the opportunity to comment on information and to benefit from it.

Basic Principle: Protection of People and the Environment

Objective: Protection for people and the environment at all stages of the fuel cycle is taken into consideration during research and implementation. Advanced fuel cycles that protect people and the environment continue to be developed.

Because nuclear fuel contains radioactive material throughout its lifetime, it can present a significant hazard for people and the environment and should be treated in accordance with IAEA safety standards [10, 15] and other relevant international and national standards at all stages of fuel design, manufacturing, operation, handling, transport, storage and reprocessing, where applicable. Spent research reactor fuel can be considered either as a waste liability or as a future fuel resource, depending on comprehensive analysis of all technical, economic, safety and non-proliferation aspects of reprocessing. Integrity of fuel should be ensured in normal and transient operational conditions in the reactor, as well as at later stages of spent fuel handling, transport and storage. Minimization of radiological emission from spent fuel storage and reprocessing plants and radiation doses to workers should be consistent with the optimization (ALARA) principle.

The handling, transportation and storage of spent research reactor fuel and reprocessing waste must be done safely and securely, with minimum environmental impact in the short and long term. A high level of safety and environmental protection is necessary. Emissions and doses from the operation of all fuel cycle facilities associated with reprocessing and fuel storage must be as low as reasonably achievable and within regulatory limits. The capture and immobilization of problematic radionuclides is preferred over their release and environmental dilution. The release of hazardous chemicals from facilities associated with reprocessing should be minimized. The design of spent fuel storage and reprocessing facilities should take into account the entire period of operation of the facilities (which for spent fuel and reprocessing waste storage facilities could extend to a hundred years or longer), to ensure the ongoing long term protection of people and the environment.

Implementation of nuclear security measures against unauthorized removal of nuclear and other radioactive material in use and storage, as well as the measures against sabotage of nuclear facilities and nuclear material in use and storage, are necessary for ensuring the protection of people and the environment throughout the lifetime of the facilities.

Basic Principle: Security

Objective: Appropriate nuclear security measures are in place at research reactor facilities.

New research reactors should incorporate features into their design to facilitate physical security, taking into account their location as well as staff and user access permissions. Older reactors may need to undergo renovations to ensure the security of materials and facilities.

Ensuring the nuclear security of material, associated facilities and activities is essential. Suitable security plans should also take into account storage of fresh and spent fuels on-site, during transport to and from the research reactor site, as well as potential sabotage to the facilities and activities.

Basic Principle: Non-Proliferation

Objective: Technological solutions are developed, and policy actions supported, that minimize the use of high enriched uranium (HEU) fuel and targets in research reactors.

For a variety of reasons, numerous research reactors still operate with HEU fuel, or use HEU targets to produce medical isotopes. In some cases, using HEU fuel and targets was the best way to achieve reliable performance or produce the most economically viable products. However, to support the objectives of security and non-proliferation, research reactors should be used to develop fuels and targets that minimize or eliminate HEU. Fuels that rely on low enriched uranium (LEU) should be developed and qualified for research reactors.

Basic Principle: Long Term Commitment

Objective: Fuel options, adequate R&D programmes, and training opportunities are available to facilitate the sustainability of national nuclear programmes, as well as preparation for the long term stewardship of spent fuel and repatriation.

Research reactor facilities should have access to appropriate fuel options to ensure the long term productivity, safety and security of the reactor during its operational life. These fuel options should be based on resource sustainability, cost efficiency and sound scientific and technological foundations. In order to have a sustainable research programme, a State must have human capital capable of carrying out that programme. Research reactors can provide numerous opportunities for training and employing researchers and operators, and for capturing nuclear knowledge from one generation for use and further development by the next.

For Member States with significant nuclear infrastructure, plans for research reactors can be integrated into plans for other nuclear facilities. In all circumstances, the sustainability of nuclear security measures throughout the life of the research reactor has to be taken into account during the design and operation of the facility.

An important aspect of long term commitment is planned, sustained funding for research reactor fuel cycle facilities. Unlike nuclear power reactors, many research reactors do not have a built-in means of generating their own revenue. Whether this funding comes from a Member State government, from private funders, or a mix of both, ensuring that research reactor facilities have the financial means to operate for their entire lives — and for safe waste disposal and decommissioning — is absolutely key.

Basic Principle: Resource Efficiency

Objective: New research reactor fuels, fabrication technologies and designs are developed for effective use of nuclear material, as are fuel cycles and strategies that ensure availability of resources over the long term.

Research reactors should strive for the most efficient operation possible. To that end, new fuels that allow for increased safety and operation time and capacity should be developed. These fuels should also be designed with reprocessing and disposal options in mind.

Basic Principle: Continual Improvement

Objective: Management systems and quality research reactor systems are oriented toward continual improvement and reliability, while accommodating the diversity of the global research reactor community. Systems, processes and components are designed with the flexibility required to respond to changes and advances over time.

For new research reactors, a large part of the planning stage should be focused on making the reactor flexible in how it can be utilized. This means taking into account not only current capabilities in the research reactor field, but anticipating advances as well. However, to take advantage of this flexibility and push for continual improvement, reactor stakeholders should plan regular operational and utilization evaluations that look for ways to improve both aspects of the reactor. New fuel advances, new operational practices, and new applications and utilization should be shared amongst research reactor stakeholders to ensure that improvements at one research reactor can help improve the research reactor community as a whole.

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Annex I

SUMMARY TABLE OF OBJECTIVES FOR EACH NUCLEAR ENERGY BASIC PRINCIPLE (BP)

BP	Resources	Fuel engineering and performance	Spent fuel management and reprocessing	Fuel cycles	Research reactors: Nuclear fuel cycle
1-BENEFITS	Uranium resources are characterized utilizing best practices that contribute to the long term management of the uranium production cycle.	Fuel material and designs are developed, and fabrication technologies are implemented to provide nuclear energy with benefits that outweigh the associated costs and risks, to achieve reliable and economic power generation, improved safety and reduced environmental impact.	Safe, secure and robust spent fuel storage or reprocessing systems are developed and implemented that minimize fuel degradation while preserving future fuel cycle options, and benefits of reprocessing are assessed to ultimately outweigh the associated risks and costs.	Fuel cycle technologies are developed to provide the benefits of improved performance in the areas of safety, proliferation resistance, sustainability and economics, which will ultimately outweigh the associated risks and costs.	Fuel material, designs and fuel cycle technologies are developed and implemented to achieve reliable and economic reactor operation, and safe, environmentally benign and proliferation resistant fuel cycles.
2-TRANSPARENCY	Information on natural uranium technologies, good practices across the uranium production cycle, and on the associated risks and benefits is distributed and discussed, engaging stakeholders and the general public.	Information on fuel design and engineering is made available to stakeholders while respecting the proprietary nature of commercial data.	Open communication on the operation of spent fuel storage and reprocessing facilities, and the provision of necessary information to stakeholders and the public, is implemented and maintained.	Decision making on the implementation of fuel cycles is based on open communication and facilitated by providing sufficient and accurate information on a range of fuel cycle options to a variety of stakeholders.	Maintain effective communication and share technical information, to the extent possible, with all stakeholders to ensure transparency, confidence and trust.

BP	Resources	Fuel engineering and performance	Spent fuel management and reprocessing	Fuel cycles	Research reactors: Nuclear fuel cycle
3-PROTECTION OF PEOPLE AND THE ENVIRONMENT	Effective legislation, regulation, monitoring and technological provisions are developed and implemented for the protection of people and the environment at all stages of the uranium production cycle.	All stages of fuel design, manufacturing, handling and operation include provisions for the protection of people and the environment.	Radiological emissions from spent fuel storage facilities and reprocessing plants are minimized, which should minimize the dose to workers and the public consistent with the optimization (the ALARA) principle, and protect the environment.	Fuel cycles are developed that protect people and the environment by minimizing the radiological impact over the entire fuel cycle.	Protection for people and the environment at all stages of the fuel cycle is taken into consideration during research and implementation. Advanced fuel cycles that protect people and the environment continue to be developed.
4-SECURITY	Nuclear security measures are addressed and implemented during all stages of the uranium production cycle.	Nuclear security measures are implemented at all stages of fuel design, manufacturing, handling, operation and decommissioning.	Appropriate nuclear security measures are applied for spent fuel storage facilities and reprocessing plants.	Nuclear security measures are considered during the design and implemented during operation of nuclear fuel cycle facilities.	Appropriate nuclear security measures are in place at research reactor facilities.
5-NON-PROLIFERATION	Non-proliferation requirements and procedures regarding mining and milling operations are implemented as required by the Additional Protocol, in the IAEA Member States where it is applicable.	Fuel design features and production technologies are developed and implemented that strengthen their non-proliferation characteristics and facilitate IAEA safeguards.	Strict compliance is required with non-proliferation and safeguards systems requirements and policies in spent fuel storage systems and reprocessing facilities.	Technologies and design features which strengthen proliferation resistance characteristics of nuclear systems are developed, which also facilitate IAEA safeguards.	Technological solutions are developed, and policy actions supported, that minimize the use of HEU fuel and targets in research reactors.

BP	Resources	Fuel engineering and performance	Spent fuel management and reprocessing	Fuel cycles	Research reactors: Nuclear fuel cycle
6-LONG TERM COMMITMENT	Evaluation of the supply of uranium includes assessments of long term supply and availability.	Adequate R&D tools and educational and training opportunities that facilitate the availability of fuel options for sustainability of nuclear power are developed and implemented on a long term basis.	The long term management of spent fuel storage and reprocessing facilities is ensured by establishing appropriate institutional, funding and legal structures.	Adequate R&D and industrial infrastructure, as well as an educational and institutional framework, and strategies for long term management and stewardship of the nuclear fuel cycle are established.	Fuel options, adequate R&D programmes, and training opportunities are available to facilitate sustainability of national nuclear programmes, as well as preparation for long term stewardship of spent fuel and repatriation.
7-RESOURCE EFFICIENCY	Uranium recovery processes continue to develop in ways that are increasingly efficient, effective and economic.	New fuels, designs and fabrication technologies are developed for the continued effective use of nuclear fissile and fertile material.	Safe, efficient and cost effective spent fuel storage systems are implemented that provide for the option of reprocessing or recycling, to extend fuel resources.	Fuel cycles and strategies are developed that ensure availability of economic fuel resources for centuries.	New research reactor fuels, fabrication technologies and designs are developed for effective use of nuclear material, as are fuel cycles and strategies that ensure availability of resources for the long term.

BP	Resources	Fuel engineering and performance	Spent fuel management and reprocessing	Fuel cycles	Research reactors: Nuclear fuel cycle
8-CONTINUAL IMPROVEMENT	The uranium production industry benefits continually from, and incorporates changes through, lessons learned and information exchange.	Continual improvement of fuel safety and efficiency is ensured through the implementation of suitable management and quality systems.	R&D and technology development, as well as shared experience from operational lessons learned in spent fuel management and reprocessing, are supported.	Nuclear fuel cycle systems, processes and components are designed to be able to respond to changes in external factors, societal values and advances in technology over a long time frame, and to ensure improved safety and economic strategies.	Management systems and quality research reactor systems are oriented toward continual improvement and reliability, while accommodating the diversity of the global research reactor community. Systems, processes and components are designed with the flexibility required to respond to changes and advances over time.

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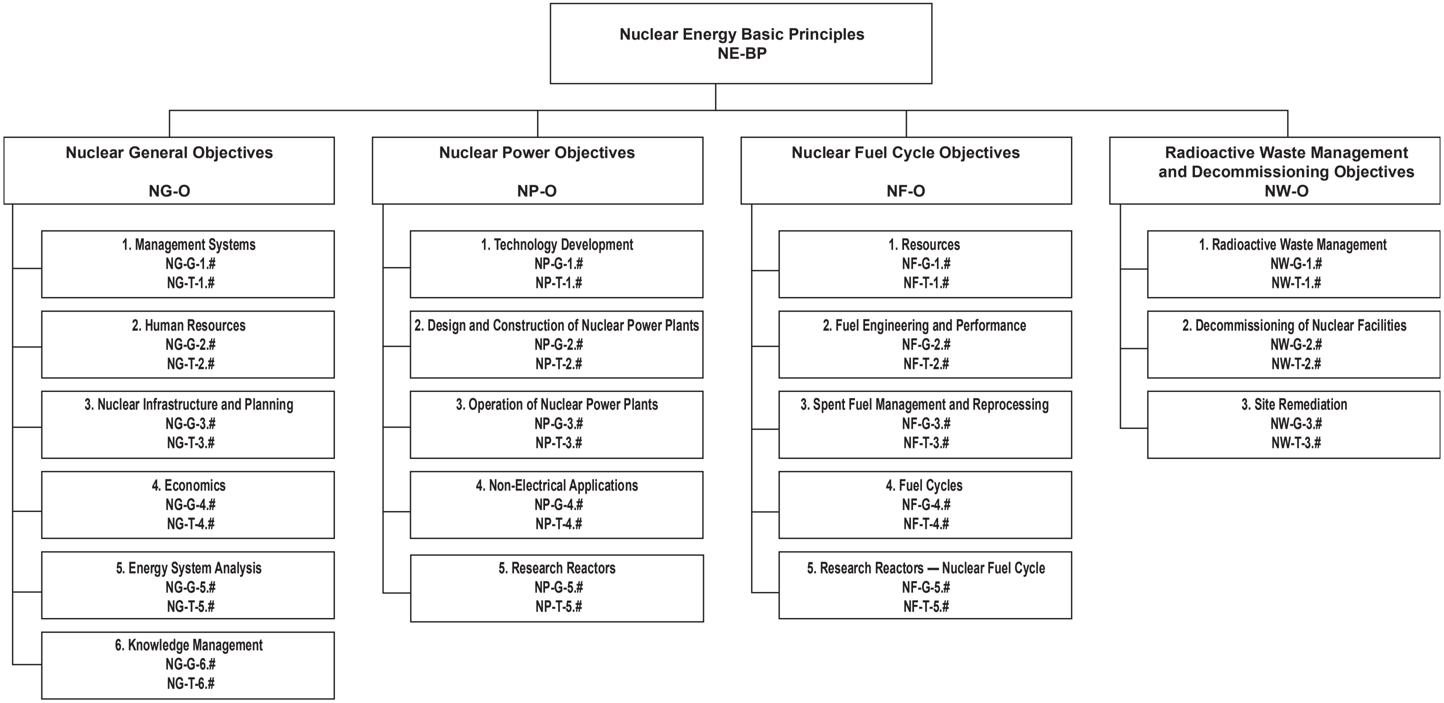

Key

BP:	Basic Principles
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