Chapter 1

Introductory Chapter: Introduction to Current Trends in Nuclear material Research and Technology

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1. Introduction

Peaceful applications of nuclear science and technology in medical, industrial, and agricultural fields have served human civilization over several decades. These applications lead to the spread uses of nuclear and radioactive materials in hospitals, clinics, factories, different research centers and universities, and other workplaces. Workers in nuclear fields recognized the importance of keeping their technologies reliable, clean, and improving its sustainability and safety. Major obstacles that face them are lack in some legalizations and technical expertise in some countries, shortage in international recourses, and the growing concerns about nuclear security and safeguards. To combat these obstacles, the International Atomic Energy Authority (IAEA) identified requirements to establish national infrastructure that can support nuclear energy program [1]. The following issues and their associated conditions could be used to judge the program.

1. National position, governmental support is a pivot element to develop a successful program and the maintenance of long-term political, social, and financial stability is a must.
2. Nuclear safety, stakeholders should be committed to achieve safety throughout the program lifecycle.
3. Management, highly competent management is key issue to attain safe and secure program.
4. Funding and financing, initial governmental funding and initial activities aim to develop human expertise to mange and regulate the facilities.
5. Legislative framework, national legal framework and international instruments, that is, conventions, agreements, and protocols signed by the country, should be integrated and implemented.

6. Safeguards, governmental commitment to nonproliferation obligations should be ensured.
7. Regulatory framework, effective independent competent national regulatory body can enhance public and international confidence in a specific program. Key aspect in this area is the development of competent human and physical resources.
8. Radiation protection, existing national infrastructure for nonnuclear energy program, that is, radiation, waste, and transport safety should be updated in compliance with international measures for nuclear energy program.
9. Electrical grid, nuclear energy is most efficient to run as base load generator and a general accepted principal that a single power plant should not exceed 10% of the total installed capacity.
10. Human resources development, development of educational and training capabilities especially in nuclear physics, nuclear material sciences for reactor operation, and fuel cycle among other specialties are needed to ensure crucial human resources sustainability.
11. Stakeholder involvement, reasonable involvement is a requisition of positive stable political and the proficiency of both regulatory body and operator is a key aspect in supporting public confidence.
12. Site and supporting facilities, stepwise selection process should be adopted that aims to identify safe, secure, and economically and socially accepted site.
13. Environmental protection, program impacts on the environment should be assessed with special consideration to regular discharge and adopted fuel cycle strategy.
14. Emergency planning, operating experiences indicated that emergency planning for operation and for workers and public outside the site boundary should be addressed as it complement facility safety and add to the defense in depth.
15. Security and physical protection, security should be supported by national legalization and multi-preventive security levels are needed and should be coordinated with nuclear safety requirements.
16. Nuclear fuel cycle (NFC), having clear nuclear fuel management strategy, is essential during the planning for a nuclear program; this should cover front- and backend fuel cycle. For front-end, international supplier can reduce the need to develop infrastructure in this field, whereas for back-end there should be national storage and the disposal development is governmental responsibility.
17. Radioactive waste, some countries that produce and use radioisotopes had developed low and intermediate level radioactive waste (LILW) predisposal and disposal infrastructure, which can support a nuclear energy program. But it should be noted that for spent fuel (SF) and high level waste (HLW), the only available technology is storage.
18. Industrial involvement, having nuclear energy program requires the enhancement of industrial capabilities, that is, supplying spare parts, consumable, instrument repair, and calibration services, according to the codes and standards under strict management system.

19. Procurement should be subjected to a strict management system.

It could be seen that these requirements are essential for any other nuclear activity and that the enhancement of waste and NFC capabilities has received considerable attention, as it is considered in six issues. In 2008, 3S concept was introduced for new users, but old users started also to consider these issues [2]. This concept aims to strengthen the relationship between safety, security, and safeguard to attain successful peaceful utilization of nuclear technology. Now, great efforts are directed to enhance safety, security, and safeguard aspects. This is achieved by identifying the impacts of current practices, determining anticipated trends toward better performances, and mitigating challenges for commercial application of innovative technologies. This chapter aims to introduce the technical efforts to improve NFC for fission technologies, trends in fusion research toward commercial utilization of its energy, challenges that face development in radioisotope production, and advances in the management of naturally occurring radioactive materials (NORMs) and technically enhance NORM (TENORM).

2. Nuclear fuel cycle technology for fission energy

Nuclear fuel cycle includes several integrated industries that produce and manage the fuel and its associated wastes before and after irradiation. As any industry, the development and operation of NFC facilities have different effects on the host society and the environment. The compensation between the added value of these facilities and its associated environmental impacts is an important challenge for the sustainability of these industries, epically with strengthen regulatory requirements that emerged recently [3, 4]. **Table 1** lists NFC processes, its associated wastes, and impacts [3, 5]. Research and development efforts in NFC could be divided into two classes: the first is directed to enhance current commercial technology's performance, in terms of operational safety improvements and cost and environmental impact reductions. The second class is concerned with getting innovative technologies into industrial scale applications. Nuclear Energy Agency (NEA) developed reports that summarize current and anticipated trends in NFC development within 20 years [5, 6]. **Tables 2** and **3** list these trends for front- and back-end NFC processes, respectively [3, 5–15].

Process		Generated wastes	Associated hazard in the facility	Impacts
	Mining	Large Liquid effluent volumes, Large amounts of NORM/ TENORM solid residues.	Radioactivity, Chemical toxicity.	Extraction of raw material, Generation of mining and milling tailings.
Front end NFC	Milling Conversion	Low and intermediate level (L&ILW) in form of: Liquid effluent, sludge, insoluble and filter aid.	Radioactivity, Chemical toxicity, Flammability.	
	Enrichment	L&ILW, calcium fluoride, calcium		Waste generation.

Process		Generated wastes	Associated hazard in the facility	Impacts
		hydroxide, contaminated water, gaseous wastes, i.e. UF_6, F_2 and HF, and depleted U_3O_8		
Back end NFC	Fabrication Irradiation and storage Fuel reprocessing and/or disposal	The amount and types of waste is dependent on the reactor type and if open or close nuclear fuel cycle is applied, but generally L&ILW, and High Level Waste (HLW)	Criticality, Radioactivity, Chemical toxicity, Flammability.	Operational & accidental release, Waste generation. Operational releases and unanticipated radionuclide migration.

Table 1. Nuclear fuel cycle and their associated nuclear waste [3, 8–11, 13].

Process	Commercial technologies	Anticipated trends	Strengthen requirement
Mining	Localized deposits are used via • Open pit, • Underground mining, • In situ leaching (ISL), • Phosphate by-product recovery, • Heap leaching.	To ensure the sustainability • New deposits will be used, that is, high-grade unconformity-deposits, multi-mineral deposits and sandstone type, • Re-enrichment of depleted uranium, • Using closed NFC and former weapon-grade materials, • Increase application of ISL and underground mining.	Increased concern to develop environmental impact assessment and environmental restoration plan.
Conversion	• Ammonium Diuranate, • Ammonium Uranyl Carbonate.	Re-conversion of depleted uranium hexafluoride to U_3O_8.	Increased measure due to the application of 3S concept.
Enrichment	• Gaseous diffusion process, • Gas centrifuge process.	Improvements in centrifuge technology.	
Fabrication	Oxide fuel by pellet pressing and vibro-packing.	Clad and fuel material improvements.	Increased concern with reactor safety and application of 3S concept.
Irradiation	Different reactor types are commercially available, that is, LWR, PHWR, AGR, FR.	• Improve fuel/moderator distribution, • Reduce parasitic absorption and	

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Process	Commercial technologies	Anticipated trends	Strengthen requirement
		radial and axial neutron leakage, • Improve core reload design, • Change reactor reload patterns.	

Table 2. Current and anticipated trends in front-end NFC [2, 3, 5–7].

Process	Objective	Commercial technologies	Anticipated trends
Storage	Provide safe and secure custody for the waste Protect operators and public from the radiological hazards of the waste.	Power plant pools, wet and dry storage.	
Reprocessing	Extraction of isotope from SF.	Purex	Development in Pyro-processing
Transmutation	Converting long-lived radionuclides into stable- or shorter-lived nuclides.	NA	R&D to reach industrial-scale applications,
Waste treatment	Volume reduction, Radionuclide removal, Changing waste composition.	Different technologies are available to treat aqueous, organic, and solid wastes.	Investigating new materials, and innovative techniques, that is, utilization of composite materials, nano-sized magnetic material.
Waste conditioning	Immobilize radio-contaminant in suitable matrix, Waste emplacement in suitable package.	L&ILW Immobilization in cement-based, polymer, and glass, HLW immobilization in glass, Cement-based or stainless steel containers.	Development of SF container, Improving host matrix performance and application, that is, improving glass-melting technology, improving cementitious material performance.
Waste disposal	Isolate conditioned waste under controlled conditions.	Different facilities of variable designs are available for I&LLW.	Improvement in design of disposal facilities, Licensing SF& HLW disposal.
Decommissioning	Facility or material is removed partially or totally from regulatory control.	Different chemical and mechanical technologies.	R&D to reduce amounts of secondary waste.

Table 3. Current and anticipated trends in backend NFC [3, 8–15].

3. Fusion technology

Fusion technology is expected to be an environmental favorable energy source that affects future energy market [16, 17]. This technology faced different challenges, that is, understand plasma physics, find suitable materials that can perform efficiently in plasma environment, and find technology that can efficiently and environmentally friendly produce electricity. In 2012, the European Fusion Development Agreement (EFDA) published a road map toward fusion energy. This publication identified the challenges, missions to tackle these challenges, and anticipated milestones till 2050 [18]. **Table 4** summarizes these issues and the anticipated actions till 2020.

Challenges	Objective	Missions	Anticipated milestones
Plasma regime operation	Minimize energy losses due to small-scale turbulence, Restrain plasma instabilities, Integrated performance with the divertor.	Maintain inductive and steady-state regime, Study compatibility at maximum power between high radiation and confinement.	Use JET to explore operational regimes Demonstrate JT60SA reliability, Define preliminary confinement scaling law in medium-sized tokamak.
Heat Exhaust	Establish exhaust system and plasma-facing materials that withstand large heat loads.	Demonstrate the control of detached conditions, Optimize radiated power, Study core contamination in case of impurity injection.	Test snowflake and super X configurations, Evaluate liquid metal targets in tokamaks.
Neutron-resistant materials	Identify baseline materials that maintain their structural and thermal performance under operational conditions.	Characterization, irradiation, and modeling the material's performance.	Use IFMIF and EVEDA to generate baseline material list, Identify risk reduction options, Demonstrate welding and joining processes performance.
Tritium self-sufficiency	Achieve efficient breeding and reliable extraction systems.	Demonstrate efficient and reliable H^3 extraction, Test the performance of blanket/first wall.	Determine the blanket, divertor, and coolant reliability, Evaluate alternate designs.
Intrinsic safety	Demonstrate inherent safety. Reduce waste management activity and define end point for the management strategy.	Safety rely on defense in depth and passive safety concepts with emphasis on vacuum vessel integrity, existence of expansion volumes, Efficient detritiation techniques and selection of disposal routes.	Safety of waste management and waste recycling.

Challenges	Objective	Missions	Anticipated milestones
Integrated DEMO design	Integrate all fusion technology into DEMO design.	Develop a magnet to reduce performance degradation in cyclic operation, Increase electron cyclotron frequency.	Capitalize ITER experience, Modest targeted investments in DEMO design, Cost minimization analysis.
Competitive electricity cost		Life cycle cost analysis, Extend the operational times, increase the power conversion cycle efficiency, Decrease re-circulating power.	
Bringing stellarator to maturity	Develop stellarator.	Validate energy and particle confinement of optimized divertor.	Investigate the performance of plasma confinement and cooling components.

Table 4. Milestones toward fusion technology application till 2020 [18].

4. Radioisotope production

There are more than 160 different radioisotopes that are used regularly in different fields; these isotopes are produced either in a medium- or in a high-flux research reactors or particle accelerators (low or medium energy) [19, 20]. In 2014, IAEA published the results of a meeting on current status and future trends on radioisotope application in industry. The meetings produced a prioritized list that identifies area of interests in this field, which includes the application of small-sized neutron generators, development and application of nano-tracers, radiotracer application in mineral industry, tracer technology for sediment transport, development of radiotracer generators, tomography, hybrid instrumentation, process modeling, application in petroleum industry, high-resolution detectors, and process industry [21].

The sustainability of radioisotope production is one of the critical areas that receive great attention. ^{99}Mo is the greatest produced isotope that decays to ^{99m}Tc, which is used in 85% of the nuclear medicine diagnostic imaging procedure worldwide [22, 23]. Currently, the world production relies on using highly enriched uranium targets (HEU). IAEA activity in this field focuses on the conversion of this technology to using low enriched uranium (LEU) targets [23]. **Table 5** summarizes available and innovative technologies in the production of ^{99}Mo.

Current methods	Application	Feature	Challenges
Nuclear reactors			
Heterogeneous reactor using HEU target	Belgium, Canada, Netherlands.	Produce 93% of the world production.	Nonproliferation concerns, Consume ≅50 kg HEU, Low production yield [20].

Current methods	Application	Feature	Challenges
Heterogeneous LEU targets	South Africa, Argentina, South Korea, and Australia [24].	No nonproliferation threat.	Improvements in target materials, Improvement in separation technology [26].
Heterogeneous reactor –Neutron activation	USA, India, Japan, Kazakhstan, Peru, Russia, and Uzbekistan.	Use natural uranium.	Less productive, Low specific activity.
Homogeneous reactor LEU target	USA and Russia.	High production yield, Flexible process optimization, Reduce waste generation, Efficiently produce isotopes, Better economics [25].	Low separation efficiency [23].
Accelerator production			
Proton based	Tested experimentally, (Molybdenum target).	Direct production of ^{99m}Tc, Yield depends on the cyclotron energy, Very low radioactive waste [26,27],	Attainment of high energy, and intensity, Optimize targets to maximize secondary neutron production and thermalization [26].
Electron	Tested experimentally, (Molybdenum target).	Theoretical High yield,	High energy electron with high power, Pure Mo target [27].
	Tested experimentally, (Uranium target).	Yield similar to reactor yield, No ficile material used.	Waste arising similar to that of LEU reactor route, High-energy electron with high-power attainment [27].

Table 5. Conventional and innovative technologies for ^{99}Mo production [20–27].

5. NORM/TENORM management

NORM and TENORM residue generation accompanies industrial activities to exploit natural resources, namely mining, physical, wet chemical, and thermal processes that aim to separate, extract, and process these resources. The problems of managing these materials are related to their huge volume, very low specific radioactivity content, their presence in non-radiological industries, and the variability of their chemical, physical, and radiological properties that differ from industry to another and from site to site [4, 28]. Historical poor management practice led to different contamination problems that vary in their extent and properties. Dealing with these problems is affected by ethical, technical, and economical considerations [3, 4, 10, 29–30]. IAEA defined six radiological bands that could be used to support the decision-making process for remediation project [31]. Research and development in this area is directed to enhance the performance of remediation technologies and their economics [4, 10].

Finding a safe management route for NORM and TENORM motivated governments to announce their policy and strategy in this area [4]. In this context, these residues were divided into two categories: the first one is characterized by its moderate-activity concentration and huge volume, whereas the second contains higher-activity concentration and small volume. Recycling/reuse option has attracted attention on the international and national scale for the first category, where this option is considered after evaluating the chemical and radiological properties of the residues and updating the regulatory and legal framework. For the second category, disposal as waste is the only option [28]. Researches in this field is concerned with NORM/TENORM hazard characterization and evaluating their environmental impacts.

6. Conclusion

This chapter introduces advances in areas where nuclear material is produced and used. It aims to highlight the gaps that need further elaboration toward sustainable, safe, and reliable utilization of these materials. It could be concluded that

1. Researches and development efforts are needed in different areas to enhance current system safety and performance and to support the commercial application for innovative technologies.
2. 3S integration is a must, and international, regional, and national organizations started to implement this concept by issuing guidelines to adjust the legal framework, and support operation of non-HEU in radioisotope production.
3. Huge efforts are needed to address the challenges that face the application of anticipated trends on the governmental, operational, and regulatory levels and to coordinate these efforts.

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