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Update of the INPRO Methodology in the Area of Waste Management

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Abstract: Judgment on the sustainable development of energy systems, including nuclear, should be based on the results of thorough, comprehensive, and unbiased assessment. To minimize the influence of human factors on assessment results, a systematic methodological approach for the evaluation of the sustainability of nuclear energy systems has been developed in the IAEA INPRO section based on the experience acquired in different countries. The methodology comprises several areas of a nuclear energy system (NES) assessment including the area of waste management. In this area it defines three major issues relevant to sustainability and the nine corresponding criteria to be used as assessment tools. Assessment of sustainability in the area of waste management is a part of the holistic system assessment to be performed to make reasonable judgments on sustainability.

Keywords: sustainability; sustainable development; nuclear energy system; assessment

1. Introduction

In 2000 the IAEA established the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) as an organizational unit in its Nuclear Energy Department to ensure that sustainable nuclear energy is available in the 21st century. To meet this objective, INPRO developed a set of principles and recommendations that comprise the methodology for assessment of a nuclear energy system (NES) with regard of its sustainability. INPRO assessment methodology is based on the concept of sustainable development introduced in the United Nations World Commission on Environment and Development Report [1] (often known as the Brundtland Commission Report), defining sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The general objective of this concept can be interpreted as striving for equity across generations and countries. This concept integrates four different viewpoints or dimensions: economic, environmental, social, and institutional, which need to be addressed in a balanced way to meet the criteria of sustainable energy development.

The leading assumption is that sustainability should be considered as a set of characteristics attributed to a given energy system and cannot be directly related only to the type of technology. The same technology (including renewable energy sources, nuclear, etc.) can be sustainable or unsustainable depending on how it was introduced and operated, the scale of facilities, costs and prices of energy products in the specific area or country, interfaces with other activities, etc. When different parts of the system are located in different geographic regions, the consideration of selected relatively clean parts of the system separately from the more dangerous or environmentally unfriendly components seems to be inappropriate within the concept of sustainable development.

The INPRO methodology is recommended to be a part of the strategic planning of energy system development. A strategy that can be assessed and developed through the use of the methodology provides a link between the objectives formulated in national policy and the specific implementation steps undertaken within the system, which helps to achieve the objectives and avoid potential pitfalls. The methodology covers all areas relevant to the NES sustainability assessment, including economics, infrastructure, waste management, proliferation resistance, physical protection, environment, safety of reactors, and safety of nuclear fuel cycle facilities organized in the nine separate manuals [2]. To make a judgement on sustainability, the full assessment of NES is expected to comprise nuclear power plants and associated fuel cycle facilities, and to cover the whole lifecycle including decommissioning and end states for all classes of generated waste. Generally, an INPRO assessment is to be performed for a specific nuclear energy-based system that has been defined in an energy system planning study and meets the energy demand, as a function of time, of a specific energy scenario in a country.

INPRO methodology is a living document based on contributions from hundreds of national experts from Member States participating in this activity. The first version was published in 2003 and it was revised and updated twice since then using feedback from self-assessments performed in different countries. Different versions of the INPRO methodology have been applied by research and technical support organizations from Argentina, Armenia, Belarus, Brazil, China, France, India, Indonesia, Japan, Republic of Korea, Russian Federation, Thailand, Ukraine, et al. Belarus agreed to publish the results of assessment as a formal IAEA TECDOC series report [3].

In 2012 the IAEA commenced the third update of INPRO methodology. Four manuals have already been published in 2014–2016. The update of INPRO sustainability assessment manual in the area of waste management was developed in 2016 by a group of national experts from different countries and IAEA professional staff. The revised manual is expected to be published in the near future and this paper represents a summary of the revised manual recommendations. The manual does not provide guidance on implementing waste management activities. Rather, the intention is to check whether such activities and processes are (or will be) implemented to meet the INPRO criteria for sustainability assessment in the area of waste management.

2. Method

The INPRO methodology for sustainability assessment does not establish any specific safety requirements or criteria for design, construction, operation, and decommissioning of nuclear facilities. INPRO methodology is an internationally developed metric for measuring NES sustainability and is intended for use in support of NES planning studies. IAEA safety requirements and guidance are only issued in the IAEA Safety Standards Series. The basic principles, user requirements, and associated criteria contained in the INPRO methodology should only be used for sustainability assessments. An application of INPRO methodology is typically a self-assessment exercise performed by the research or technical support organizations in a given country. Therefore, the INPRO methodology should not be used for formal or authoritative safety assessment or safety analysis to address compliance with the IAEA safety standards or for any national regulatory purpose associated with licensing or certifications of nuclear facilities, technologies, and activities.

Every manual of the INPRO methodology covers one of the areas relevant to the sustainable development of NESs. A key objective to be achieved in a given area is formulated as the INPRO basic principle. The structure of the methodology is the same in all areas of assessment, as presented in Figure 1. Basic principle splits into a few user requirements associated with the actions needed to achieve the system sustainability. Every user requirement consists of a few criteria to be used by the assessor to make judgement on the fulfilment of user requirement. Every criterion comprises an indicator and corresponding acceptance limit.

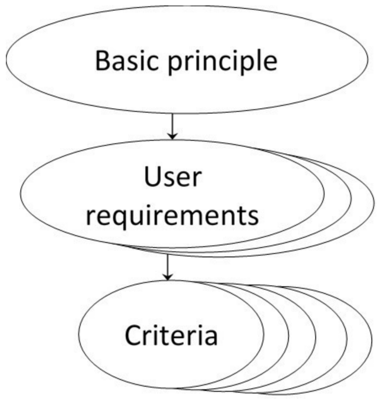

Figure 1. Hierarchy of the INPRO methodology requirements.

The criteria include measures that take into consideration the three-part test proposed within INPRO and based on the Brundtland Commission's definition of sustainable development. The first part of the test requires that current development should be fit to the purpose of meeting current needs with minimized environmental impacts and acceptable economics. Second part defines that current RD&D programs should establish and maintain trends that lead to technological and institutional developments that serve as a platform for future generations to meet their needs. Finally, the approach to meeting current needs should not compromise the ability of future generations to meet their needs.

With respect to nuclear waste management, it is known that any use of nuclear power technologies produces radioactive waste as a byproduct, which necessitates waste management in order to ensure the sustainability of a NES. To minimize the burden passed to future generations, the waste arising from a NES should be minimized and waste should be moved to the end states, ideally, passively safe in the long term, as soon as is practical. The generation that enjoys the benefits of the activities giving rise to the waste should assume responsibility for it and, as much as possible, not pass this responsibility on to their descendants. If such a transmission of responsibility can be reasonably justified, then the 'user pay' principle has to be applied and the necessary resources have to be accumulated and transferred along with waste that is generated.

Countries operating nuclear installations need to have a commensurable waste management system. Many different waste streams may arise from the NES or even from a single installation and many potential waste management steps may be needed to eventually achieve the end states with the intention of not treating them further. For each waste stream, including secondary waste from a given facility of a NES, a waste management plan needs to be developed setting out how the waste will be managed through the whole lifecycle from generation to the end state. End states may include free or unconditional release, recycling and reuse, and permanent disposal in different types of engineered disposal facilities. Waste storage or spent fuel storage are the interim steps and geological disposal for spent fuel or high level and long-lived waste is considered in the INPRO methodology to be superior compared to permanent storage due to the lower burden passed on to future generations, regardless of the potential economic preferences.

Any NES needs to involve measures protecting humans and the environment from adverse effects of radioactive waste now and in the future. Having in mind Brundtland's definition of sustainable development, it is recommended that such a system should include provisions for covering the lifecycle expenses of waste management facilities introduced and operated now, as well as provision of resources for safe management of waste and occasionally for the disposal of waste in the future. Recognizing that the reliability of safety features involving long-term institutional arrangements is expected to decrease over time, the plan for radioactive waste management should not rely on them.

Having analyzed the feedback from the national experts who performed sustainability assessments of different NES using previous versions of the methodology, INPRO has formulated one basic principle and three user requirements that elaborate on the basic principle and cover the three major parts of the waste lifecycle that are important from a sustainability prospective, i.e., generation of waste, predisposal waste management, and end states. Nine criteria were proposed for the assessment of these three user requirements, as presented in Figure 2.

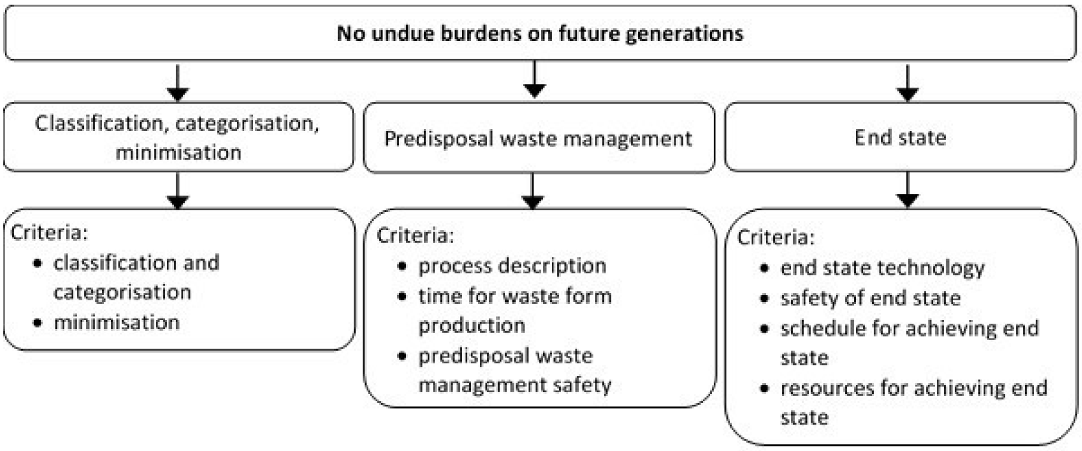

Figure 2. Structure of the INPRO methodology in the area of waste management.

3. Results

3.1. INPRO Methodology Basic Principle for Sustainability Assessment in the Area of Waste Management

The INPRO methodology basic principle in the area of waste management is derived from the ethical consideration that the generation receiving benefits from nuclear power utilization should be responsible for the management of all associated waste. Limited actions may be passed to succeeding generations along with corresponding resources sufficient to cover the associated expenses. The INPRO basic principle states that radioactive waste in a NES should be managed in such a way that it will not impose undue burdens on future generations [4].

3.2. Classification, Categorization, and Minimization of Waste

The first INPRO user requirement states that radioactive waste should be classified and categorized to facilitate waste management in all parts of the NES, which should be designed and operated to minimize the generation of waste at all stages, with an emphasis on waste containing long-lived radiotoxic components that would be mobile in a repository environment [4].

This INPRO user requirement discusses the optimization of the waste management process, which requires a waste classification and categorization scheme that enables unambiguous segregation for processing, storage, disposal, and identification of waste and facilitates optimal management of various waste types within a NES. National authorities have to develop a waste categorization scheme based on origin, type, properties, and process options in addition to an efficient waste classification scheme for disposal based on radioactivity levels and the half-life of isotopes. The classification and categorization scheme should be applicable to the entire system and should provide a link between the waste characteristics and the safety requirements of the end states. Waste in the same category of the classification and categorization scheme should have a common end state.

The first INPRO user requirement also refers to minimization of waste. Keeping generation of waste to a minimum is consistent with the objective formulated in the INPRO basic principle calling for avoiding undue burdens on future generations. Reduction of waste at the source is the preferred method. Waste characteristics to be minimized involve the total activity, mass, and volume of waste generated per GW·a produced or per ton of heavy metal processed; the amount of alpha-emitters and other long-lived radionuclides that would be mobile in a repository environment; and the amount of chemically toxic elements that would become part of the radioactive waste. A waste minimization study needs to be developed by the designer of the nuclear installation to determine actions reducing waste. The main elements of waste minimization strategies usually comprise source reduction, including both volume reduction and prevention of cross-contamination, recycling and reuse of materials from waste streams, the establishment of clearance levels, and optimization of waste processing [5].

3.3. Predisposal Waste Management

The second INPRO user requirement states that intermediate steps between the generation of the waste and the end state should be taken as early as is reasonably practicable and the processes should not inhibit or complicate the achievement of the end state [4].

Factors influencing the timing of both the waste management process interim steps such as pre-treatment, treatment, conditioning, storage, and transportation, and the achieving of end states can be competing. Potentially superior future technologies may be precluded by the requirement of early processing of waste. Delaying of some interim steps and disposal may provide essential savings. However, the decrease of uncertainty and higher level of safety obtained through the early achievement of the end state are considered to be higher priorities in this situation. Long and unjustified delays in moving radioactive waste towards permanently safe forms and conditions entails a risk that it will never be placed into the end state. For example, previous experience of storing high-level waste in liquid form resulted in the accumulation of large amounts of such waste, which could lead to accidental release to the environment and now requires investment in processing and remediation of the sites. INPRO methodology concluded that significant stress has to be placed on avoiding unnecessary delays.

At the end of any waste management process step, the waste form has to be compatible with the next step, and the implementation of different waste management steps, even in a complex system, should not complicate or inhibit the achievement of the end state. Interdependences among different steps need to be taken into account and the waste management processes should be considered throughout the lifecycle of the NES as an integrated whole in order to avoid converting the waste into forms that increase the difficulty of attaining end states or are incompatible with subsequent steps planned [6]. Safety assessment of the waste management steps including transportation has to cover all relevant technical issues including removal of heat from the systems, storage in a sub-critical condition, properly confining the radioactive materials, etc.

This user requirement comprises three criteria, briefly discussed below.

3.3.1. Process Descriptions

The evidence confirming that all steps in the waste management plan have been considered as an integrated whole and that the progress of implementation can be duly monitored may be obtained through the first criterion in this user requirement. It recommends that a description of the process encompassing the entire waste lifecycle, from generation to end state, should be available in sufficient detail to make evident the feasibility of all steps [4].

Process descriptions are expected to be based on proven practice since most of the waste management steps and technologies, except geologic disposal of high-level waste and spent nuclear fuel, have already been implemented in different countries. New technologies can be included in the process description only along with evidence of their feasibility.

3.3.2. Time for Waste Form Production

The requirement of reaching the end state within as short a time frame as is reasonably practicable implies that the waste in predisposal waste management steps within the same period of time should also be converted into a form fitting to the end state. A waste management strategy may consider a variety of possible scenarios and it is important to develop an implementation plan for the selected options to ensure the timely achievement of the end state waste form. The second criterion on predisposal waste management recommends that the technologies for producing the waste form specified for the end state are either part of an existing practice or there is a well-defined plan for bringing them into operation compatible with the required schedule for transferring the waste to its end state [4].

3.3.3. Predisposal Waste Management Safety

The third criterion on predisposal waste management in the INPRO methodology recommends that safety measures for all predisposal waste management facilities have to meet national regulatory standards (i.e., to be approved by national authorities) and to be consistent with applicable International Safety Standards [4].

3.4. End State

The third INPRO user requirement states that an achievable end state should be specified for each class of waste and the waste should be brought to this end state as soon as is reasonably practicable [4].

To avoid undue burdens on future generations, the waste needs to be placed in a state providing permanent safety without any further modifications required, i.e., in an end state. Identification of the end state includes the waste form and package; the final repository associated with characteristics of a specific site; a safety case for the final repository; and a schedule for achieving the end state. The appropriateness of the waste form, package, and repository has to be justified in a given environmental condition. Future generations should not be exposed to a level of risk that is not acceptable now and the safety case of end states should include an analysis of the potential failures of institutional measures. Theoretically, the development of a safety case can be easier for the end states where long-term institutional measures are not necessary for safety.

Depending on the class of waste, the characteristics of facilities and technologies used in these facilities may differ in the depth of repository, host formations, monitoring period, etc. Several countries plan to dispose of spent fuel, high-level, and long lived waste in deep, stable geological formations. Progress is being made; however, the siting and licensing of such facilities have proven to be challenging and, although some such facilities are in the late stage of development, currently no operating repository exists for this class of waste. End states based on established industrial practices can be used for the vast majority of waste streams; however, the geological disposal of high-level waste or spent nuclear fuel in many cases cannot be considered an existing technology yet. Technologies that improve the safety of the end state also require further development. Partitioning and transmutation of long-lived radioisotopes [7,8] can improve the safety of the final repositories, reducing the total amount of long-lived radioactive material.

Future generations should be provided with the resources to maintain the safety of the waste. These resources, including financial, have to be accrued by the generations benefiting from the use of energy from the NES, meaning that the costs of the management of waste throughout its lifecycle has to be included in the cost of energy.

Unlike the existing practice of underfunding the present liability, planning on the future value of money to compensate usually fails to properly internalize the costs associated with waste production, and implicitly provides an incentive to delay processing and disposal of the waste, so the INPRO methodology recommends that the assets accumulated to manage the waste should cover the accumulated liability.

This user requirement comprises four criteria, briefly discussed below.

3.4.1. Technology and Safety of End State

The first INPRO criterion associated with the end states recommends that end states are to be identified for all waste streams and all required technology is to be currently available or reasonably expected to be available on a schedule compatible with the schedule for introducing the waste management for all NES facilities [4].

The second INPRO criterion on the end states recommends that the safety measures for the end state should meet the regulatory standards of the specific Member State (i.e., accepted by the regulatory body) and should be consistent with applicable International Safety Standards [4].

3.4.2. Schedule and Resources for Achieving End State

Siting of waste disposal facilities may be controversial and subject to public opposition. This opposition can lead to the reluctance of decision makers to make final decisions on end states. Delays in decision-making due to public concerns and a corresponding lack of political will may be complemented by the existing safe storage facilities or plans to dispose the waste outside of the country's territory.

Recognizing that the pace of project implementation of the waste disposal facility can be affected by many factors including societal factors (e.g., a necessary level of public acceptance needs to be obtained), technical factors (e.g., availability of waste disposal technology, availability of waste processing facilities to produce waste forms and packages suitable for disposal, or adequate storage facilities), and economic factors (funding), the INPRO methodology recommends that once an end state has been defined and accepted by the regulatory body, the waste disposal plan should be constructed and put into operation (subject to further approvals) without undue delay. The third INPRO criterion on end states recommends that the time to reach the end state should be as short as is reasonably practicable [4].

The last INPRO criterion in the area of waste management is focused on the estimation of resources for achieving end states, primarily on the sufficiency of the planned financial resources. The study should cover the complete lifecycle of the NES components, including decommissioning, providing an adequate estimate of waste from the entire system. A waste management plan needs to be specified for all waste streams and for all categories of waste the costs of all interim steps and the costs of final disposal, including the cash flow over time for considered scenarios of management of waste, including all potential future expenses, need to be identified and accounted for in the cost of the energy produced. The funds required to meet this liability may be placed in a segregated fund or a State guarantee can be provided to cover the costs needed for dealing with the waste in the future. In both cases, fees are to be paid by the utilities and included in the electricity price.

The fourth INPRO criterion on end states recommends that resources (funding, space, capacity, etc.) have to be available for achieving the end state and the costs of all waste management steps have to be included in the product's cost estimate [4].

4. Discussion

INPRO methodology is an IAEA tool that was developed for the assessment of the sustainability of the NESs. The role of INPRO methodology is to define a set of criteria that can be used for making a judgment on the NES sustainability. It converts the concept of sustainable development into a selection of measurable indicators (numerical or logical). This methodology is being used by national experts for self-assessment of nuclear power programs. Users of the INPRO methodology are expected to identify potential major "gaps" in the strategy and to define follow-up actions necessary to close these gaps. However, the methodology does not involve any recommendations on the aggregation of assessment results.

Application of multi-criteria decision analysis (MCDA) methods is run within an INPRO project outside of the INPRO methodology developments. The MCDA tools that have been developed and tested within the INPRO project use the INPRO methodology criteria as an input necessary for further processing. The results of such an analysis will be published in the near future.

The INPRO methodology has been developed and continuously updated as a collection of criteria sufficient for NES sustainability assessment. It covers all NES characteristics relevant to sustainability: economics, including cost analysis, attractiveness for investment (differs from cost analysis), sensitivity study, investment risk evaluation, etc.; infrastructure, including nuclear law, regulatory body, public acceptance, human resources, nuclear security etc.; safety of reactor and safety of fuel cycle facilities, which are based on the concept of continuous improvement; proliferation resistance; waste management; environmental stressors; and depletion of resources. Most of the requirements used in INPRO methodology are not unique or uncommon; however, the combination of requirements providing a complete set of criteria for the assessment of NES sustainability is unique. Users of the INPRO methodology are encouraged to give their proposals of potentially missing criteria for further discussion within INPRO.

The new edition of the INPRO manual, providing guidance for sustainability assessment in the area of waste management, sets out nine criteria covering all major links between the concept of sustainable development and the waste management activities associated with the NES. A summary of the INPRO recommendations in the area of waste management is presented in Table 1.

Table 1. Summary of the INPRO recommendations in the area of waste management.

INPRO User Requirements	INPRO Criteria
Classification, categorization, and minimization of waste	Classification and categorization scheme permits unambiguous, practical segregation for processing, storage and disposal, and identification of waste arising.
	Characteristics of waste generated by the NES (mass, volume, total activity, amount of alfa-emitters, long-lived radionuclides, and chemically toxic elements) have been minimized.
Predisposal waste management	Process descriptions should encompass the complete chain of processes, from generation to final end state, and should be sufficiently detailed to make evident the feasibility of all steps.
	The time to produce the waste form specified for the end state should be consistent with the schedule for transfer of the waste to its end state.
	Safety case for predisposal waste management facilities meets national regulatory standards and is consistent with applicable International Safety Standards.
End state	End states are identified for all waste streams and all required technology is currently available or reasonably expected to be available on a schedule compatible with the schedule for introducing the waste management to all NES facilities.
	Safety case for the end state meets national regulatory standards and is consistent with applicable International Safety Standards.
	Time to reach the end state should be as short as is reasonably practicable.
	Resources (funding, space, capacity, etc.) available for achieving the end state are compatible with the size and growth rate of the NES. Costs of all waste management steps are included as a specific line item in a product's cost estimate.

The INPRO manual provides detailed explanations and recommendations for the assessment of every single criterion, including the acceptance limits provided for every criterion. These details are outside the scope of the current publication.

Finally, it is worth noting that the scope of consideration of the three INPRO areas, waste management, environmental stressors, and depletion of resources, is closely related to the scope of lifecycle assessment (LCA), which is often used for the evaluation of environmental impacts from a given product or service. In several areas of INPRO, including these three, the assessment does not involve the analysis and uses the results of analysis (environmental impact assessment report, safety assessment report, design documentation, etc.) as an input for assessment. LCA normally does not cover such areas as economics, nuclear safety, nuclear infrastructure, and proliferation resistance. However, if the results of LCA are available in sufficient detail for a given NES, they may be used as an input for INPRO assessment of waste management, environmental stressors, and depletion of resources, making the task much easier.

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Conflicts of Interest: The authors declare no conflict of interest.

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