EDITORIAL NOTE

ANNEX I.

ROAD MAPPING AS AN INTEGRATED APPROACH TO HELP MAINTAIN, ENHANCE AND MONITOR NES SUSTAINABILITY

I.1. GENERAL CONSIDERATIONS FOR ROAD MAPPING

Roadmap is a generic term used as a synonym for ‘guide to future goals’, ‘guideline’, ‘plan’, ‘direction’, ‘instruction’, ‘map’, ‘protocol’, ‘standard’, ‘procedure’ [I.1]. Road mapping is a targets-oriented planning process to help identify, select, and develop alternatives to satisfy a set of certain requirements and provide information to make better decisions (technology or policy alternatives, R&D allocations, etc.) by identifying critical elements and gaps.

A specific roadmap is a structured output of the road mapping process including identified critical system elements (actions, technologies) and milestones (timeframes, time lags, interconnections) to meet performance targets and requirements (Fig. I.1). There are many types of roadmaps related to the energy sector and nuclear energy in particular, depending on their focus. Some roadmaps are strategic plans focused on achieving a large outcome such as CO_2 emissions reduction. Other roadmaps are focused on maturing a specific technology, such as a new type of nuclear reactor. Some are a combination of both types, especially when strategic goals require the use of new technologies, as is often the case in the energy sector.

Application of road mapping techniques to nuclear technologies is not new. Many national and international projects have been carried out related to examination of diverse issues on the elaboration of nuclear technology related roadmaps using different analytical tools that had already found extensive applications in various subject areas. Within such studies different issues were considered from elaboration of R&D roadmaps associated with a specific nuclear technology to consideration of issues related to national NES deployment. These studies provide good illustrations of best practices which may serve as a pool of useful patterns, templates, and frameworks exemplifying main steps of the roadmap development process that are to be accomplished in road mapping toward enhanced NES sustainability.

I.2. PREVIOUS ROAD MAPPING STUDIES

This section provides a list of the more representative open-access road mapping activities and specific studies related to nuclear technology, complete with references. These studies cover problems of different natures, type and scope, e.g. R&D road mapping, NES deployment strategy road mapping, road mapping for specific technological or institutional arrangements, etc.).

Familiarization with the studies described in brief below can be helpful to articulate the general scope of road mapping towards enhanced NES sustainability and to produce recommendations for a road mapping process towards enhanced NES sustainability.

General information on technology roadmaps and technology foresight can be found in the Refs [I.2–I.4] covering a wide range of different methods, approaches and frameworks including those which may be applied for nuclear technologies and, eventually, for NES of enhanced sustainability. Issues related to the elaboration of nuclear technologies-oriented roadmaps are addressed in Refs [I.5–I.11]. The technology roadmaps associated with the Generation IV International Forum and specific examples of the technology roadmaps associated with the accelerator driven transmutation of waste can be found in Refs [I.12–I.18]. National nuclear roadmaps and different cross-cutting issues are discussed in Refs [I.19–I.25]. Some of these resources are presented in brief below.

(a) The IEA technology roadmaps

The International Energy Agency (IEA) in cooperation with governments and industry has developed a series of global low-carbon energy technology roadmaps for the most important energy technologies [I.2]. The overall objective of these roadmaps was to examine and advance the development of key energy technologies to reach a 50% reduction in energy-related CO_2 emissions by 2050. The roadmaps specify the actions to be implemented by different stakeholders (governments, industry, financial partners and civil society) for advancing technology development towards meeting the international climate change goals. All of the roadmaps elaborated by IEA are based on the ETP 2°C Scenario (2DS) considering an energy system deployment pathway and an emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C. Each roadmap characterizes international consensus on milestones for technology development, legal/regulatory needs, investment requirements, public engagement/outreach and international collaboration.

(b) The UNIDO technology foresight

The technology foresight is rated as an important step to precede the technology development process. It is expected to provide solid inputs for elaboration of the technology policies and strategies, which are needed to guide the development of a technological infrastructure. The technology foresight supports technology management and transfer to provide enhanced competitiveness and growth [I.3]. The United Nations Industrial Development Organization (UNIDO) is implementing global and regional initiatives on technology foresight with the aim to build the capability of using the foresight methodology as a practical tool in planning of the policies and strategies related to emerging and critical technologies. The UNIDO technology foresight initiative offers the methodologies to encourage sustainable and innovative development, fostering economic, environmental and social benefits at national and regional levels. The major outcomes of the UNIDO technology foresight are policies and programmes that deal with innovation, industrial growth and competitiveness.

(c) Developments of the Institute for Manufacturing, Department of Engineering, Cambridge, UK

The Centre for Technology Management at the Institute for Manufacturing (IfM) is involved in research and application of the road mapping techniques for more than a decade, with a focus on development of the efficient methods for the initiating of road mapping at a firm and a sector level. The activities are carried out in close collaboration with different organizations from the defence, aerospace and transport, chemical and packaging and services industrial sectors (Fig. I.2) [I.4]. A series of relevant publications were prepared covering a wide range of topics and applications of the road mapping techniques, such as [I.26].

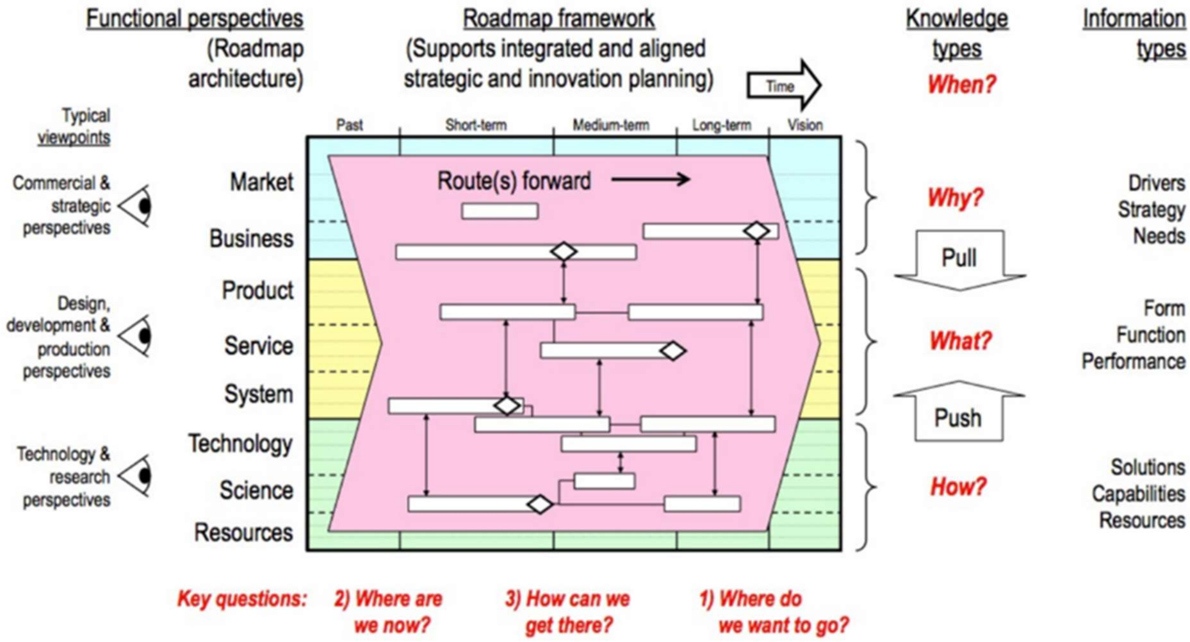

FIG. I.1. Schematic multi-layered roadmap, aligning multiple perspectives, highlighting fundamental generic strategic questions (reproduced from [I.27] with permission courtesy of [Phaal, Robert]).

(d) Technology Roadmap: Nuclear Energy, 2010 and 2015 editions, NEA/IEA

Technology Roadmap: Nuclear Energy has been prepared jointly by the IEA and the OECD Nuclear Energy Agency (NEA) [I.5]. In line with the IEA's 'Energy Technology Perspectives 2010' 'BLUE Map' scenario [I.6] for a 50% cut in energy-related carbon dioxide (CO_2) emissions, this roadmap targets nuclear capacity of 1 200 GW by 2050, to provide around 24% of global electricity. The key findings and recommendations of the road mapping are provided for all significant areas related to nuclear energy: safety and performance of nuclear installations, energy policy and environment, financing and economic issues, the management and disposal of radioactive wastes, safeguards and physical protection, international agreements and co-operation, next-generation nuclear systems and relevant fuel cycles, political and public acceptance, human resources, and legal and regulatory frameworks.

The 2015 edition of the nuclear roadmap prepared in cooperation between the IEA and NEA takes into consideration recent challenges facing the nuclear technology and aims to [I.7]:

- Outline the present status of nuclear technology development and the need for additional R&D to address improved safety requirements and economics;
- Provide a vision of the nuclear energy role as a low-carbon energy source, taking into consideration national nuclear policies and the economics of nuclear technologies;
- Specify barriers and actions needed to speed up the nuclear technology development to meet the roadmap vision;
- Share lessons learnt and good practices in the nuclear safety and regulation, the NFC front-end and back-end, construction, decommissioning, financing, training, capacity building and communication.

(e) Nuclear energy research and development roadmap, DOE, 2010

Reference [I.8] presents an integrated strategy and R&D framework for the DOE Office of Nuclear Energy, U.S.A., which targets making it possible for nuclear energy to play an important role in meeting the goals of energy security and greenhouse gas reductions. This reference identifies the mission of the DOE Office of Nuclear Energy in support of national goals. The mission is to enable the development and deployment of fission systems for the production of electricity and process heat. The following four R&D objectives have been identified to direct the programmatic and strategic planning:

- Develop technology and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors;
- Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the energy security and climate change goals;
- Develop sustainable NFC;
- Recognize and minimize the risks of nuclear proliferation and terrorism.

(f) Technology roadmap for the Generation IV nuclear systems

A technology roadmap outlining the endeavours to date and presenting the recent status of each system internationally has been developed for each Generation IV International Forum (GIF) nuclear system. [I.9]. The GIF technology roadmaps provide an overview of the major R&D objectives and milestones for the coming decade, targeting to achieve the Generation IV objectives on sustainability, safety and reliability, economic competitiveness, proliferation resistance and physical protection. Lessons learnt from the Fukushima Daiichi nuclear power plant accident are taken into consideration to ensure that all Generation IV systems achieve the highest levels of safety on specific safety design criteria. Completing the ten-year R&D targets set out in the roadmap should allow the more advanced Generation IV systems to move forward towards the demonstration phase. The Nuclear Hydrogen Initiative (NHI), which is a part of an integrated DOE programme, develops the technologies needed for the production of emission-free transportation fuels by Generation IV nuclear systems. Figure I.2 presents an example of R&D plan for the development and demonstration of a nuclear hydrogen production capability by a very high temperature reactor.

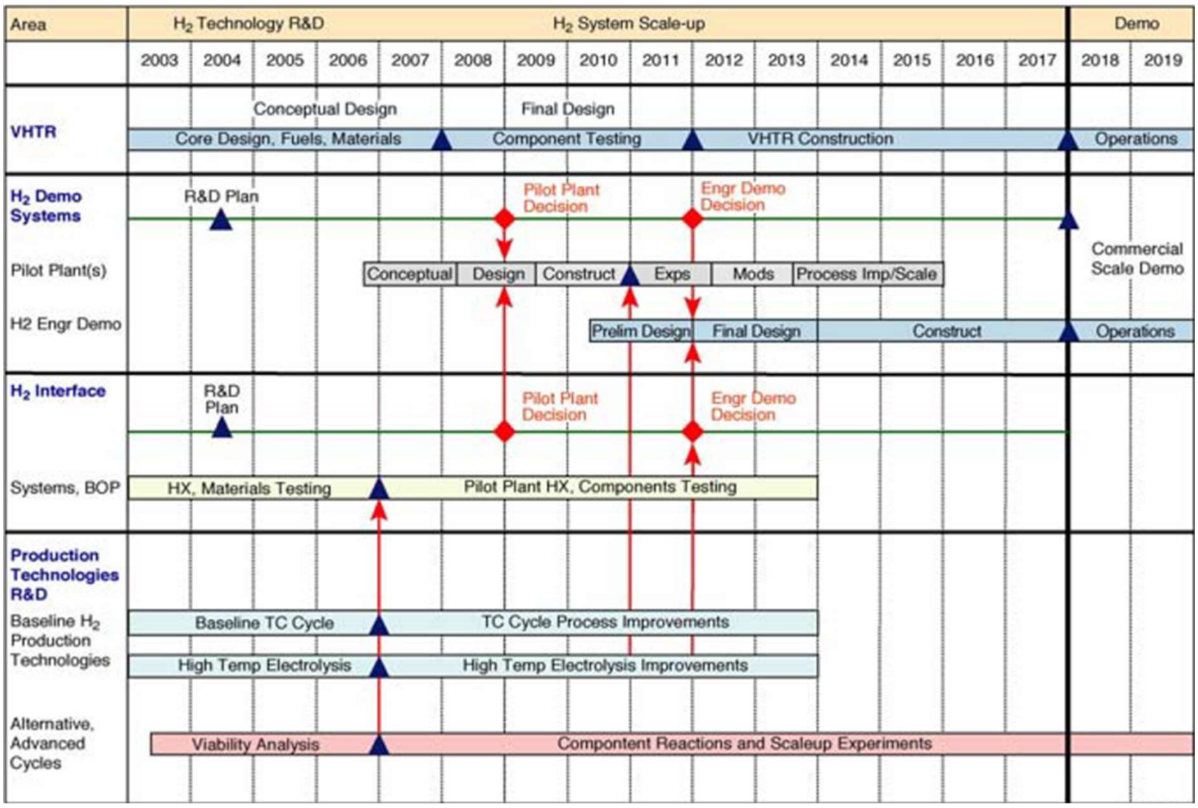

FIG. I.2. Summary of NHI R&D plan for the development and demonstration of a nuclear hydrogen production capability by 2017 (reproduced from Ref. [I.28], permission is not required).

(g) The UK nuclear energy research and development roadmap: future pathways, 2013

The UK Nuclear Energy R&D Roadmap sets out the research outcomes to support implementation of future technology pathways and considers the present R&D programmes, the R&D infrastructure and landscape, the associated R&D resources, and the international engagement and opportunities [I.10]. This roadmap takes into account synergies with other areas of energy research and considers the pathways along which greater benefit can be gained to maximize R&D capability and capacity.

Within the roadmap assessed are the needs and opportunities for nuclear energy R&D in the UK in the context of nuclear power deployment to levels required in a range of scenarios that the Government considers plausible. It sets out the upcoming R&D pathways that encompass the full range of technologies and capabilities considered capable of delivering a nuclear power of up to 75 GW(e) by roughly the middle of the 21st century (Fig. I.3).

The roadmap considers which capabilities are required to realize the plan, which technologies are needed and what are the R&D competences, activities and facilities that would be required. Based on such considerations, the R&D programmes are suggested to deliver the means for addressing these needs and opportunities.

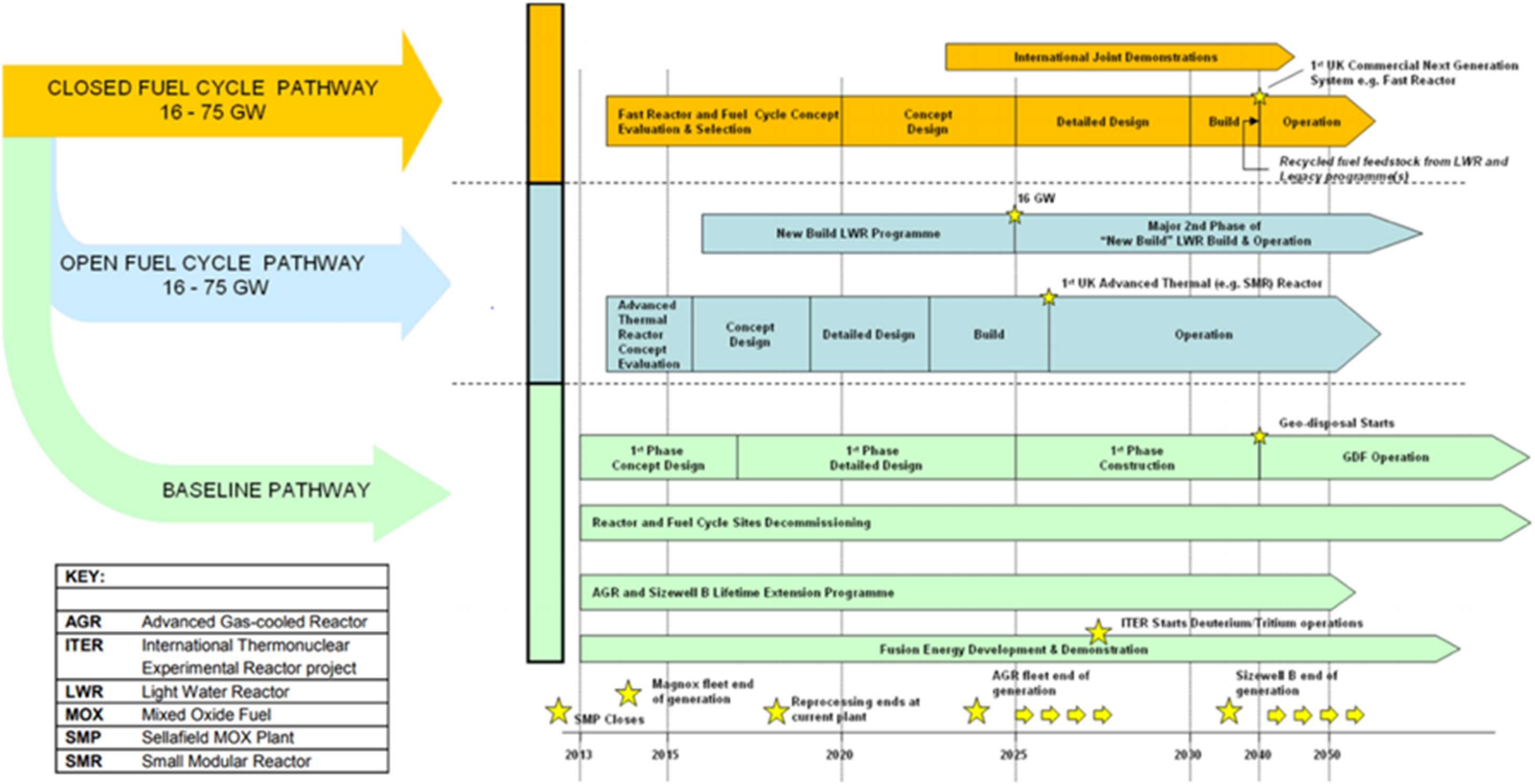

FIG. I.3. UK nuclear research roadmap (reproduced from Ref. [I.9], permission is not required).

(h) The roadmap of the Sustainable Nuclear Energy Technology Platform, European Sustainable Nuclear Industrial Initiative

The Sustainable Nuclear Energy Technology Platform (SNETP) was established in 2007 to support research, development and innovation for nuclear energy. SNETP has actively participated in the preparation of the Strategic Energy Technology (SET) Plan Integrated Roadmap to address further R&D required to better integrate different low-carbon energy technologies in future energy systems (Fig. I.4).

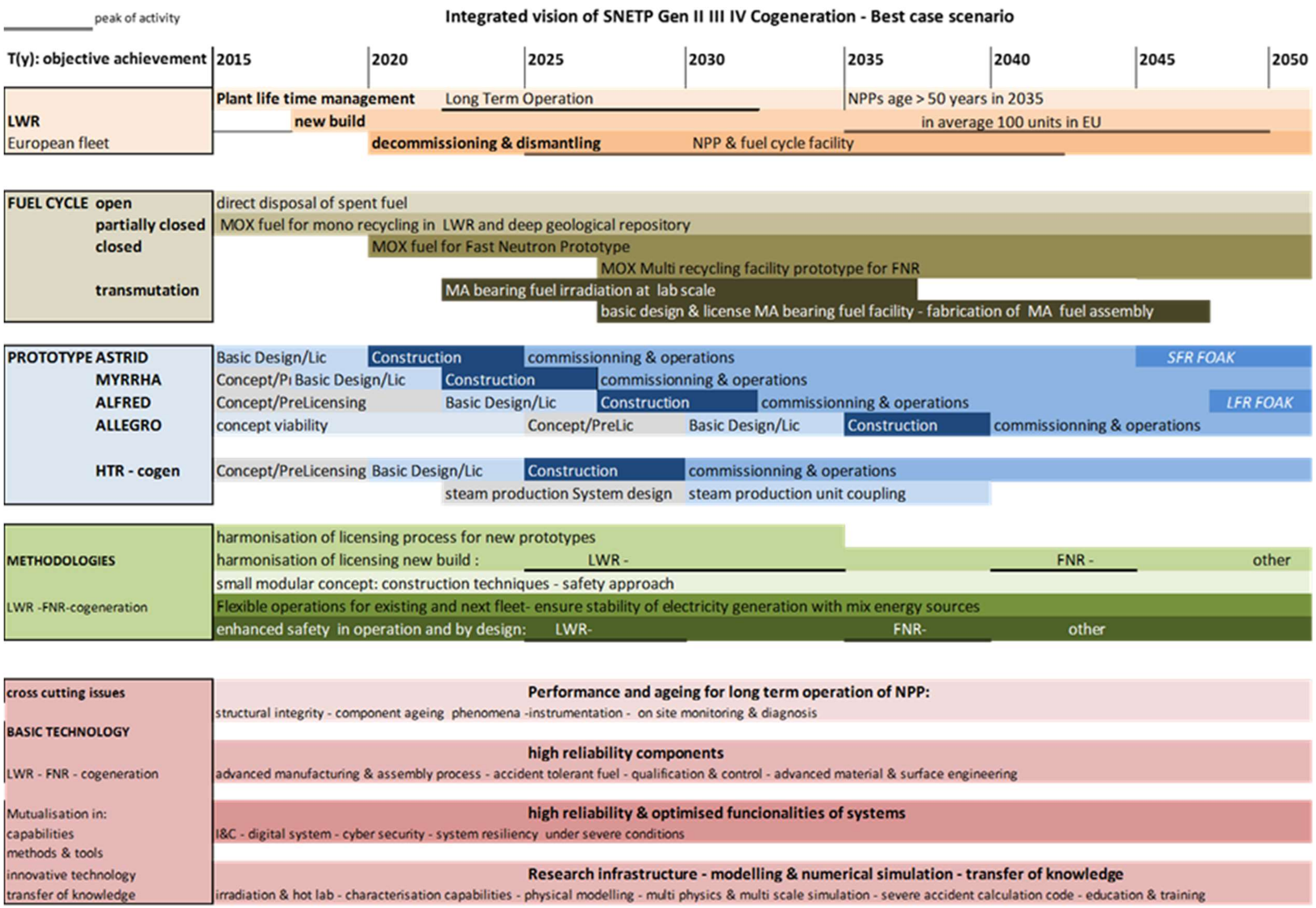

FIG. I.4. The SNETP deployment strategy (reproduced from Ref. [I.29] with permission).

SNETP defines its strategic orientations around the following three technology pillars:

- NUGENIA covering GEN II and III light water reactors, which aims to maintain safety and competitiveness in fission technologies accompanied with long term waste management solutions;
- The European Sustainable Nuclear Industrial Initiative covering fast reactor systems with a closed NFC and aiming to complete preparations for the demonstration of next generation fission reactors for enhanced sustainability [I.26, I.27];
- The Nuclear Cogeneration Industrial Initiative covering high temperature reactors, process heat, electricity and hydrogen, aiming at testing the first co-generation plants to test the technology for coupling with industrial processes.

(i) Short conclusion

As it can be seen from the brief summaries provided above, nuclear roadmaps can take many forms but, generally, comprise multi-layered time-based diagrams that enable technological and institutional developments to be aligned with expected trends, drivers and impediments. Another common observation is, that within road mapping, identification of key gaps associated with the system deployment is being performed and a baseline set of technological and collaborative options, as well as principal milestones for perspective system deployment, is being established.

I.3. SPECIFICS OF ROAD MAPPING TOWARDS ENHANCED NES SUSTAINABILITY

This section highlights specifics of NES-oriented road mapping studies and points to some issues that are relevant for the activities on planning NES sustainability enhancement.

As it has already been noted he ROADMAPS project has integrated the outputs of several other INPRO activities and developed a structured for enhancing sustainability of global nuclear energy, providing models for international cooperation and framework for documenting actions, scope of work, and timeframes for specific collaborative efforts by particular stakeholders. It also developed the roadmap template and ROADMAPS-ET that could be used in road mapping studies (Fig. I.6).

Harmonization of the road mapping toolkit and the approaches elaborated within the INPRO activities in the areas of NES scenario modelling and comparative evaluation of NESs ensures effective coverage of the basic steps of road mapping activities: visioning, roadmap elaboration, and monitoring.

Road mapping towards enhanced nuclear energy sustainability is deemed to serve as a tool to support strategic management of the NES deployment in the long term. It has some specifics: experts need to consider long term perspectives taking into account the dynamic nature of NES deployment process, a variety of requirements and performance metrics that are often of conflicting nature, as well as multiple choices and associated uncertainties. Generically, this leads to multiple and contradictory gaps, challenges, options, milestones, and requirements.

The dynamic nature of NES needs to be adequately taken into account in road mapping for correct representation of national experts' and decision makers' preferences regarding NES, as assigned to different timeframes. It means that a set of goals, milestones and performance metrics would need to be distributed over time: some of them may be more important within certain timeframes, but less important within the others.

In road mapping studies, it is necessary to perform identification of key gaps associated with current NES and to establish a set of baselines for technological and collaborative sustainability enhancement options. It is also necessary to define principal milestones for perspective NES deployment. Based on this data one needs to propose and justify additional measures to maintain and enhance sustainability, which would serve as a basis for experts to develop an action plan, i.e., a roadmap identifying which kind of technological and collaborative options would need to be implemented and when to meet the overall goal of NES sustainability enhancement.

The three characteristic road mapping stages are (Fig. I.5):

- The preliminary stage;
- The roadmap development stage;
- The roadmap implementation stage.

Being adequately implemented, road mapping towards enhanced nuclear energy sustainability would yield an integrated framework to support decision making regarding short to medium to longer term NES deployment strategy

Both, top-down and bottom-up approaches can be applied for examination of the aggregated roadmaps that comprise several national NES. A top-down approach begins with shaping-up of a targeted aggregated NES with its subsequent breakdown into components – national NESs. A bottom-up approach is the piecing together of national NESs to give rise to a combined NES: national NESs as components of the aggregated NES are initially to be specified in detail and then combined to arrive at a complete top-level NES. Apart from better reflecting the reality, where decisions on nuclear energy programmes are made by individual sovereign countries, the bottom-up approach in road mapping towards enhanced nuclear energy sustainability allows specifying and analysing in detail the various possible mechanisms of collaboration among countries. On the contrary, in a top-down approach all collaborative nuances would inevitably appear hidden.

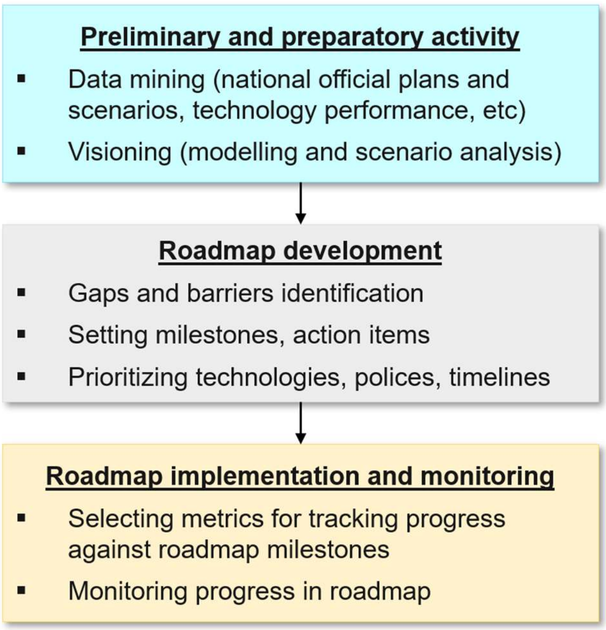

FIG. I.5. General road mapping flowchart.

I.4. ROAD MAPPING TO ENHANCE NUCLEAR ENERGY SUSTAINABILITY AND ITS PLACE IN THE CONTEXT OF OTHER IAEA/INPRO ACTIVITIES

For the purpose of the ROADMAPS collaborative project road mapping is understood as developing long term nuclear energy planning towards enhanced nuclear energy sustainability. When more than one country is involved, road mapping needs to include consideration of potential collaboration and associated synergies. Following the NES sustainability definitions of the INPRO methodology [I.30, I.31–I.34] and the definitions of options to enhance nuclear energy sustainability from Annex V of Ref [I.35], road mapping targets a nuclear energy sustainability enhanced through both, technology innovation and cooperation among countries.

Road mapping towards enhanced nuclear energy sustainability provides for addressing the timelines, the technologies, the institutional mechanisms, and the economic arrangements that support a collaborative enhancement of nuclear energy sustainability, as well as the drivers and impediments for such an enhancement. In this, the roadmap is assumed to indicate, inter alia, where savings in time, effort and resources could be achieved through collaboration with other countries.

Road mapping is assumed to be based on official national plans (when available) in the short to medium term (typically till ~2020-2035) and longer-term projections based on national studies (till the century end). As such, road mapping would require periodic updates as plans are corrected and new studies on projections are performed and, therefore, would benefit from being established as a continuous process rather than a once-at-a-time effort.

(a) Road mapping and other IAEA/INPRO activities

The INPRO methodology for NES sustainability assessment [I.30, I.31–I.34] and findings of the GAINS, SYNERGIES and KIND collaborative projects [I.35, I.36, I.37] and several other INPRO and IAEA activities, including the INPRO Dialogue Forums, as well as results of some studies carried out by other international organizations provided a sound basis for the elaboration of a general guidance on the development of national, regional and global roadmaps towards enhanced nuclear energy sustainability. The relationship of road mapping to other INPRO/IAEA activities is schematically shown in Fig. I.6 and explained in brief below.

Altogether, these outputs are expected to facilitate further studies on road mapping towards enhanced nuclear energy sustainability in Member States.

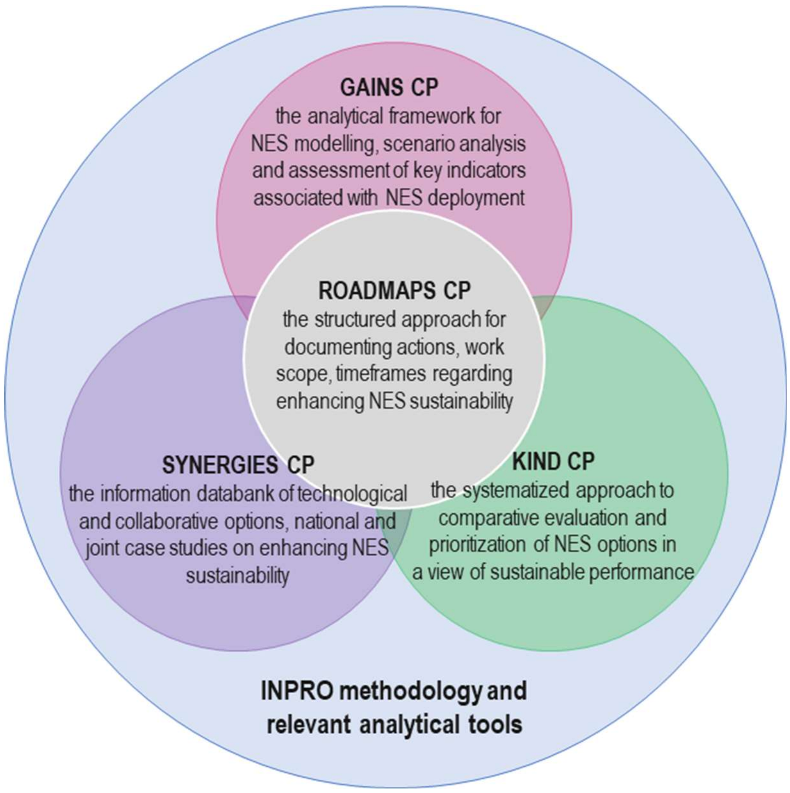

FIG. I.6. Interconnection of the INPRO collaborative projects.

Road mapping involves analysis of nuclear energy evolution scenarios based on official plans (for the short and medium term) and on projections (for the longer term). As such, is would benefit from the findings, models and software tools (e.g., MESSAGE-NES) developed jointly by the IAEA's Planning and Economic Studies Section and the INPRO Section within the INPRO collaborative projects GAINS and SYNERGIES [I.35, I.36, I.38–I.40], as well as the NEST tool developed by the INPRO Section [I.31, I.41]. However, scenario modelling and analysis within road mapping is not to be limited to just material flow characteristics and economics (as it was the case in GAINS and SYNERGIES). It may include targets and indicators defined in all subject areas of the INPRO methodology for NES sustainability assessment.

A specific feature of road mapping is that an objective of NES development is formulated not as achievement of a certain remote value of a certain, for example, economic indicator under some modelling constraints, but as a step-by-step, spread over time resolution of certain intermediate tasks on improvement in each significant area of NES sustainability. An example of setting the sustainability enhancement targets in line with basic principles of the INPRO methodology [I.30, I.31–I.34] is provided in Table I.1. As in the end NES sustainability is to be judged by society, it could be reasonable that the roadmap sustainability targets are defined at a higher INPRO hierarchy level, for example, at the basic principle level, and not at lower levels clear only to experts in particular fields.

Road mapping considers achieving enhanced NES sustainability through innovations in nuclear technology and infrastructure. There are plenty of reliable inputs to support this task, including publications by national and international organizations and by the IAEA's Nuclear Power Technology Development Section. However, several completed INPRO activities and, in particular, the GAINS and SYNERGIES collaborative projects [I.35, I.36] can serve as a reference point for developing a national roadmap. Taking into account the approach to classification of the technological systems proposed therein, a complete technology set can be divided into groups as follows:

(a) Proven well demonstrated technologies, successfully used in NESs and to be used for extensive NES deployment:
    (i) LWRs and HWRs operated in a once-through NFC;
    (ii) Advances in LWRs and HWRs operated in a once-through NFC replacing existing LWRs and HWRs technologies which are likely to be commissioned during a projected time horizon;
    (iii) Graphite light water reactors (GLWRs) operated in a once-through NFC;
    (iv) LWRs and advanced LWRs with mono-recycling of plutonium, and some other.
(b) Evolving technologies for which demonstration and pilot industrial facilities have been set up:
    (i) Fast reactors for nuclear fuel breeding/burning;
    (ii) Synergistic systems of LWRs and fast reactors for Pu and U multi-recycling, and synergistic systems based on other types of reactors.
(c) Conceptual technologies proposed for development, for which only individual features and prospects for application have been enunciated so far:
    (i) Thermal and fast reactors to operate in Th fuel cycle;
    (ii) Fast reactors and molten salt reactors (MSRs) dedicated to plutonium burning or minor actinides management;
    (iii) Accelerator driven systems (ADS);
    (iv) Synergistic systems of reactors and ADS.

Regarding innovations in nuclear infrastructure, some publications of the IAEA's Nuclear Infrastructure Development Section [I.42] and outputs of the INPRO activities on "Legal and institutional issues for transportable NPPs" [I.43] could serve as inputs for road mapping.

An essential driving force for enhancing sustainability of a national NES is regional and interregional cooperation. In this, both the existing and the expected forms and mechanisms of cooperation could be included in road mapping. The fundamental effect underlying cooperation is that all countries participating in it can enhance sustainability of their NESs without deploying a complete, fully sustainable NESs domestically. In the case of cooperation, what matters is sustainability of a NES integrated among the partners. If the sustainability of an integrated NES is enhanced, this would mean that each national NES of each of the partners in cooperation will also be enhanced. For example, a provider country could improve economies and, thus, sustainability of the national NES by adding more export share to its energy business, improving economies of scale and reducing unit costs. The recipient country could then also improve economics by receiving the products and services at lower prices without excessive burden to the domestic deployment and infrastructure.

TABLE I.1. AN EXAMPLE OF ROADMAP TARGETS DEFINED ALONG BASIC PRINCIPLES OF THE INPRO METHODOLOGY

Basic principles of the INPRO methodology	**Roadmap targets (example)**
Infrastructure	
"A country shall be able to adopt, maintain or enlarge an NES for the supply of energy and related products without making an excessive investment in national infrastructure" [I.31].	Nuclear infrastructure is optimized taking into account internal resources and opportunities of international cooperation. Public acceptance is achieved for national NES enlargement.
Safety	
"Incorporate enhanced defence-in-depth as a part of their fundamental safety approach and ensure that the levels of protection in defence-in-depth shall be more independent from each other than in existing installations" [I.30].	The need for relocation or evacuation measures outside the plant boundary is excluded by design.
Economics	
"Energy and related products and services from NESs shall be affordable and available" [I.32].	Comparable or best economic performance in the energy sector is provided.
Nuclear waste management	
"Radioactive waste in an innovative NES shall be managed in such a way that it will not impose undue burdens on future generations" [I.30].	Final end state defined for each category of radioactive waste is defined, that would require no safety and safeguards measures to be implemented by future generations.
Proliferation resistance	
"Proliferation resistance intrinsic features and extrinsic measures shall be implemented throughout the full life cycle for innovative NESs to help ensure that innovative NESs will continue to be an unattractive means to acquire fissile material for a nuclear weapons program. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself" [I.30].	Safeguards agreement and Additional protocol are signed and ratified. Low attractiveness of nuclear materials and nuclear technologies is ensured. Balance of production and consumption of a fissile material in the nuclear fuel cycle is achieved.

Environment	
"The expected adverse environmental effects of an NES should be well within the performance envelope of current NESs delivering similar energy products" [I.34]. "The NES shall be capable of contributing to the energy needs in the twenty-first century while making efficient use of non-renewable resources" [I.33].	Health risks are at a level of the best energy sector technologies. Full use of the energy potential of fissile materials is provided.

(b) Instruments supporting road mapping

Countries planning to embark on a nuclear energy programme should first develop a national infrastructure for nuclear power. In this context, it could be recommended that newcomer countries include the IAEA Milestones approach [I.44] supporting the development of a national infrastructure for nuclear power and the INIR missions as implementation tool for such a support [I.45] as part of road mapping. As the infrastructure support services provided by IAEA with respect to construction of a first NPP are well established and self-standing, they will not be addressed in detail in this report.

Since nuclear power impacts the social/economic aspects of human life and the environment, a national position would require effective communication of the nuclear energy community with public and different stakeholders (both within and outside of government). An attitude of a broad range of people towards nuclear power creates a certain atmosphere in society, influences governmental decisions and largely determines a national roadmap of NES development and deployment. In addition to the IAEA Milestones approach [I.44], INPRO publications [I.46] and [I.35] could be helpful to produce an insight on sustainability requirements for public acceptance and on the approaches to measure and quantify it.

Road mapping is assumed to be based on official national plans (if any) in the short and medium term and on projections based on studies in the longer term. While plans appear as something fixed at each moment in time, projections could vary for a number of reasons. First, different groups of researchers may bring out different longer-term projections at the same time. Then, a need to evaluate and compare these different projections arises followed by a need to communicate the results of such comparative evaluations to decision makers. Second, as time goes by, projections produced by the same group of researchers may change, reflecting on the changed boundary conditions, for example, in national, regional or global economy, etc. Third, longer term projections are typically uncertain, so that analysing and comparing them without a duly performed uncertainty analysis makes little sense. All of the above mentioned specific features need to be taken into account in road mapping.

To deal with comparative evaluations of NES or NES evolution scenarios, including options of collaboration among countries, an approach to comparative evaluation and the supporting KIND-ET evaluation tool developed within the INPRO collaborative project KIND could be instrumental [I.37]. The approach is based on a set of problem-specific key indicators reflecting upon certain subject areas of the INPRO methodology for NES sustainability assessment and on the application of a selected verified judgment aggregation and uncertainty analysis method.

Regarding projections being changed as time goes by, the solution is to periodically repeat the road mapping effort and update the resulting conclusions. This could be facilitated by developing a computer software allowing to store the completed sets of studies and periodically repeat them with changed preferences and/or boundary conditions. Such an instrument – the ROADMAPS Excel Tool (ROADMAPS-ET) – has been developed within the ROADMAPS collaborative project and is provided on a CD-ROM attached to this report.

In addition to ROADMAPS-ET and KIND-ET, other software tools could be helpful in road mapping, within their specific application areas. These include NEST [I.32, I.41], MESSAGE-NES [I.39, I.40] and the supporting collections of reference data for nuclear reactors and fuel cycles. Upon requests from Member States, the INPRO Secretariat provides the "Analysis Support for Enhanced Nuclear Energy Sustainability (ASENES)" Service, which includes training and Webex-based consultations on application of all tools developed within the INPRO project.

Apart from the IAEA tools, many national tools, as well as tools developed by international organizations have potential of being effectively used in road mapping. In particular, a number of national and public domain tools for dynamic material flow analysis in NES evolution scenarios have been cross-verified on a number of benchmark problems within the GAINS collaborative project. The results of verification and recommendations on the use of these codes are presented in Ref. [I.30].

One of the INPRO project objectives is to bring together nuclear technology holders and users to consider jointly international and national actions that would result in desired innovations in nuclear reactors, fuel cycles or institutional approaches. To better achieve this objective one of the tasks of INPRO named "Policy and dialogue" convenes INPRO Dialogue Forums which offer a platform for IAEA Member States to share information, perspectives and knowledge on issues related to sustainable nuclear energy development. The Forums are typically being convened on a twice-per-year basis and are characterized by broad participation of experts from many Member States, not necessarily INPRO Members, representing a variety of technology holder, technology user and newcomer countries.

On a number of occasions, the INPRO Dialogue Forums are organized to provide direct support to the on-going INPRO collaborative projects and activities. In this case they provide broad Member States' insights on scope and content of the activities, help find new participants and obtain critical reviews of produced outputs. In the context of the ROADMAPS collaborative project, the following two Dialogue Forums could be mentioned:

- The 4th INPRO Dialogue Forum "Drivers and impediments for regional cooperation on the way to sustainable nuclear energy systems" convened on 30 July–3 August 2012 at IAEA at IAEA Headquarters in Vienna; the report of this forum was published as Appendix IV of Ref. [I.35].
- The 11th INPRO Dialogue Forum "Roadmaps for a transition to globally sustainable nuclear energy systems" convened on 20-23 October 2015 at IAEA at IAEA Headquarters in Vienna; the summary report of this Forum is included as Annex VII in this report.

The findings and conclusions of these Forums may provide a valuable input for road mapping. In particular, INPRO Dialogue Forum 11 included an exercise in which all participants were requested to fill out the questionnaire forms which were actually a simplified roadmap template. All participants, including those from newcomer countries, were successful in accomplishing this which made it possible to produce an integrated picture of 'global' nuclear energy evolution till the end of this century and analyze the roles of different groups of countries in such an evolution. It is on itself a proof of viability of the road mapping approach.

(c) Benefits of road mapping

Carrying out road mapping for a national NES could assist in national strategic planning for nuclear energy development by facilitating finding answers to the following questions:

- How could national NES evolve in time?
- What could be the preferred place of a country in regional and global NES and how would it evolve in time?

- Which products and services could be provided indigenously and which imported, and at what time horizon?
- What could be country’s preferences regarding advanced and innovative nuclear technologies?
- What could be country’s preferences for cooperation with other countries?

Regarding national strategic planning for nuclear energy development, road mapping complements nuclear energy system assessment (NESA) in that it provides a time dependent picture of NES evolution, includes instruments to set the enhanced sustainability targets and to identify and evaluate pathways to achieve these targets.

When road mapping is performed in cooperation among technology users and possible technology providers, additional benefits resulting thereof are strategic insights on international market of products and services for peaceful applications of nuclear energy. With this, providers could better plan expansions or cut-downs of their industrial capacities for certain products and services, while recipients would have a clearer picture of wherefrom the desired products and services could be procured and where could be the bottlenecks. However, synergies leading to enhanced sustainability can be achieved regardless of the developmental status of the countries involved in cooperation (e.g., two newcomers can achieve synergies by working together).

Road mapping also supports timely planning and development of an infrastructure for NES sustainability enhancement, including that through collaboration among countries.

REFERENCES TO ANNEX I

[I.1] UNIVERSITY OF CAMBRIDGE, Centre for Technology Management Institute for Manufacturing, , http://www.ifm.eng.cam.ac.uk/road mapping

[I.2] IEA Roadmaps publications list, https://www.iea.org/roadmaps/

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ANNEX II.

CHINA'S EFFORTS ON THE SUSTAINABILITY OF A NES BASED ON CLOSED FUEL CYCLE AND FAST REACTOR TECHNOLOGY

Based on China's national conditions, China is strongly determined in the development of nuclear energy. China has identified a three-step nuclear energy development strategy of 'thermal reactor-fast reactor-fusion reactor' and adhered to the closed fuel cycle strategy from the 1990s. The China Experimental Fast Reactor (CEFR), which is a 65 MW(th) sodium cooled fast reactor, and the Chinese Pilot Plant for power reactor spent fuel reprocessing have been constructed, and a lot of meaningful research on the technologies of fast reactor, Accelerator Driven System (ADS) and closed fuel cycle has been carried out. Many unremitting efforts are being conducted in China to ensure sustainable development of nuclear energy, China's energy structure adjustment and nuclear energy development strategy.

China is the largest developing country, and the Chinese government is committed to the balanced development of the society. Energy is a necessary condition for social development. In order to optimize the energy structure, the Chinese government will gradually develop the environment-friendly energy forms such as nuclear power, wind power, hydroelectricity, and the advanced grid technologies, such as the Ultra High Voltage (UHV) and smart power grids, instead of the over-reliance on coal power which was the case during the early stage of industrialization.

Developing nuclear power is one of important options for China's energy structure optimization. The Chinese government has consistently advocated the development of nuclear power meeting the highest standards of nuclear safety. To ensure the quality and safety of nuclear power projects, China has established a complete system of nuclear safety laws and guidelines and implemented a comprehensive supervision system for nuclear safety, as well as an environmental supervision system and a nuclear accident emergency response system. The Chinese government uses these regulations and institutional systems to conduct a comprehensive supervision of the site selection, and the design, construction and operation of nuclear power plants to ensure the realization of the goal of 'safety first and quality first'. China's nuclear industry places a special emphasis on the whole process quality assurance system and pays special attention to the training of nuclear power operational personnel, in order to continuously improve safety and safety culture. At the same time, embarking on a new generation of nuclear technology is also expected to improve safety and economy.

After the Fukushima Daiichi nuclear accident, China did not change the policy for nuclear power development, but instead pays more attention to the safety of nuclear power and its economic competitiveness compared to other forms of energy. On one hand, China's companies focus on research and development of the nuclear power technology with the independent intellectual property rights. The Chinese third-generation PWR nuclear power technology, such as HPR1000 and CAP1400, will be promoted in domestic and international markets. On the other hand, China's vast nuclear power demand also requires the introduction of technologies from the Russian Federation, France, Canada and the United States of America.

Since the Qinshan Nuclear Power Plant – the first nuclear power plant in China – was put into operation in 1991, a total of 28 units of nuclear power plants with a capacity of 26.42 GW have been put into commercial operation by the end of 2015. Most of the units are PWR type reactors (24 units), with a total capacity of 24.98 GW. China has a huge nuclear power development vision, looking forward to the development of nuclear power with 40 GW in operation and 18 GW under construction by 2020. In the follow-up years a larger scale increase in the proportion of nuclear power in the energy mix is anticipated.

China needs large-scale development of nuclear power, but it has limited uranium resources, which is detrimental for the ambitious nuclear power development plan. In order to ensure the effective utilization of nuclear resources and the effective disposal of the high-level radioactivity and the long-lived nuclear waste (spent nuclear fuel including plutonium, minor actinides and long-lived fission products) produced by nuclear power plants, the top-level design of China's nuclear power development since the 1990s is a three-step strategy of 'thermal reactor – fast reactor – fusion reactor'. And China adheres to the closed nuclear fuel cycle strategy to ensure the sustainable development of fission nuclear energy. China has carried out a lot of research and engineering practice in the fast reactor and the closed nuclear fuel cycle technology.

II.1. CHINA FAST REACTOR TECHNOLOGY DEVELOPMENT

China's fast reactor technology has been developed during nearly 40 years, mainly based on the sodium cooled fast reactor technology. The research and development programme is divided into the basic and application research phase (1967–1993) and the engineering phase of CEFR (1994–up to present).

II.1.1. The basic and application research phase

From the end of the 1960s China has been studying the fast reactor technologies including materials, sodium technology, fuel, reactor physics and safety, etc.

(a) The zero power facility

A zero-power fast neutron facility (Fig. II-1) was launched in the 1970s to study the characteristics of fast neutron reactors.

FIG. II.1. China's first zero power fast neutron facility DF-6.

(b) Sodium loops

More than twenty loops have been constructed for different purposes covering sodium operation, thermal hydraulics, material studies, sodium equipment studies, safety studies, etc.

(c) Sodium purification technology

In order to supply nuclear grade sodium to the CEFR, the sodium purification technology has been developed. The first step was to construct a medium scale purification facility with a capacity of 300 kg/day. The quality of sodium produced by this facility is about 28 ppm of oxygen content. Based on the experience of this facility, a large-scale facility has been constructed at the Wuhai Sodium Factory with a capacity of 1 500 kg/day. The production shows that the adopted technology could meet the requirements very well. The sodium quality index is up to 10 ppm.

(d) Clad and structure materials

Cr-Ni 316 stainless steel was selected as the cladding material. The preliminary study shows that the requirements for cladding characteristics are met in full. For the future, the Oxide Dispersion Strengthened (ODS) alloy is one of the options.

316 and 304 stainless steels are selected as structural materials. The sodium equipment of CEFR adopts mostly these kinds of materials. The studies show that the materials could work very well under sodium environment.

(e) Anti-earthquake performance study

Based on the consideration of possible sodium movement conditions in the reactor vessel with distinguished different liquid regions, analytical methods including finite element numerical simulation, integrated parameter simplified model and semi-resolving approach have been adopted to analyse the anti-earthquake performance and earthquake response of the CEFR's main vessel structure.

A vibration test of the CEFR's reactor block model fabricated in 1:6.25 scale using the Alumina alloy has been conducted. The above mentioned theoretical analysis approaches were applied to simulate the test model performance using the ANSYS computer code.

II.1.2. The engineering phase of CEFR

The design activities for the CEFR began in 1994 and were finished in 2004. As the first step, the power of the reactor was set at 65 MW(th). In order to get more experience, this experimental reactor adopts a pool-type electricity generating design. Most of the main parameters are similar to the prototype fast reactor.

The CEFR is a sodium cooled experimental fast reactor with UO_2 as the first fuel load, and with Cr-Ni austenite stainless steel as fuel cladding and reactor block structure material. The reactor consists of two primary pumps and two loops for primary and secondary circuit, respectively. The water steam tertiary circuit is incorporated into one pipe which is connected to a turbine generator of 20 MW(e).

The reactor block is composed of the main vessel and the guard vessel supported from the bottom. The main vessel contains 260 tons of liquid sodium with argon as a cover gas. The total weight of the block is about 1 200 tons. The reactor core, its support structure and the internal structure by which two main pumps and four intermediate heat exchangers are supported are installed on the vessel support structures. The double rotating plugs on which 8 control rod driving mechanisms, the subassembly handling machine and the instrumentation structure are installed are located at the top of the reactor vessel. The core layout and the reactor block are shown separately in Fig. II.2 and Fig. II.3.

The main design parameters of CEFR are summarized in Table II.1.

TABLE II.1. MAIN DESIGN PARAMETERS OF CEFR

Parameter	Unit	Preliminary design value
Thermal power	MW	65
Electric power, net	MW	20
Reactor Core		
Height	cm	45.0
Diameter (equivalent)	cm	60.0
Fuel		$(Pu,U)O_2$ / first loading UO_2
Pu, total	kg	108
Pu-239	kg	65.76
U-235 (enrichment)	kg	92.33 (36%)
Linear power (max.)	W/cm	430
Neutron flux	$n/cm^2 \cdot s$	3.7×1015
Fuel burn-up	MWd/t	100 000
Fuel burn-up, first load (max.)	MWd/t	60 000
Inlet temp. of the core	˚C	360
Outlet temp. of the core	˚C	530
Diameter of main vessel (outside)	m	8.010
Primary circuit		
Number of loops		2
Quantity of sodium	t	260
Flow rate, total	t/h	1328.4
Number of IHX per loop		2
Secondary circuit		
Number of loops		2
Quantity of sodium	t	48.2
Flow rate	t/h	986.4
Tertiary circuit		
Steam temperature	˚C	480
Steam pressure	MPa	14
Flow rate	t/h	96.2
Plant life	year	30

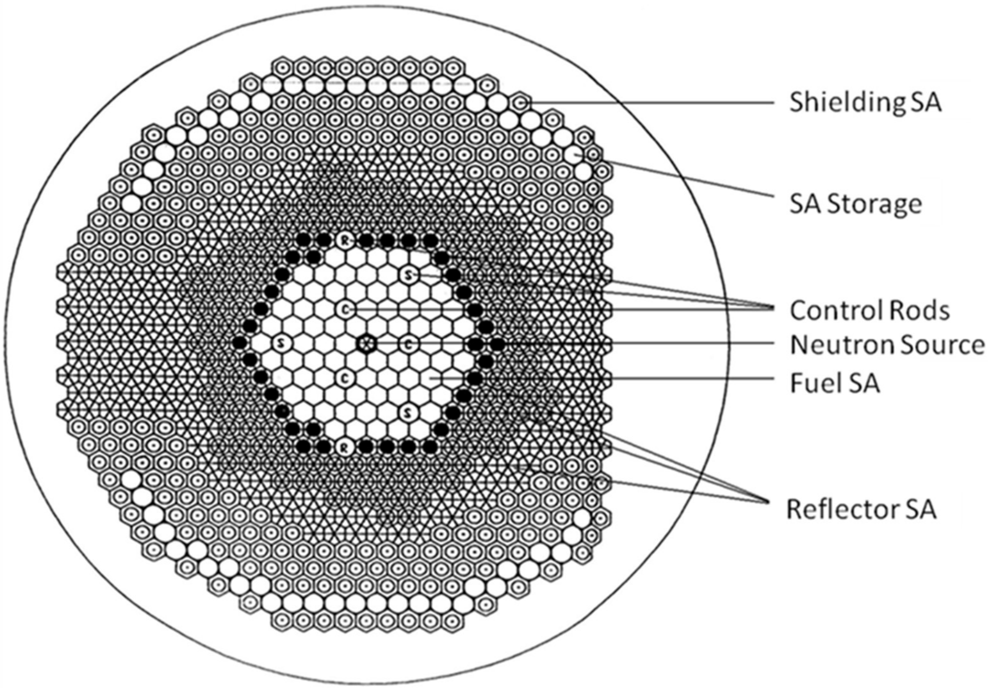

FIG. II.2. CEFR core layout

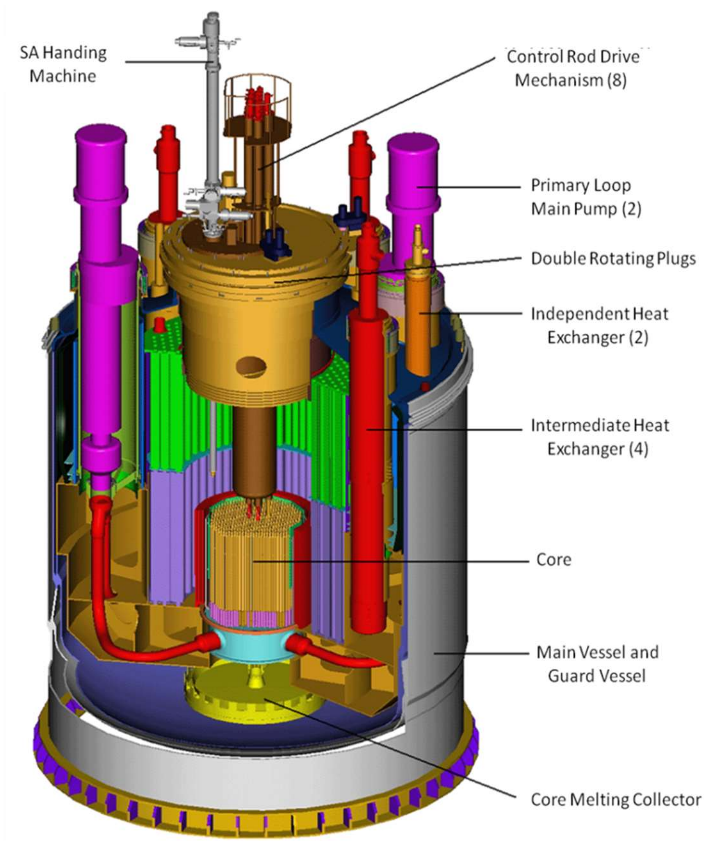

FIG. II.3. CEFR reactor block

A total of 37 activities for design demonstration have been performed. They include core physics mock-up tests, tests on the reactor block water mock-up for the decay heat removal (DHR) system, anti-earthquake test for the control rod mechanism, sodium fire detection and aerosol filtration proof tests, etc.

The CEFR's first tank of concrete was poured on 15 March 2000. The first criticality was reached on 21 July 2010. The 24-hour grid-connect test was finished in July 2011. The reactor was brought to full power at 5:00pm on 15 December 2014 and operated at this level continuously for 72 hours. All these tests have been completed successfully, which indicates that the CEFR project (Fig. II-4) has reached the national acceptance of its objectives.

FIG. II.4. Exterior view of CEFR

II.2. CHINA CLOSED NUCLEAR FUEL CYCLE TECHNOLOGY DEVELOPMENT

Nuclear fuel cycle technology mainly refers to the spent fuel reprocessing technology and MOX fuel manufacturing technology. China has carried out productive research on all relevant aspects, built a pilot plant and the nuclear fuel reprocessing and radiochemical laboratory facilities, and is building a fast reactor MOX fuel experimental production line.

II.2.1. Reprocessing technology development

Nuclear fuel reprocessing technology development envelopes both the aqueous and the dry method. The basic process in the aqueous reprocessing technology is the Plutonium-Uranium recovery by extraction (Purex). The dry reprocessing technology, also known as high-temperature reprocessing technology, was initially developed by Argonne National Laboratory (ANL) in the United States of America and the Research Institute of Atomic Reactors (RIAR) in the Russian Federation.

China began the research of an NPP spent fuel reprocessing technology in the 1970s. In 1986 China started the NPP spent fuel reprocessing pilot plant project (referred to as 'the Chinese Pilot Plant'), which was designed for the capacity of processing 50 tons of spent fuel annually. The Chinese Pilot Plant used a two-cycle process based on advanced Purex which was a Chinese independent and innovative technology. Spent fuel storage tanks (Fig. II.5) began to receive spent fuel from the Daya Bay NPP in 2003. The active commissioning of the Chinese Pilot Plant for spent fuel reprocessing was successfully completed on 21 December 2010 [II.1].

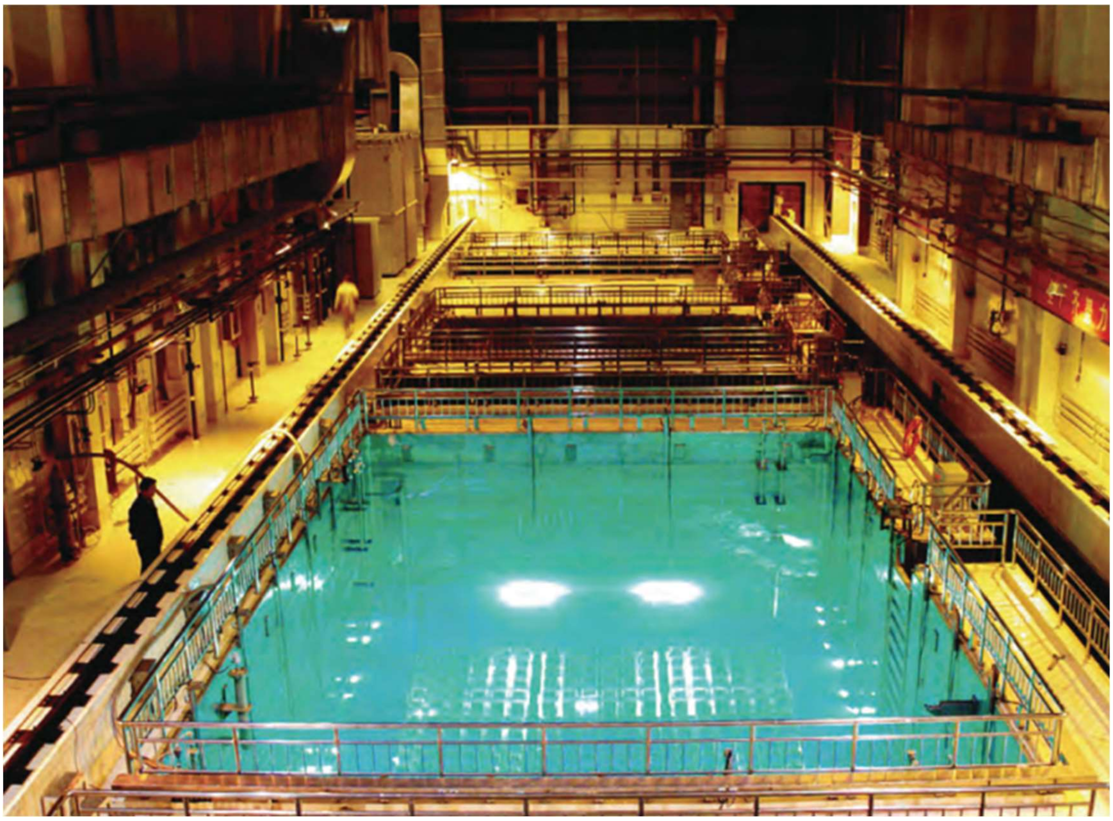

FIG. II.5. The storage pool of the Chinese Pilot Plant

After the design and construction of the Chinese Pilot Plant, a number of nuclear fuel reprocessing industry standards were established. The completion of the Chinese Pilot Plant shows that China has made significant progress in technology development and engineering application of the NPP spent fuel reprocessing technology, which provides valuable experience for the design and construction of industrial scale reprocessing plants. In 2008, research and development (R&D) on a commercial reprocessing plant was incorporated into the National Nuclear Power Science and Technology Major Project, and preliminary research was carried out. A larger scale commercial reprocessing plant project was planned based on the cooperation among China and France.

In the China Institute of Atomic Energy (CIAE), the project of the Nuclear Fuel Reprocessing and Radiochemistry Experimental Facility (referred to as 'the Radiochemistry Building', Fig. II.6) was approved in 2004. Construction of the Radiochemistry Building was completed in September 2014. In September 2015, the first thermal test was carried out. Through this project, China has mastered the design and manufacturing technology of the key reprocessing equipment. After being put into operation, the Radiochemical Building will serve as a R&D platform for reprocessing experiments and actinide chemistry, and will provide technical support for the construction of large-scale reprocessing plants in China, which would play an important role in the sustainable development of China's nuclear energy.

FIG. II.6. Exterior view of the Radiochemistry Building

China's research on the dry reprocessing technology began in the 1960s; basic research for the fluoride volatilization technology and the molten salt/metal reduction and extraction technology had been carried out. In the early 1990s, the basic research on molten salt electrochemical separation was carried out.

In this century, China's dry reprocessing technology research has undergone rapid development. The related pre-study for the fast reactor spent fuel, the ADS transmutation target and the molten salt reactor fuel reprocessing was carried out.

CIAE has initially established the uranium electrolytic refining research device which processes kilograms of heavy metal in each batch and employs the metal electrolytic refining process which has been verified in the experiment with 100 grams of cold uranium. CIAE and the China Institute of High Energy Physics (CIHEP), respectively, carried out research on the aluminium chloride melting, the aluminium alloy and fluoride melting, and on the electrolysis separation method. The Shanghai Institute of Applied Physics (SIAP) put forward some research on the Thorium-based molten salt reactor (TMSR) fuel reprocessing technology.

II.2.2. MOX fuel fabrication technology development

China's MOX fuel technology R&D has a larger technology gap compared to other technology holder countries. China decided to use the mechanical mixing method to produce the first batch of MOX fuel pellets. The MOX fuel pellet experimental production line has been completed, which has a building area of about 1 400 m^2 and a design output of about 500 kg heavy metal per year, and 14 sets of key devices have been manufactured. At present, samples of UO_2-CeO_2 pellets – MOX simulators – with uniform element distribution (Fig. II.7) have been produced and the MOX fuel pellet manufacturing process has been designed. This provided training to the scientific research team with certain theoretical knowledge and design research experience, which enabled carrying out the test production of the MOX fuel pellets. Matched with the process ability of the Chinese Pilot Plant and the refuelling demand of CEFR, the production line can be used to carry out MOX fuel R&D and small-scale batch production.

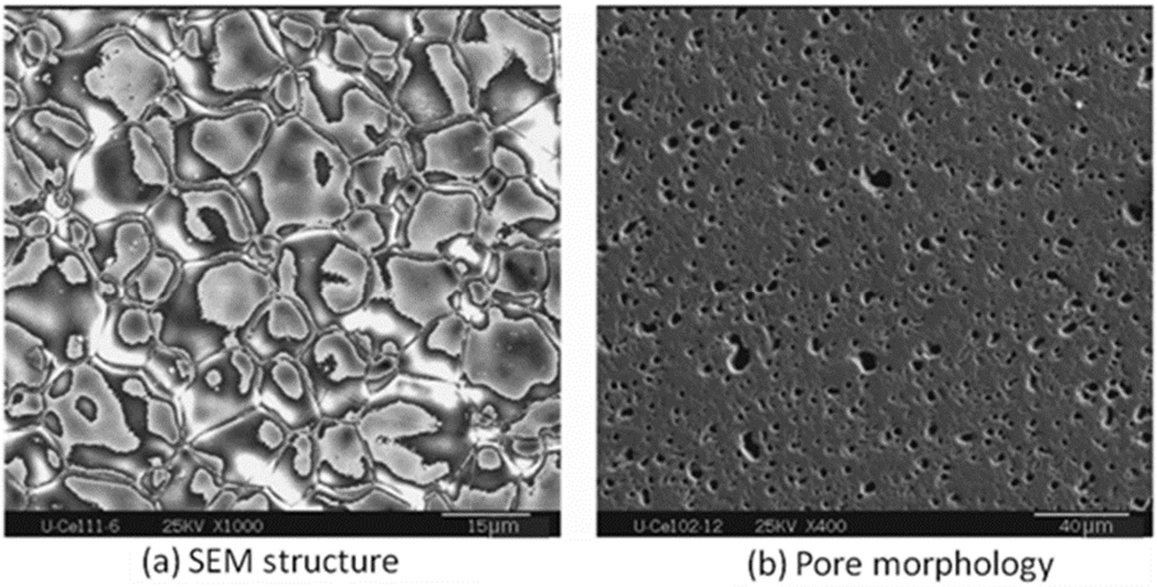

FIG. II.7. Microstructure of the simulated MOX fuel pellets fabricated in China

II.2.3. China's proposals for closed NFC and fast reactor development planning

Based on China's nuclear development strategy, the proposed closed nuclear fuel cycle system is shown in Fig. II.8:

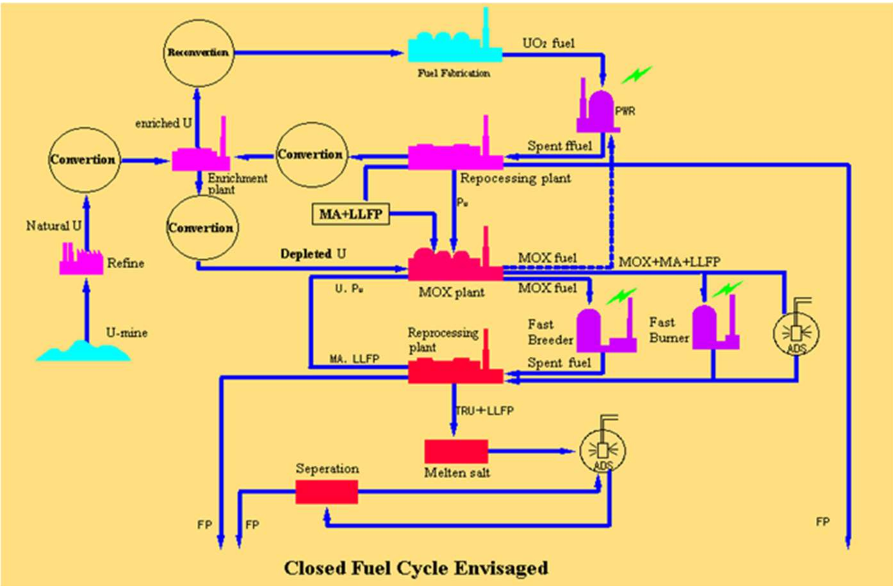

FIG. II.8. China's nuclear development strategy.

The fast reactor technology R&D platform is to be built which will be centred on the CEFR and will match the corresponding experimental and verification facilities. Radiation studies on advanced fuels and structural materials will be carried out at the CEFR.

Based on the experience of CEFR, the second step of China's fast reactor engineering technology is the 600 MW(e) demonstration fast reactor CFR600. The principles for the demonstration reactor design are as follows: a) it should be large enough to enable industrial verification; b) the technology should be advanced enough to meet the requirements for nuclear power plants several decades later; c) the technology and economy risks should be low enough; and d) the whole fuel cycle should be considered. The CFR600 is a sodium cooled, pool-type reactor which is very similar to CEFR. This reactor is a medium sized reactor, which could be designed as a breeder and a burner in a single reactor core. The main design features of CFR600 follow the requirements for the Generation IV nuclear technology including sustainability, safety and reliability. The main parameters for the design are as follows.

- ~1 500 MW(th), 600 MW(e);
- MOX fuel;
- Breeding ratio: ~1.2;
- Sodium as coolant;
- Na-Na-H_2O loops with 2 primary and secondary loops;
- One turbine;
- Negative feedback;
- Confinement;
- Core damage frequency <10^{-6}/year; the probability of a large-scale release of radioactivity <10^{-8}/year;
- Design life: 60 years.

The schematic diagram of CFR600 is given in Fig. II.9.

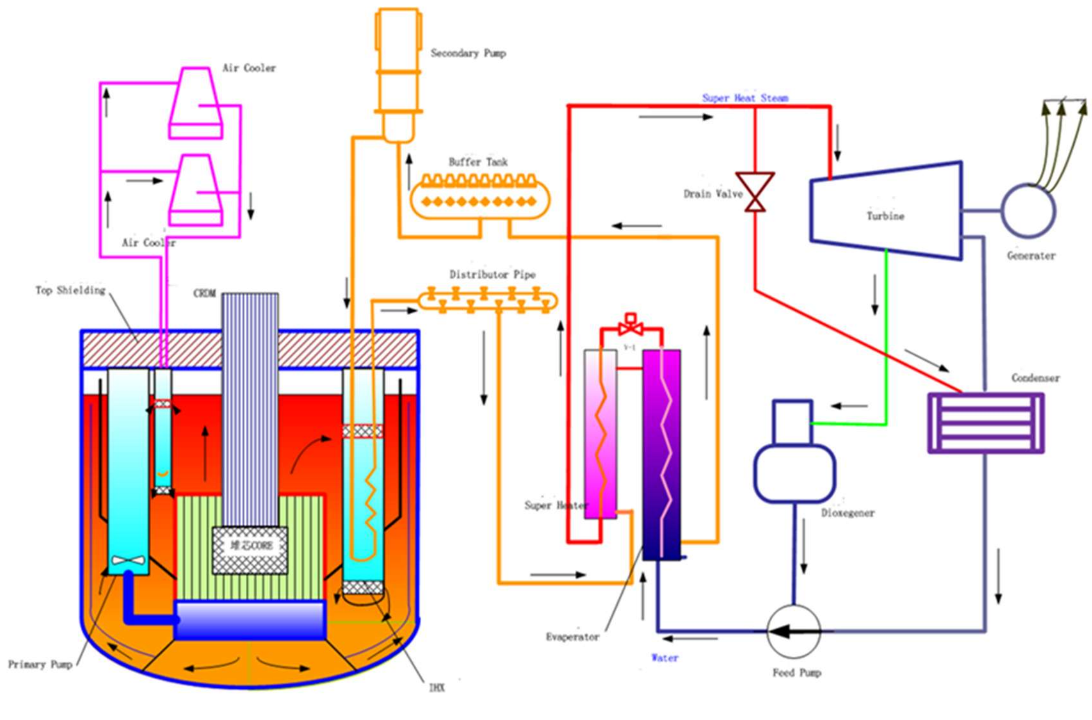

FIG. II.9. The schematic diagram of CFR600.

The design of CFR600 was initiated in August 2013. The conceptual design had been finished in 2014 and the primary design was expected to be completed by the end of 2016. At the same time, research work has been carried out on some key equipment and technology. The first CFR600 is expected to be operational in 2023 and five commercial NPPs of the same size are expected to enter the market in 2028.

The third step of the China's fast reactor engineering technology is a 1000~1200 MW(e) large-scale commercial fast reactor CFR1200. CFR1200 will attempt to use metal fuel and the integrated fuel cycle located in the plant area to ensure greater resource utilization efficiency and better proliferation resistance. It is envisaged that the first CFR1200 will be operational by 2028 with further broad commercial deployment foreseen around 2035. The proposed development scenario of the fast reactors in China is shown in Table II.2 [II.2].

TABLE II.2. PROPOSED PLANS FOR FAST REACTOR DEVELOPMENT IN CHINA

	NPP	Electric power	Construction start	Construction finish	Fuel type
1	CFR600	600 MW(e)	2017	2023	MOX
2	5×CFR600	5×600 MW(e)	2023	2028	MOX
3	CFR1200	1 200 MW(e)	2023	2028	Metal/MOX
4	n×CFR1200	n×1 200 MW(e)	2030	2035	Metal/MOX

"n" is the number of fast breeder reactor (FBR) units determined by the amount of industrial plutonium.

A 200-ton reprocessing plant based on the Chinese Pilot Plant technology is being designed. Another 800-ton reprocessing plant is being planned. A 20-ton MOX plant has also been proposed. Matching requirements for the critical fuel cycle facilities are shown in Table II.3

TABLE II.3. MATCHING REQUIREMENTS FOR CRITICAL FUEL CYCLE FACILITIES

Time	Reprocessing plant	MOX fuel manufacturing	FBR
2015	50 t/year Chinese Pilot Plant (RP-P) operation	0.5 t/year MOX product line (MOX-L) operation	
2017			CEFR MOX loading
2020	200 t/year reprocessing plant (RP-1) operation (PWR spent fuel)		
2021		20 t/year MOX manufacturer (MOX-1) operation	
2023			CFR60 operation
2026	800 t/year reprocessing plant (RP-2) operation	40 t/year MOX manufacturer (MOX-2) operation	
2028			CFR1200 and 5×CFR600 operation

a) RP-2 using advanced aqueous or dry method;
b) RP-1 simultaneously reprocessing MOX;
c) The construction requirement of 40 t/a MOX-2 was determined according to the research and verification of metal fuel and high temperature reprocessing

II.3. CHINA'S ADS TRANSMUTATION TECHNOLOGY RESEARCH PROGRESS AND PLANNING

A study on transmutation in a large sodium-cooled fast reactor was carried out, including core design and analysis of transmutation capability. At the same time, China has also carried out accelerator driven system (ADS) related research work. ADS will use the technology of the lead coolant.

In China, conceptual research of ADS was carried out in the 1990s. Since 1999, two '973' projects have been supported. At the China Institute of Atomic Energy (CIAE), a fast-thermal-coupled ADS sub-critical experimental facility 'QIMINGXING 1' was built. At the same time, a series of exploratory studies on the high-current Electron Cyclotron Resonance (ECR) ion source, on special computer software system for supporting ADS neutron research, on the ADS special neutron and proton micro data evaluation library, on accelerator physics and technology and on sub-critical reactor physics and technology were carried out.

At the same time, the Chinese Academy of Sciences (CAS) also focused on supporting the superconducting accelerator technology research and development, etc. The acquired experience and the accumulated data enabled CAS to start the project "Advanced Fission Energy Program – ADS Transmutation System" within the framework of the CAS Strategic Priority Research Program.

Based on the evaluated technical feasibility, CAS proposed the development of a roadmap for China's ADS technology (CIADS, Fig. II.10) to meet the significant demand of sustainable development of the national nuclear energy and to match existing R&D layout combined with the international development trend [II.3]. The major elements of this roadmap are described in brief below.

Phase 1: Principle Verification – Accelerator Driving Transmutation Research Facility. The main purposes are to resolve key technical issues of the ADS system, to determine the technical route to achieve small system integration, to master major key technologies of the ADS and the system integration technology from the machine integration level, and to accumulate the ADS debugging experience for the next step, which would be construction of the ADS demonstration devices.

Phase 2: Technical Validation – Accelerator-driven Transmutation Demonstration Unit. The main purposes are to enhance the technical indicators of the accelerator, spallation target and reactor, and to build an accelerator (~1 GV, 10 mA/Cockcroft–Walton) driven sub-critical system of ~0.5 GW(th). The system reliability is to be improved to achieve the availability of greater than 75% to meet the industrial requirements. The objective of this phase is to achieve engineering verification. The key issues to be addressed are reliability, fuel and material issues, and fuel and material selection for industrial extension units.

Phase 3: Industrial Promotion. In this phase the enterprise will implement the construction project, and the power of the reactor system would be extended to ~1 GW(th), to reach the industrial application level and verify the reliability and system economy at this level.

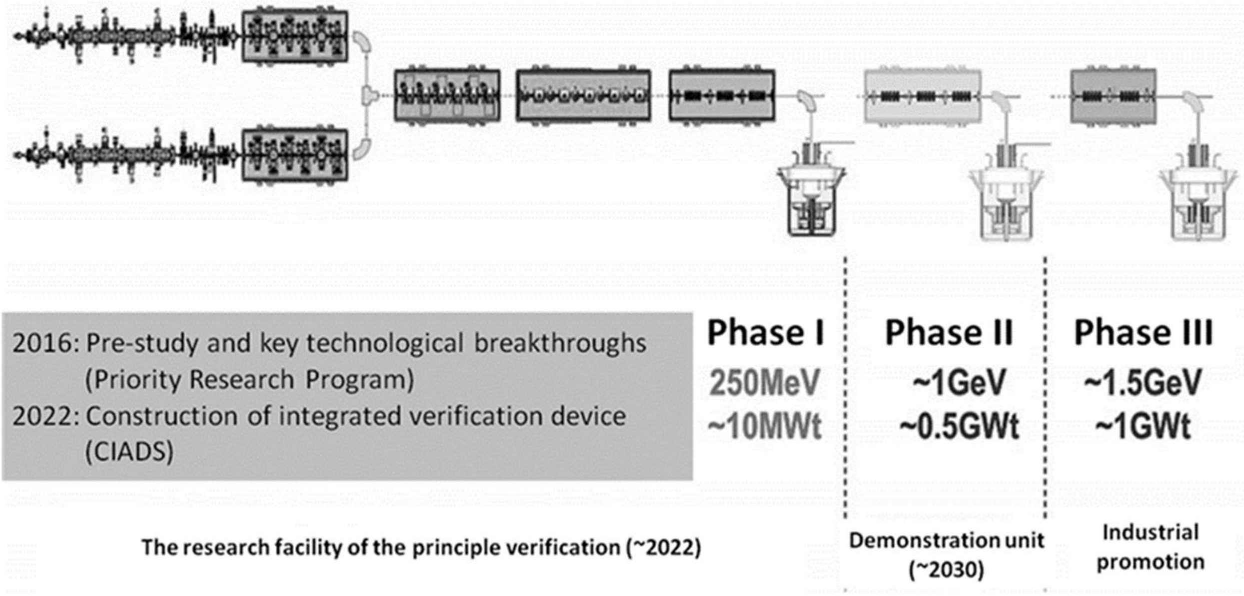

FIG. II.10. R&D roadmap of China ADS technology

In January 2011, CAS has performed a timely launch of the ADS Strategic Priority Research Program, as a part of the Advanced Fission Nuclear Energy Program. This Priority Program is aimed at the needs of China's nuclear energy development strategy. It focuses on resolving the key technical problems in the ADS accelerator, spallation target and reactor system for the first stage of the ADS technology development roadmap, including:

- a breakthrough for high current, high efficiency and reliable proton acceleration technologies;
- a breakthrough for the high-power heavy metal spallation target and coolant key technologies;
- a breakthrough for the subcritical fast neutron reactor related key technologies;
- implementation of prospective research work according to the needs of demonstration devices; and
- development of the ADS research platform.

According to the implementation plan of the Priority Program, five research tasks were implemented, including the overall scheme and related basic research, the proton linear accelerator, the heavy metal spallation target, the sub-critical reactor, and a platform and the supporting facilities. At present, every task has made relevant progress.

II.4. INTERNATIONAL COOPERATION

China has a huge market with very high national demand for nuclear energy technology and R&D. Maintaining an open and cooperative attitude in the fast reactor and nuclear fuel cycle technology, China actively carries out international cooperation under bilateral agreements with other technology developer countries, such as with the Russia Federation, France, the United States, Japan, the Republic of Korea, Belgium etc. as well as under international projects, such as INPRO and GIF. There are some on-going major cooperation activities, for example, China and France are carrying out technical cooperation on large-scale nuclear fuel reprocessing plant, and the China National Nuclear Corporation is working with

Terra Power from the United States on the Traveling Wave Reactor (TWR) which is one kind of advanced sodium cooled fast reactor.

II.5. CONCLUSION

China will have a large-scale demand for nuclear power in the future. In order to ensure the sustainable development of nuclear energy, the utilization of uranium resources should be improved, and the disposal of high-level radioactive waste should be reduced. This is as important as improving the safety and economy of the nuclear energy. China adheres to the nuclear energy development strategy of developing fast reactors and closed fuel cycle technologies.

China has built the China Experimental Fast Reactor, the pilot nuclear fuel reprocessing plant, the experimental reprocessing facilities, the experimental MOX production line, etc. Gratifying progress has been made on the R&D for the fast reactor and the closed fuel cycle technology. China is designing and building a larger-scale sodium cooled fast reactor and a nuclear fuel reprocessing plant, and is realizing the mass production of MOX fuel. A large number of studies are being carried out for the dry reprocessing, the ADS, the TWR and other advanced technologies.

China has carried out a fruitful cooperation with other countries on the fast reactor and closed fuel cycle technology and will actively participate in the development of a sustainable global nuclear energy in the future.

II.6. ACKNOWLEDGEMENT

The authors express their heartfelt gratitude to their colleagues, especially to Dr. YU Hong, Dr. ZHOU Peide and Dr. HU Yun for their contribution to this material.

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ANNEX III.

JAPAN'S EFFORTS FOR THE COMMERCIALIZATION OF A FAST REACTOR CYCLE

III.1. INTRODUCTION

Japan, with few energy resources, has been actively engaged in nuclear energy development to secure semi-domestic energy resources, while planning to put the light water reactors (LWRs) cycle into practical use and to transition to the fast reactor (FR) cycle that efficiently utilizes plutonium recovered by the reprocessing of LWR spent fuel. The original design of LWRs in Japan had been introduced from overseas, but Japan achieved the domestic production and the improvement and standardization of LWRs resulting in operating 54 units (total installed capacity: 49 GW(e) of LWRs), which accounted for about one-third of the power demand before TEPCO's Fukushima Daiichi Nuclear Power Station (F1) accident in March 2011. Elements of the LWR fuel cycle were in practical use at the time of the F1 accident except the Japan Nuclear Fuel Limited's (JNFL) Reprocessing Plant (processing capacity: 800 t U/year) and the JNFL's MOX Fuel Fabrication Plant (processing capacity: 130 t HM/y).

The Nuclear Regulatory Authority of Japan (NRA) was established in 2012 based on lessons learned from the F1 accident and the NRA enforced new regulatory requirements for nuclear facilities in 2013. The new regulatory requirements include strengthening measures against severe accidents and the introduction of a system for adopting the latest technical findings into existing facilities (back-fit system). In July 2013, the NRA started a review of the adoption by the commercial power plants to the new regulatory requirements and then, in December 2013, of the conformity of nuclear fuel cycle facilities. Until now (as of March 2019), safety review applications for the restart of 27 units of 16 nuclear power stations under the new regulation were submitted to the NRA, and as a result of NRA's review, 15 units have obtained permission of licence amendment and, out of these, nine reactors are in operation. Regarding nuclear fuel cycle facilities, safety review is underway for JNFL's Reprocessing Plant, JNFL's MOX Fuel Fabrication Plant and so on. JNFL announced that the construction of the Reprocessing Plant will be completed in the first half of fiscal year (FY) 2021 and that of the MOX Fabrication Plant in the first half of 2022.

Meanwhile, Japan's fast reactor fuel cycle development, which had been addressed mainly by the Japan Atomic Energy Agency (JAEA), aimed at early commercialization. However, the "Fast Reactor Cycle Technology Development (FaCT) Project" was frozen after the F1 accident. The Council on Fast Reactor Development was established in September 2016 to discuss and prepare a draft paper on policies concerning the future development of fast reactors in Japan. Based on the outputs of these discussions, the Inter-Ministerial Council for Nuclear Power (Inter-Ministerial Council) made a decision on the new policy for fast reactor development in Japan, which stated that a strategic roadmap will be compiled by 2018 for the realization of the policy. The Inter-Ministerial Council also decided that the Prototype Fast Breeder Reactor (FBR) Monju will not resume operation as a reactor and will be decommissioned [III.1]

The following sections introduce Japan's efforts for the commercialization of a fast reactor cycle, such as the history of fast reactor cycle development, the scenario of early commercialization of fast reactor cycle (currently no progress) described in the "Japan's Nuclear Energy National Plan" formulated by the Ministry of Economy, Trade and Industry (METI) in August 2006 [III.2, III.3], and the summary of international collaborations in which Japan has been involved for the fast reactor cycle technology development.

III.2. THE SIGNIFICANCE AND IMPORTANCE OF FAST REACTOR CYCLE DEVELOPMENT

Fast reactors can significantly contribute to sustainable nuclear energy production, as well as to solving the shortage of natural resources and reducing the volume and radiotoxicity of radioactive wastes as follows.

A fast reactor with related fuel cycle (fast reactor cycle) is 60 times more productive compared to a thermal reactor by breeding fissionable material and recycling uranium and plutonium recovered from reprocessing of spent fuel and enhances the sustainability of nuclear energy providing fissionable material supply for thousands of years (Fig. III.1, Fig. III.2).

Furthermore, the fast neutron spectrum has physical characteristics capable of burning the long-lived minor actinides (MA: neptunium, americium and curium) reducing the volume of high-level radioactive wastes, reducing the heat load to the geological disposal and reducing the required time for isolation of fission products from tens of thousands of years to hundreds of years (Fig. III.3).

III.3. THE HISTORY OF FAST REACTOR CYCLE DEVELOPMENT IN JAPAN

The Japan Atomic Energy Commission (JAEC) adopted the “Basic Policies on Development of Power Reactors” in May 1966, which included the development of the sodium-cooled fast reactor (SFR) using plutonium and uranium mixed-oxide (MOX) fuel by self-dependent technologies, the construction of an experimental reactor and a prototype reactor for solutions and so on[1]. In order to carry out the fast reactor development in an integrated fashion, the Power Reactor and Nuclear Fuel Development Corporation (PNC; current JAEA) was established in October 1967 based on the adopted policy.

JAEA launched the O-arai Engineering Center (currently O-arai Research and Development Center) in Ibaraki, intensively constructed large-scale test and research facilities to conduct basic and engineering researches for sodium-handling technologies, post-irradiation examinations, etc., and constructed the Experimental Fast Reactor Joyo (thermal output: 50–75 MW(th) in Mk-I breeding core; 100 MW(th) in Mk-II irradiation core; 140 MW(th) in Mk-III irradiation core) at the O-arai Research and Development Center and the Prototype Fast Breeder Reactor Monju (electric output: 280 MW(e)) in Tsuruga, Fukui, reflecting upon the research results. JAEA also launched the Tokai site (currently Nuclear Fuel Cycle Engineering Laboratories) to carry out researches on MOX fuel fabrication, reprocessing, treatment and disposal of radioactive wastes, etc. (Fig. III.4).

Joyo achieved first criticality in April 1977 and started operation in Mk-I breeding core in 1978. Initially generating 50MWt of heat, its power was raised to 75MWt in 1979. Following an upgrade, power was increased to 100MWt in 1983, and was further raised to 140MWt in 2003 in order to upgrade the irradiation test capacity of the reactor [III.4].

Monju achieved first criticality in April 1994 and was connected to the grid in August 1995. Towards the end of the commissioning test, on 8 December 1995, a sodium leak accident from the secondary heat transport system occurred in a piping room of the reactor auxiliary building at Monju. It resumed operations in May 2010 after having been shut down for almost 15 years following a sodium leak. In August 2010 another accident, involving dropped machinery (in-vessel transfer machine), shut down the reactor again [III.4, III.5].

[1] The Japanese government has decided to develop fast reactors step by step such as: "experimental reactor" to confirm the design principles in a pilot scale and to accumulate the fuel and material irradiation data; "prototype reactor" to establish a sodium handling technology and to demonstrate the reliability as a power generation plant; "demonstration reactor" to clarify the outlook for the economy in the stage of practical use and "commercial reactor".

Meanwhile, the development of a demonstration reactor was carried out in earnest mainly by utilities in the 1980s, and the Japan Atomic Power Company (JAPC) was selected as the construction manager and operator of the demonstration fast reactor in 1985 and was commissioned to develop it. However, a series of demonstration fast reactor developments was paused in the end of FY 1999 because of changes in the environment and various factors, such as increased demands including improvement in economics of the fast reactor due to the alleviation of the natural uranium supply problem and the deregulation of electric utilities.

The results of the accomplished demonstration fast reactor development were passed on to the "Feasibility Study on Commercialized Fast Reactor Cycle Systems" (FS), which was started in July 1999 by JAEA and electric utilities in collaboration with the Central Research Institute of Electric Power Industry (CRIEPI) and the manufacturers for the purpose of presenting an appropriate picture of commercialization of the fast reactor cycle as a future base-load power source, including the research and development (R&D) programmes leading up to the commercialization.

A wide range of technical options have been evaluated to select several promising concepts as candidates for the commercialization in the Phase I study of FS from July 1999 to FY 2000.

In the Phase II study (FY 2001–2005), component tests and analyses related to the feasibility were conducted, designs were examined in light of the results of Phase I, and plant concepts of the fast reactor system and the fuel cycle system that maximize the benefits were developed. These plant concept technologies were evaluated for their compatibility with the design requirements and technical feasibility requirements based on development goals (safety, economic competitiveness, efficient utilization of nuclear fuel resources, reduction of environmental burden and proliferation resistance). As a result, the Japan sodium-cooled fast reactor (JSFR) with MOX fuel, advanced aqueous reprocessing, and the simplified pelletizing fuel fabrication system was selected as the most promising concept (main concept) for commercialization [III.6].

In FY 2006 the Fast Reactor Cycle Technology Development (FaCT) Project was started and advanced the R&D, focusing on the main concept with the aim to present the conceptual design of the demonstration and commercial fast reactor fuel cycle facilities and the research plan covering the path to commercialization after the judgment of innovation technologies in FY 2010. However, the FaCT project was frozen in 2011 due to the F1 accident.

There have been a variety of changes in the environment surrounding the fast reactor R&D recently, particularly since the F1 accident. These changes include the formulation of new regulatory requirements, the inauguration of Japan-France cooperation in developing fast reactors, and the Electricity Systems Reform. In light of the latest situation, the Council on Fast Reactor Development was established to discuss future approaches to the fast reactor development at a meeting of the Inter-Ministerial Council for Nuclear Power (Inter-Ministerial Council) held in September 2016. The new policy for fast reactor development in Japan and the policy on the Monju were decided at the meeting of the Inter-Ministerial Council held in December 2016 [III.1].

The new policy for fast reactor development in Japan states that Japan should maintain and develop technical infrastructures at a world-class level and develop and commercialize fast reactors with high level of safety and economics, thereby aiming to play a leading role towards the realization of international standards. It also states that a Strategy Working Group will be established under the Council on Fast Reactor Development to develop "Strategy Roadmap of Fast Reactor Development" (tentative name) that would specify development tasks in the coming 10 years in around 2018.

The policy on the Monju acknowledges that various technological outcomes and knowledge at Monju have been accumulated and basic technologies for establishing a system of power-generating plant have been acquired in this prototype reactor, which has already secured its important role in future fast reactor development. However, it has been decided that Monju should not resume operation but be decommissioned for the following reasons:

- Expected increase of time and cost for the restart of Monju by the adoption of the new regulatory requirements (it will take at least 8 years to resume operation and cost more than 540 billion yen (5 billion dollars) until the end of operation if it is supposed to operate for eight years (five cycles) including performance tests).
- There was no alternative Monju operator who accommodates the NRA’s recommendation issued in November 2015.
- After the restart of Monju it could have been expected that useful data for the realization of a demonstration fast reactor, particularly a loop-type demonstration fast reactor, would be obtained. However, it was found that such useful data can also be obtained by using the domestic test facilities and through international cooperation, as well as through R&D for the next demonstration reactor stage.

The Strategy Roadmap of Fast Reactor Development that was drafted by the Council on Fast Reactor Development based on the discussion in the Strategy Working Group, was decided at the Inter-Ministerial Council on 21 December 2018. The Fundamental Concepts and Action Plans for fast reactor development in the Roadmaps are as follows [III.7]:

Fundamental Concepts

- The significance of fast reactor development in Japan:
  - Effective use of uranium resources, and reduction of volume and potential toxicity of high-level radioactive wastes.
  - An appropriate fast reactor will start its operation at the appropriate time in the mid-21st century.
- The major roles of the policy on the nuclear technology including fast reactor:
  - To primarily ensure the highest level of safety.
  - To develop approaches by which uncertainties in the future can be flexibly dealt with.
- The roles of each of the parties involved over the next decade:
  - The Government shows the basic direction of the fast reactor development, and sets the objective. It also provides appropriate financial support on the development by private sectors.
  - Stakeholders including electric utilities conclusively decide one of the technologies. They should participate in the development of the promising technology from its early stage.
  - JAEA maintains and advances the R&D while accommodating private sectors’ needs. It also establishes global standards of design techniques and safety criteria.
  - Manufacturers further innovate the technology by their creativity and originality.

Action Plans

- Build the technology base (platform) and innovate the technology toward the practical use of fast reactors with international cooperation.
- The development process can be roughly divided into three phases:
  - Phase 1: Promotion of competition (over about the first five years).
    The government promotes the competition of various innovative technologies among private sectors.
  - Phase 2: Narrowing down and focusing on the technology (from around 2024).

The government, JAEA, and electric utilities, in cooperation with the manufacturers, will narrow down the technology that will be possibly adopted.

- Phase 3: Examination of issues and the process of the development.
  The development process will be examined when all the relevant parties have arrived at a consensus about the selection.

III.4. THE SCENARIO FOR FAST REACTOR CYCLE COMMERCIALIZATION

In October 2005, the Japanese government approved the Framework for Nuclear Energy Policy [III.8, III.9] formulated by JAEC; it defines the basic principles for nuclear energy development. In order to realize the Framework for Nuclear Energy Policy, METI issued the Japan's Nuclear Energy National Plan in August 2006. This section describes the basic scenario adopted for commercialization of the fast reactor cycle discussed in the Japan's Nuclear Energy Nation Plan and the challenges and points of relevance to be considered, etc. [III.2, III.3]. Currently, after the F1 accident, there is no progress along this trend, while the new Strategic Roadmap was formulated, as already mentioned in Section III-3.

III.4.1. Basic targets presented in the Framework for Nuclear Energy Policy

The Framework for Nuclear Energy Policy formulated by JAEC in October 2005 was adopted by the Cabinet as the basic policy, and the basic targets are as follows (Fig. III.5):

– Aiming at maintaining or increasing the current level of nuclear power generation of 30 to 40% of the total electricity generation even after 2030;

– Steady advancement of the nuclear fuel cycle;

– Aiming at commercial introduction of a fast reactor by 2050.

Based on these basic policy and basic targets, the scenarios of transition were studied including the "Basic Scenario" which was assumed in the Japan's Nuclear Energy National Plan and the challenges for the period of commercialization of the fast reactors around 2050. The outlines of the "Basic Scenario" are as follows.

III.4.2. The scenario of transition towards the commercialization of the fast reactor cycle (as of 2006)

III.4.2.1. Basic Scenario

The Basic Scenario (Fig. III.6 and Fig. III.7) included the following provisions:

- Resume the operation of the Prototype Fast Breeder Reactor Monju at the earliest possible time with the aim of achieving the goals of "demonstrating its reliability as an operational power plant" and "establishing sodium handling technology based on operational experience";
- Recycle Pu recovered in the reprocessing of spent fuel from LWRs (plutonium use in LWRs) until the introduction of a commercial fast reactor and store the spent fuel from plutonium use in LWRs for future use in fast reactors;
- Complete the "Feasibility Study on the Commercialized Fast Reactor Cycle Systems (FS)" by around 2015; present an appropriate picture of the commercialized fast reactor cycle and a R&D plan;
- Implement the necessary demonstration processes based on the results of the FS, aiming at the realization of demonstration fast reactors and other related facilities by around 2025; conduct engineering-scale hot testing and commercial-scale testing related to reprocessing and fuel fabrication for the commercialization of the fast reactor cycle;

- Develop next generation LWRs for the replacement of existing reactors which are to be decommissioned around 2030;
- Complete the demonstration processes of reactor and fuel cycle facilities for the introduction of commercial fast reactors before 2050;
- Start operation of the second reprocessing plant by the time the JNFL's Reprocessing Plant finishes its operation around 2045; reuse plutonium recovered from the reprocessing plant for fast reactors; and
- Start introducing commercial fast reactors before 2050; subsequently replace existing LWRs with fast reactors when they finish operation.

III.4.2.2. Sub Scenarios
("Accelerated fast reactor introduction case" and "Delayed fast reactor introduction case")

In order to secure flexibility to meet future uncertainties, given possible changes in the climate surrounding the nuclear industry, such as technological trends, trends in uranium supply and demand, and the international situation, the two sub scenarios (Sub Scenario 1: the case of accelerated fast reactor introduction where the fast reactor introduction starts early because of acceleration in uranium demand due to a rapid spread of nuclear energy, etc.; and Sub Scenario 2: the case of delayed fast reactor introduction where the fast reactor introduction is delayed because of delays in fast reactor technology development or stagnant uranium demand), were studied in addition to the Basic Scenario.

The common issues were considered for each scenario when these scenarios were studied. The results of these studies are summarized below as obtained at the time of the completion of the study. No reference to further developments is made.

III.4.3. Common issues for scenarios

III.4.3.1. Considerations for the selection of scenarios and technologies for the fast reactor cycle commercialization

In selection of the scenarios leading to fast reactor cycle commercialization and of the technologies to realize such commercialization, it is necessary to keep in mind that Japan should follow the global trends without isolation or delay, based on the progress of technological development in the world, on the situation with nuclear power generation, on market trends, etc.

It is necessary to examine and find a proper way for the development and construction of the demonstration fast reactor towards the establishment of a fast reactor cycle. There are two ways here: 1) domestic implementation, which is appropriate from the viewpoints of technology cultivation, human resource development, security, etc., and 2) joint development in international frameworks which is applicable in terms of the diversification of investments, etc.

In the demonstration process from the Prototype Fast Breeder Reactor Monju to the commercial fast reactor cycle, possible options are A) the demonstration reactor and the introduction of commercial reactor, B) remodelling of the Monju and the introduction of commercial reactor, or C) a large-scale test facility for component testing and the demonstration reactor. Comparing the options, C has an advantage in terms of suppressing the investment cost because it does not include introduction of a commercial reactor, but A is desirable in terms of ensuring reliability of technological demonstration.

III.4.3.2. Functions of the second reprocessing plant

As mentioned in the Framework for Nuclear Energy Policy, the examination on the construction of the second reprocessing plant should have been started around 2010. It should have been prepared through performing the research studies and data accumulation related to functions of the second reprocessing plant.

III.4.3.3. Development of fuel cycle technologies (reprocessing technologies, etc.)

It is important to construct an engineering-scale fast reactor cycle reprocessing plant to promote R&D on fuel cycle technologies, such as reprocessing technology, and to devote efforts to the design, construction and operation of the facility considering the technology transfer for the second reprocessing plant to be constructed in the future. It is also necessary to explore measures for maintaining know-how through international cooperation.

In addition, considering that the interval between the construction of the reprocessing plants (around 40 years) is longer than that for nuclear power plants, the research on methods is needed for systematizing know-how on technologies in an engineering manner and for effectively handing down the technologies.

III.4.3.4. Succession of technologies and know-how related to the fast reactor cycle to the next generation

In order to transfer technologies and know-how related to the fast reactor cycle to the next generation taking into account the ages of staff members who are experienced in the research on Monju (this experience currently belongs to manufacturers, JAEA, etc.), it is necessary to establish in the FS a succession in the development of technologies and in human resources and to start working on the demonstration reactor before the skilled staff retires.

III.4.3.5. Results for technology transfer and succession of technological development

Including the scheme and human affairs, how to transfer results of technological development amid the industrialization from the development stage to commercial stage, or in the case of delay in the schedule of commercialization, is a matter for consideration in the future. Moreover, it is an important to consider whether the subject of research should take up not only the development of performance specifications but also the development of structural specifications as in the past in terms of preventing the spread of research results and retaining technologies within the country as the internationalization of the nuclear industry progresses.

III.4.3.6. Response to efforts toward non-proliferation

It is necessary to consider how to respond when Japan's fast reactor cycle system needs to be recognized as part of the regional (Asia, etc.) fuel cycle system as discussions on non-proliferation become more intense.

III.4.4. Major points of attention

III.4.4.1. Natural uranium demand

The amounts of natural uranium demand assumed in the Basic Scenario and the Sub Scenario 1 are much lower than that in the Sub Scenario 2. When the uranium supply becomes tight, there is a risk of hindrance to the maintenance of stable energy supply in the Sub Scenario 2.

III.4.4.2. Human resources

In the case of Sub Scenario 2 where technological development, etc. until the fast reactor introduction should be continued for a long period, there is a strong possibility to have problems in maintaining and securing engineers engaged in the area of fuel cycle and succeeding technologies compared with the Basic Scenario and Sub Scenario 1.

Meanwhile, the Sub Scenario 1 has a possibility to operate two reprocessing plants simultaneously. In that case it is necessary to consider appropriate staff allocations in addition to the maintenance and security of engineers in order to operate both plants smoothly.

III.4.4.3. Ensuring of reliability required for commercialization and schedule

In the Basic Scenario it is required to conduct technological development and reliable demonstrations in a shorter period of time until the introduction of the commercial fast reactor cycle in comparison with the time period of the Sub Scenario 2. It is also necessary to note that the number of options in the demonstration stage is limited in the Sub Scenario 1 since its time period for technological development and demonstrations is shorter than that of the Basic Scenario (i.e. it would be difficult to have the 2-step approach introducing the demonstration and commercial fast reactors).

III.4.4.4. Technological development

In the Sub Scenario 2, it is necessary to conduct technological validation and development for using plutonium recovered from spent MOX fuel from LWRs again in LWRs (plutonium use in LWRs), adding to the technological development required in the Basic Scenario and Sub Scenario 1.

III.4.4.5. Stockpile of spent fuel

The stockpiles of spent fuel in the Basic Scenario and Sub Scenario 1 are lower than that of the Sub Scenario 2.

III.5. INTERNATIONAL COOPERATION IN TECHNOLOGICAL DEVELOPMENT OF THE FAST REACTOR CYCLE

III.5.1. The necessity and importance of international cooperation in fast reactor cycle development

Toward the realization of the Basic Scenario, Japan has strived to establish the fast reactor cycle technology with Japan's own developed technologies. On the other hand, in the course of Japan's technological development there have been international cooperation activities with other countries on the establishment of fast reactor cycle as well, and a lot of experience and knowledge have been accumulated. After Japan's own experience and knowledge reached a certain level, Japan started promoting many collaborative activities such as joint research, personnel exchange, and sharing of facilities based on mutually beneficial cooperation. Advantages of international cooperation for Japan through shared experiences, knowledge and infrastructures of other countries help Japan to proceed with efficient and effective R&D, in the following ways:

- Reducing risk and required resources of R&D by promoting fast reactor cycle R&D in international frameworks for joint research and joint development;
- Establishing the domestic technical basis of the fast reactor cycle leading to the early commercialization by promoting international cooperation;
- Improving the safety and reliability of the fast reactor cycle by developing and maintaining safety standards for fast reactor cycle technologies in international cooperative frameworks and setting international standards;
- Developing international consensus on fast reactor cycle technologies to improve social acceptance as it is vital to build consensus domestically and internationally as well as to technologically ensure non-proliferation and nuclear security due to considerable amounts of fission products including plutonium (sensitive substance) contained in a fast reactor cycle system; and
- Fostering world class personnel by dispatching to partners overseas.

The next section explains the history of Japan's international cooperation and major examples.

III.5.2. The history of international cooperation

Figure III.8 shows fast reactors that have been developed in various countries to date and future development plans in each country. When JAEA was established in 1967, it was said that the level of Japanese nuclear technologies was 10 years behind the level of the developed countries. The aim of establishment of JAEA was to make up for the delay as well as to carry out development of independent technologies on advanced reactors and the nuclear fuel cycle. Thus, JAEA concluded cooperation agreements with developed countries such as the United States, the United Kingdom and France shortly and made efforts to obtain information of advanced technologies from these countries as well as to strengthen ties with these countries through meetings under cooperation agreements and exchanges of personnel (Fig. III.9). However, since most facilities of O-arai Research and Development Centre were in design stages or under construction for several years after the establishment of the agreements, JAEA was able to provide only studies for future plans and obtained valuable information from partners after paying a proper price.

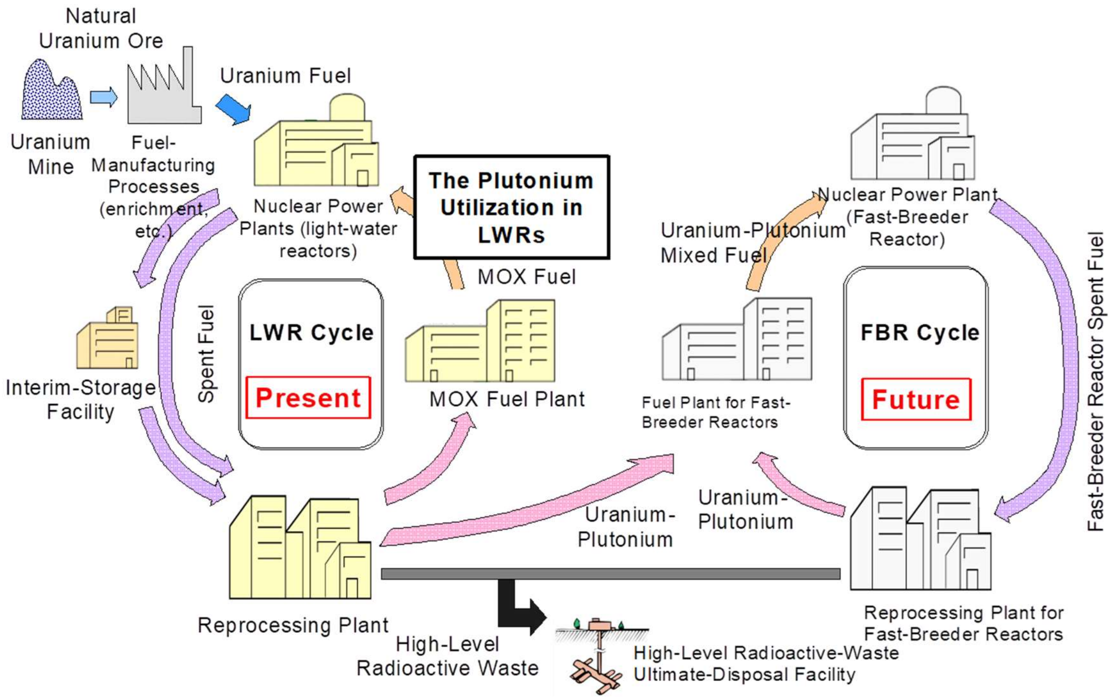
In 1977 the Experimental Fast Reactor Joyo achieved criticality, and around this time large-scale test facilities in O-arai were completed, sequentially resulting in the great improvement of JAEA's R&D capability and achievement of valuable results. As the amount of information that JAEA could provide increased, the nature of international cooperation changed to one based on the principle of reciprocity and the number of joint research efforts and exchanges of engineers increased rapidly around this time.

The bilateral and multilateral cooperation on sodium-cooled fast reactors and related fuel cycle in which JAEA is engaged are shown in Fig. III.10.

III.6. CONCLUSION

Fast reactors with closed fuel cycle contribute to sustainable nuclear development in terms of effective use of uranium resources and reduction of volume and potential toxicity of high-level radioactive wastes. Japan, a resource-poor country, has been carrying out the fast reactor cycle R&D for the commercialization through the stages of the construction and operation of the Experimental Fast Reactor Joyo and the Prototype Fast Breeder Reactor Monju, as well as the R&D of a demonstration reactor, as a national policy from the initial stage of nuclear energy development. Although it was decided in December 2016 after the F1 accident that Monju will not resume operation as a reactor, but is set to be decommissioned, Japan intends to firmly maintain the basic policy to promote the nuclear fuel cycle and work on the fast reactor development.

The Strategic Roadmap of Fast Reactor Development was decided in December 2018 and it states that an appropriate fast reactor will start its operation at the appropriate time of the mid-21st century, and the technology base (platform) and innovative technology towards the practical use of fast reactors should be built with international cooperation.



Source : The Challenges and Directions for Nuclear Energy Policy in Japan - Japan's Nuclear Energy Renaissance Plan -, Nuclear Energy Policy Planning Division, Ministry of Economy, Trade and Industry (METI) (December 2006)

FIG. III.1. Nuclear fuel cycle.

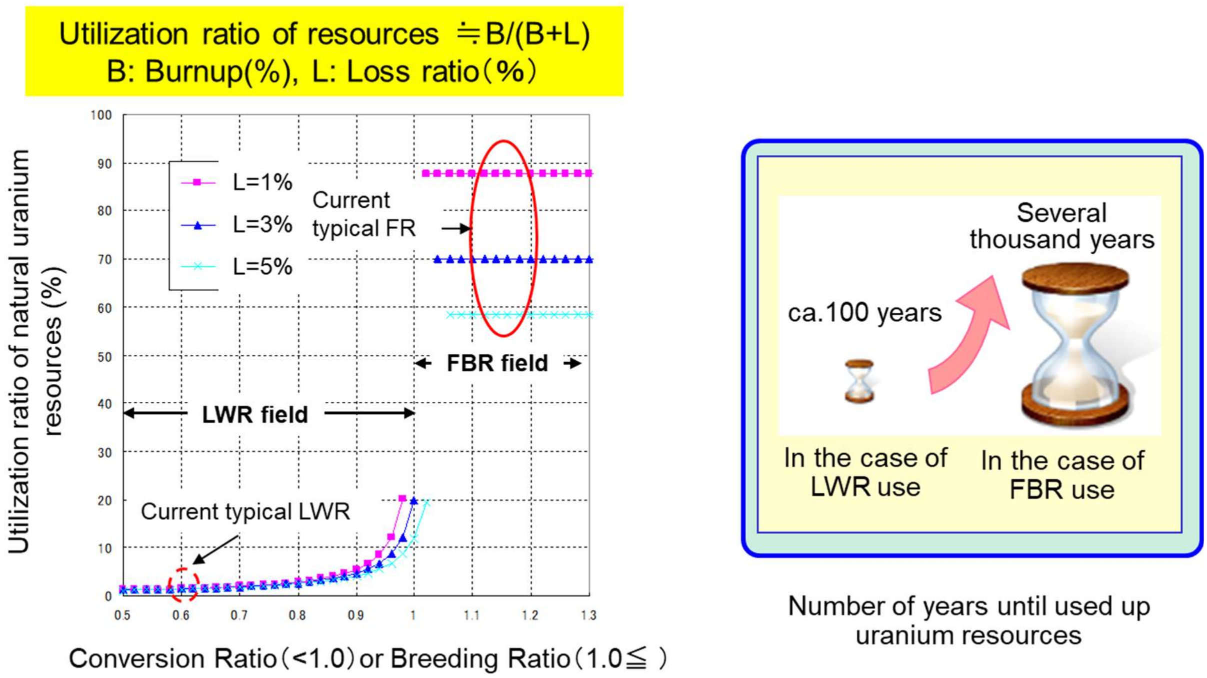


FIG. III.2. Effective use of uranium resources.

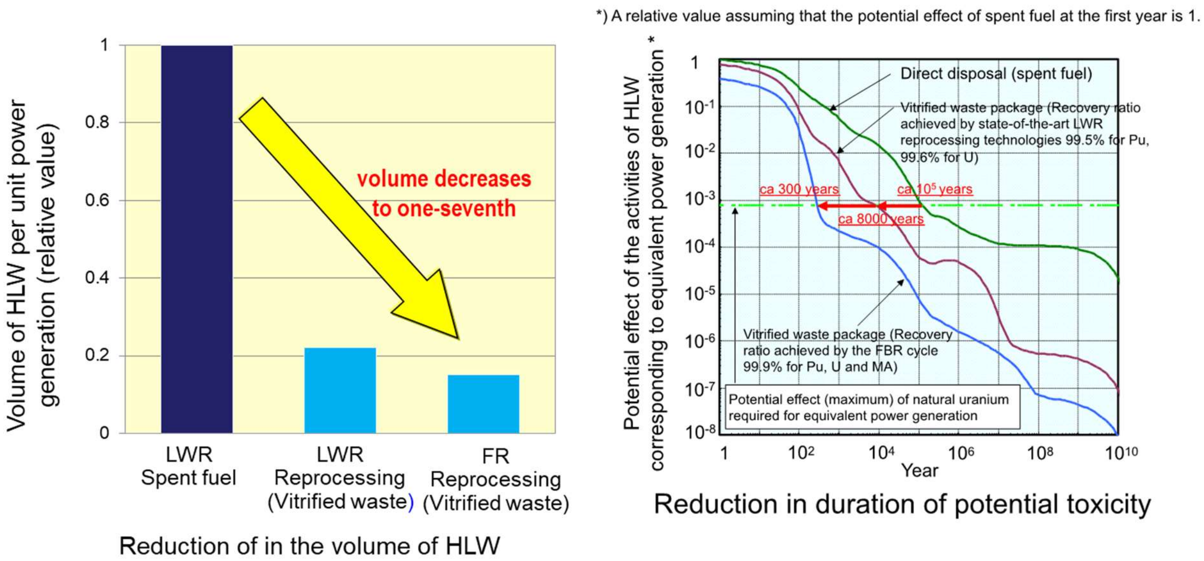


FIG. III.3. Reduction of the amount and radiotoxicity of radioactive wastes.

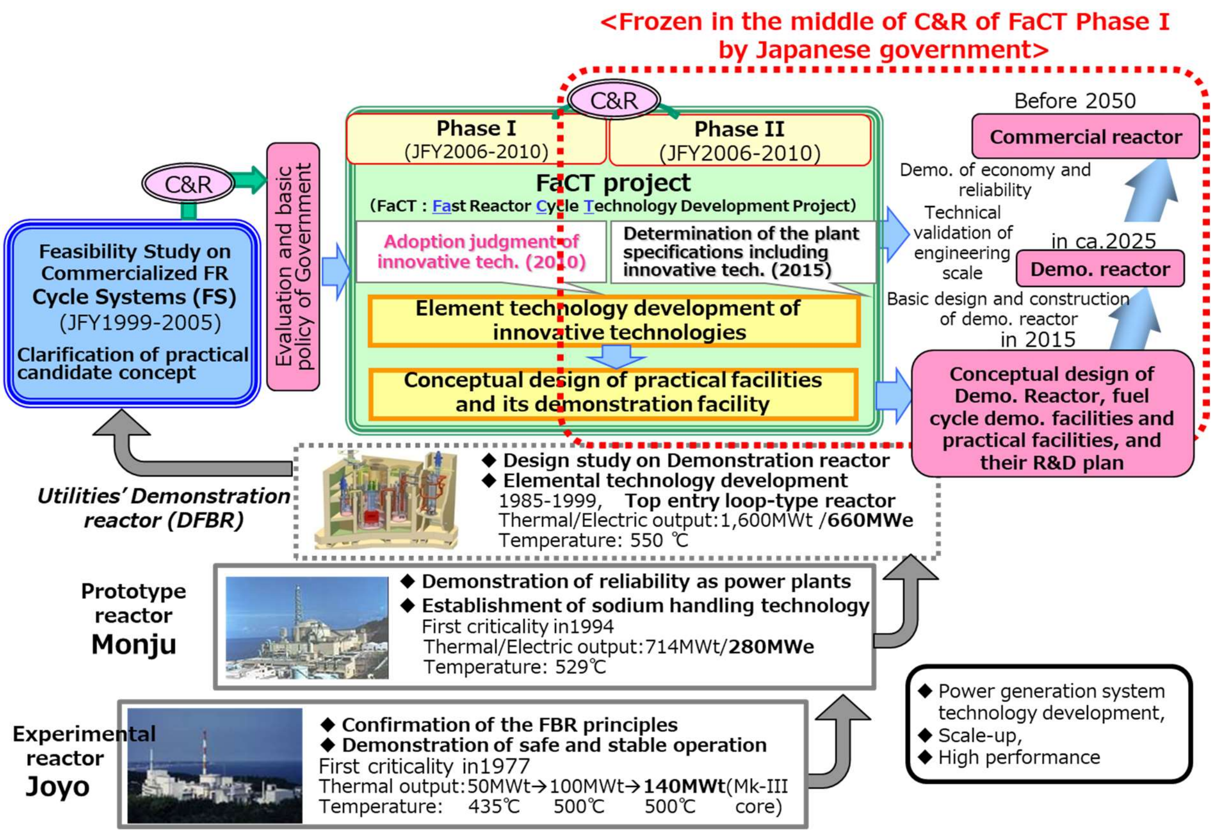
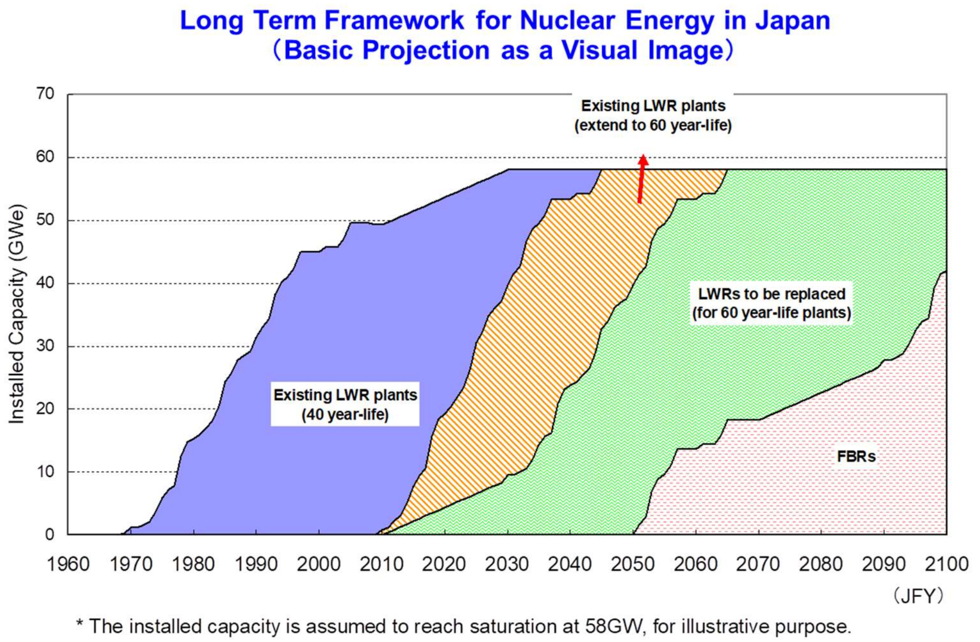
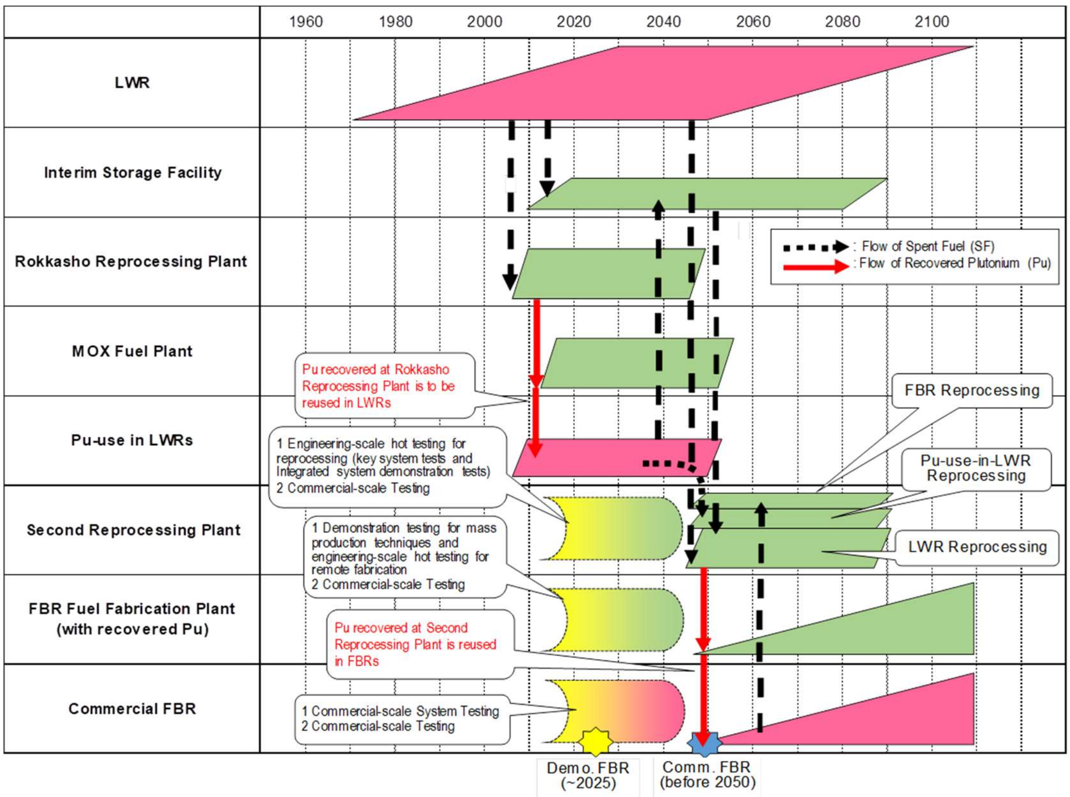


FIG. III.4. Fast reactor development step in Japan.



Source : The Challenges and Directions for Nuclear Energy Policy in Japan- Japan's Nuclear Energy Renaissance Plan -, Nuclear Energy Policy Planning Division, Ministry of Economy, Trade and Industry (METI) (December 2006)

FIG. III.5. Medium and long-term direction of nuclear power introduction in Japan.



Source : Japan's Nuclear Energy Nation Plan, Ministry of Economy, Trade and Industry (METI) (August 2006)

FIG. III.6. Base scenario (1/2).

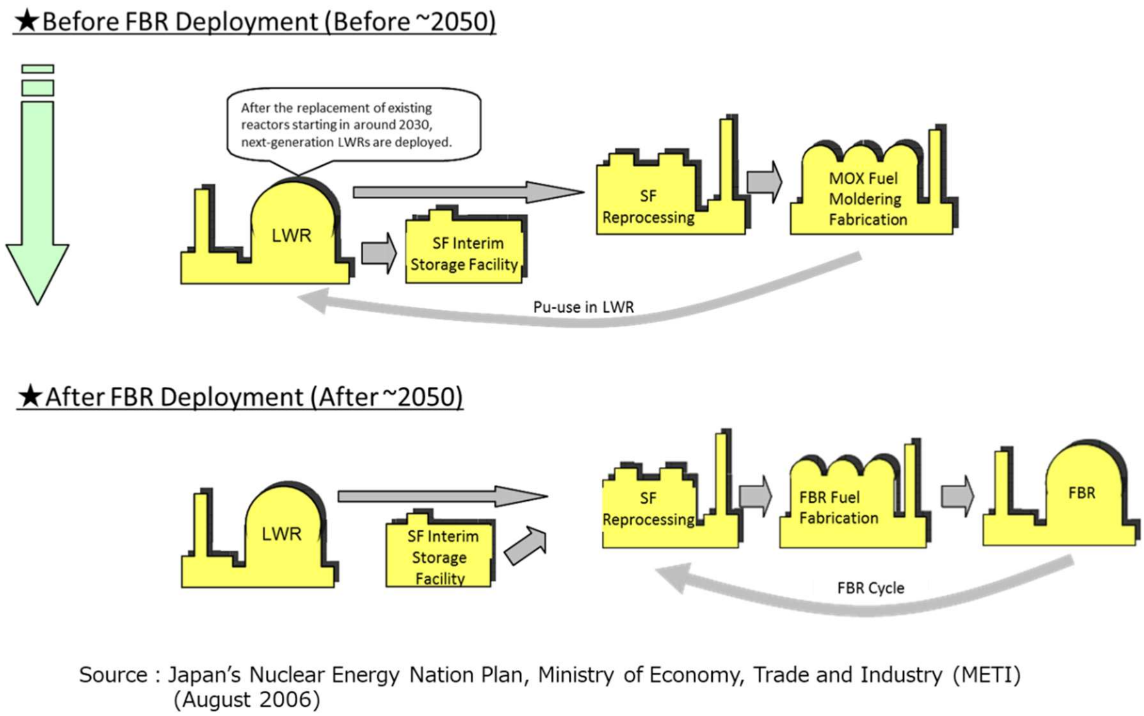


FIG. III.7. Base scenario (2/2).

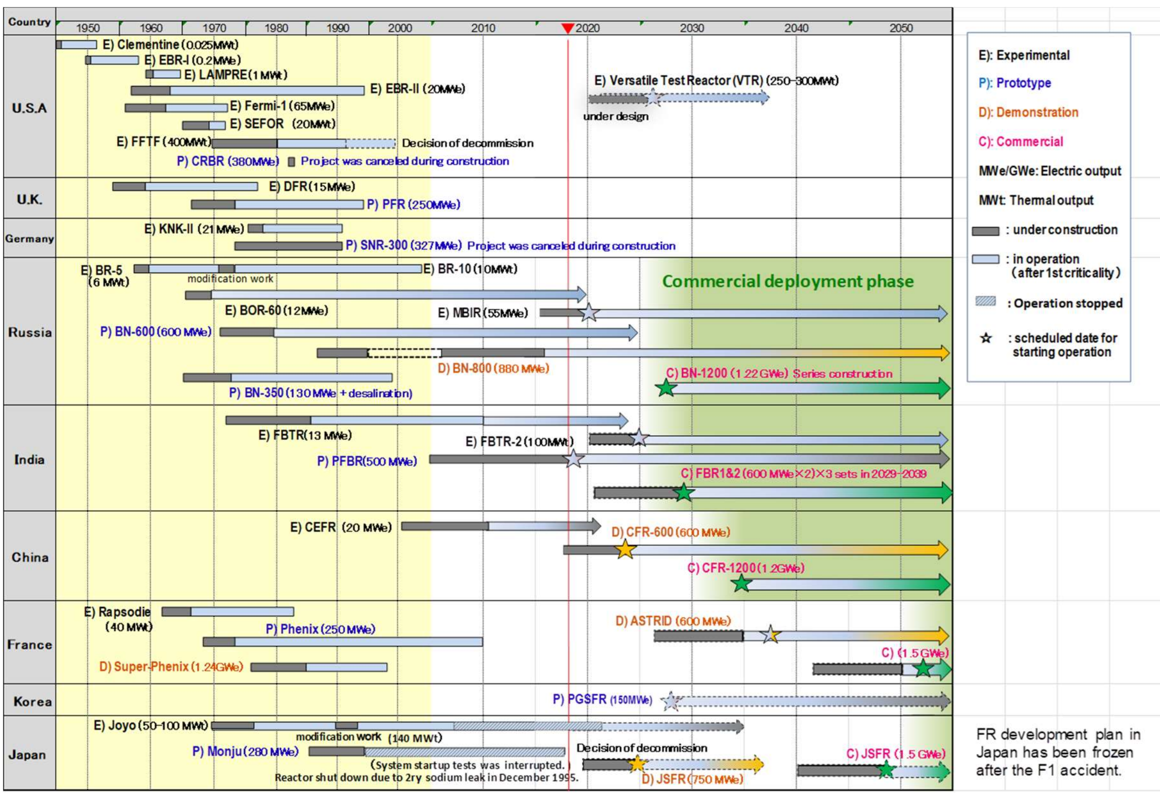


FIG. III.8. History and plan of fast reactor development in the world.

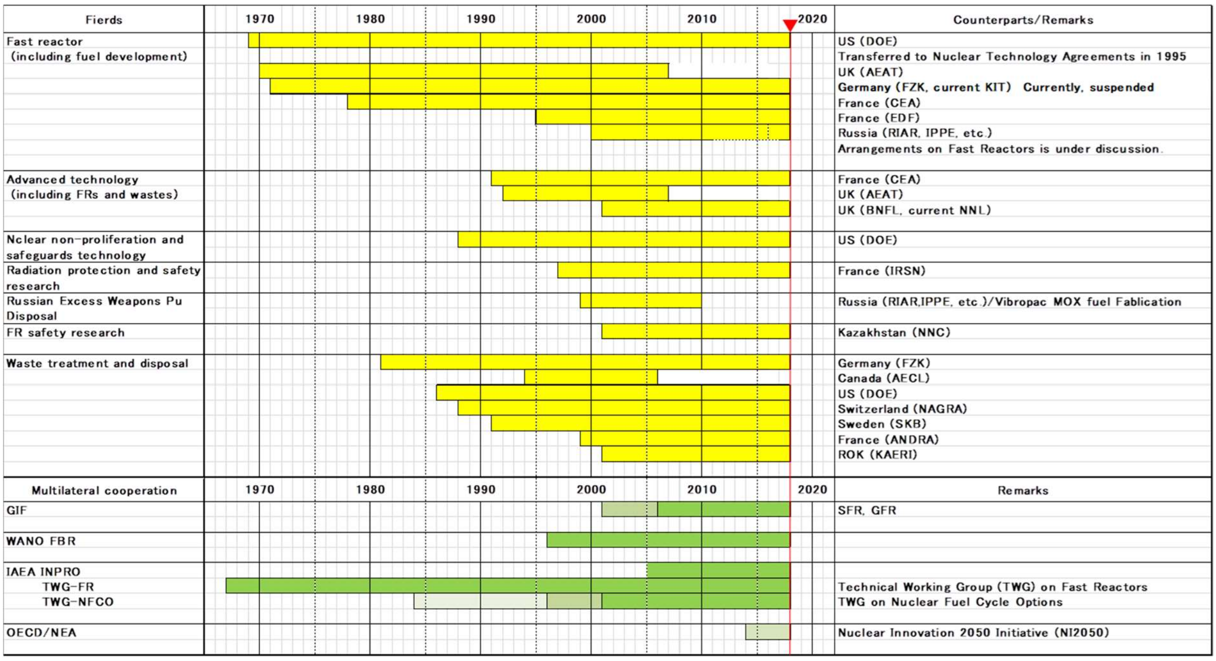


FIG. III.9. Major bilateral/multilateral cooperation associated with fast reactor cycle in JAEA.

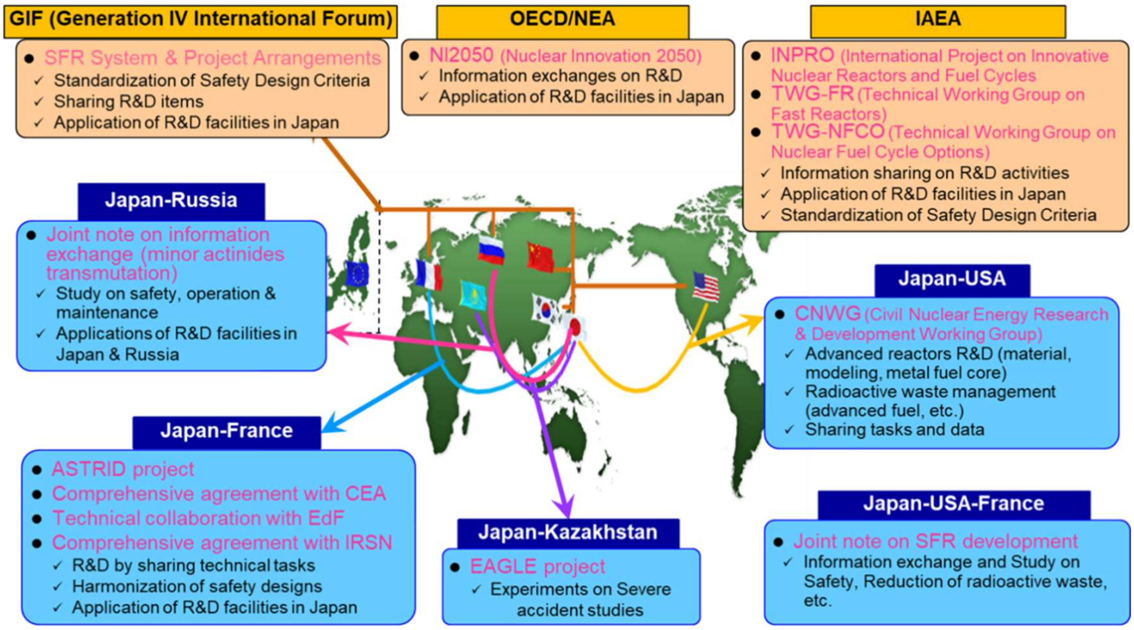


FIG. III.10. Current state of international cooperation on sodium-cooled fast reactor (SFR) and related fuel cycle in JAEA.

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ANNEX IV.

STUDY ON HTGR NON-ELECTRIC APPLICATIONS POTENTIAL IN THE ROADMAP FOR NUCLEAR ENERGY DEVELOPMENT IN THE RUSSIAN FEDERATION

The case study presented in this Annex was additional to the Russian Federation roadmap template, prepared by the Institute of Physics and Power Engineering (IPPE), which was considered as basic scenario for Russian nuclear power development.

In accordance with the Energy Strategy of the Russian Federation, a demonstration NPP with a High Temperature Gas Cooled Reactor (HTGR) will be commissioned in 2030 [IV.1]. Additional data, concerning a cluster of HTGRs operating in the non-electrical mode, were calculated in the National Research Centre “Kurchatov Institute” [IV.2].

The “Energy Production” worksheet of ROADMAPS-ET contains the following information: data of electricity production, and electricity production by type of reactor, including HTGRs. The main result of HTGRs cluster operation is the opening of a new energy market – brown coal reprocessing for synthetic liquid fuel production. Quantities of lignite consumption for production of synthetic liquid fuel are also shown in the “Energy Production” sheet. The number of HTGR reactors and their installed thermal and electrical capacity are presented in the worksheet “Reactor Fleet”.

IV.1. BRIEF DESCRIPTION OF CASE STUDY

In 2015, the media reported that the mining division of state Corporation Rosatom “Atomredmetzoloto” (ARMZ) and China national petroleum Corporation “Sinopec” signed the agreement on the possibility of creating a joint project for the construction in the Trans-Baikal region of the plant for processing lignite into synthetic liquid fuels with capacity of 500 thousand tons per year based on Chinese CTL (Coal-To-Liquid) technology, in correspondence with the ‘roadmap’ for the development of cooperation among the Russian Federation and China in the coal sector [IV.3]. The roadmap was updated in the meeting of the Russian-Chinese working group on cooperation in the coal sector, held in Beijing in 2016.

As shown by previously performed studies, HTGR is the most perspective multi-purpose reactor candidate for the energy technology applications, because of its capability to produce both electricity and high-temperature heat [IV.2]. Therefore, HTGR can be considered for use as an energy source in a pilot manufacture of synthetic liquid fuel from coal. This work analyses an innovative nuclear energy system that combines HTGR with chemical production of synthetic liquid fuels from coal on one platform, from the point of view of implementation of system requirements, resourcing, ecology and non-proliferation according to the INPRO methodology for investigating perspective nuclear energy systems [IV.4, IV.5].

The location of the plant for processing coal into diesel fuel is assumed to be on the site of JSC “Priargunsky Production Mining-Chemical Union” (Krasnokamensk in the Trans-Baikal Region), which is operated by the management of ARMZ.

The purpose of the construction project at the Krasnokamensk plant with a capacity of 500 thousand tons per year, based on Chinese CTL technology would be the creation of a high-tech industrial complex for coal processing to produce synthetic diesel fuel and other related chemical products.

In the Trans-Baikal region a chemical industry enterprise aimed at production of synthetic liquid fuels from domestic lignite could be built on the site of the nuclear enterprise which is operated by of Rosatom. The evaluations presented below for the case of a traditional chemical plant (without a nuclear energy source), show that only about 50% of the coal would be consumed as raw material specifically for the production of CTL. The remaining coal burned on the site would produce industrial process heat, i.e. is not used as a raw material but would be fuel to provide technological heat for chemical processing of coal.

Economic efficiency of such production is a separate topic for investigation, since in this case it is necessary to consider many factors simultaneously, including distance from the places of oil extraction and production of motor fuels. A number of studies suggest that this sort of production can be profitable in the conditions of Yakutia and the Russian Far East (Primorsky Krai) [IV.6–IV.8]. Such evaluations with respect to the Trans-Baikal territory are not known. In this annex, based on literature data [IV.6, IV.9], a preliminary analysis regarding the competitiveness of the considered plant versus other technologies without nuclear power is performed (see Table IV.1). As a criterion of competitiveness, the equality of prices for synthetic gasoline and gasoline produced from oil is used. In another words, the structure of the cost of production of synthetic gasoline from coal is analysed. Each of the technologies for production of synthetic gasoline has its own advantages and disadvantages. The method of hydrogenation provides higher conversion efficiency, but the resulting product requires further purification. The effectiveness of the synthesis gas production method is lower, but it results in a purer product. As noted in [IV.7], the method of hydrogenation, while effectively tested on the brown coal from the Moscow basin has, however, not been implemented in large-scale industrial production.

The presence of liquid fuel oil in the waste (see Table IV.2) makes it possible to reduce the cost of synthetic fuel from US$ 121.24 to US$ 86.13, because fuel oil is on itself a billable product claimed by utilities. As the approach is not to reduce the price of fuel, a reduction in the cost of synthetic fuel could result in the increase of the taxes fraction from 44% up to 49% in the total cost structure:

- The cost of synthetic liquid fuels production from coal significantly exceeds the cost of gasoline produced from oil;
- Synthetic liquid fuels become competitive only if taxes and specific excise duties on it are reduced;
- The liquid oil fraction present in waste could be used as fuel for low temperature heat production in the private sector, i.e., there is an option to sell it. In this case, the cost of the main product – synthetic fuel produced by hydrogenation method - could be reduced accordingly;
- Reduction of taxes and excise duties is only possible if this type of power technology can be categorized as a green technology. (Currently in the Russian Federation only renewable energy sources are considered green technologies). Therefore, a key question is whether it is possible to consider the energy technological complex with HTGR and chemical processing of coal as a ‘green technology’? This question is addressed below.

It should be noted that the Trans-Baikal region does not have deposits of lignite that are not contaminated with natural radionuclides, and the reserves of such lignite are quite significant (See Table IV.3) [IV.10]. Therefore, the processing of lignite to synthetic liquid fuel will automatically lead to a significant reduction in the emission of radioactive substances (especially in the case of indirect liquefaction). It should also be noted [IV.10] that the coal radioactivity is not a unique characteristic feature of the Russian deposits – this is a problem of the entire world’s coal deposits (see Table IV.4) [IV.10].

TABLE IV.1. PRICE COMPONENTS OF SYNTHETIC GASOLINE FROM COAL AND GASOLINE FROM OIL

(conventional CTL plant without HTGR, prices are at 2015 level)

Component of price	Gasoline Au-92 (from oil)		Coal Liquefaction (synthesis-gas technique)		Lignite (hydrogenation technique)	
	price (US$/t)	share (%)	price (US$/t)	share (%)	price (US$/t)	share (%)
Mining	66.20	10.37	60.99	9.55	105.38	16.51
Processing and shipment	56.92	8.92	298.95	46.82	121.24	18.99
Excise duty, tax on extraction of mineral resources, etc	384.41	60.21	147.59	23.12	280.91	44.00
Profit	82.39	12.90	82.39	12.90	82.39	12.90
Costs of the seller	48.54	7.60	48.54	7.60	48.54	7.60
Full price	638.46	100	638.46	100	638.46	100

TABLE IV.2. PRODUCT STRUCTURE IN HYDROGENATION TECHNIQUE

Gasoline	5.74 %
Diesel fuel	15.53 %
Sulphur	0.03 %
Ammonia	0.21 %
Slags	22.00 %
Fuel gas	19.70 %
Waste	36.57 % (21.28 % liquid, 15.29 % solid)
Loss	0.21 %

TABLE IV.3. BROWN COAL RESERVES AND THE AVERAGE LEVELS OF NATURAL RADIONUCLIDES IN DEPOSITS FROM THE TRANS-BAIKAL REGION [IV.11]

Deposit	Coal reserves, million t	Uranium content, g / t	Thorium content, g / t
Okino-Klyuchevsky	288	4.7	1.8
Tataurovskoye	495.8	4.8	1.8
Kharanorskoye	810	4.8	1.6
Urtuyskoe	72.6	18.0	2.8
Kutinskoe	82.5	27.0	1.0
Weighted average for all deposits		6.4	1.7

TABLE IV.4. SOME VALUES OF URANIUM AND THORIUM CONTENTS IN COAL DEPOSITS AROUND THE WORLD [IV.11]

	Uranium (g/t)	Thorium (g/t)
Lignite (Turkey)	0.21 - 64	0.29 – 8.5
Brown coal (Australia)	0.04 – 4.3	0.4 - 17

Coal (Canada)	0.07 – 7.5	0.3 - 11
Lignite (Spain)	298	–
Subbituminous coal (Spain)	6.1	5.6
Midwest coal deposits (US)	1.06 – 40.4	0.89 – 2.05
Eastern coal deposits (US)	1.5	4.4
Vermont Creek coal deposits (US)	9 - 20	–
North-Eastern coal deposits (Greece)	18-4460	–

One ton of coal gives an output of approximately 1 200 m^3 of synthesis gas, which in turn provides about 530–570 kg of synthetic liquid fuels. Given the fact that the proposed plant capacity for the production of synthetic liquid fuels from coal is 500 thousand t per year, annual coal production should reach at least 943 400 t. The coal reserves in the last two fields from Table IV.3 will be sufficient to supply two plants with a capacity of 500 thousand t of fuel oil per year for 80 years. Considering the possibility of other fields, the power of such plants can be increased more than ten times.

The Trans-Baikal region produced 7.9 million tons of industrial coal in 2014, which is 40.1% less than in 2000. The share of the Trans-Baikal coal production in the Russian total coal production amounted to 2.2% in 2014, while in recent years there was a downward trend in coal production [IV.11].

In general, by 2035, in case of development of new deposits, the production of coal from mines in the Trans-Baikal region may increase by 4.5 times compared to the levels of 2014 (the 'maximum' option), otherwise the decrease in coal production can reach 2.8% compared to 2014. According to the estimates of primary energy resources of coal in the Trans-Baikal region minimum coal production is suggested to be at the level of 7.7 to 8.8 million t per year [IV.12].

It should be noted that the possible growth of coal production [IV.11] is expected to be achieved mainly due to the extraction of high quality, including coking coal. JSC "Razrez Ugol"– the Russian-Chinese company plans an open pit mining on a complex of sites: "Krasnochikoyskiy","Shimbilinsliy" and "Zusulanskiy" with total coal production up to 15–20 million t per year. With that the "Arctic development" company plans to mine up to 6–8 million t per year coking coal on Apsate coal field by 2018–2020.

The annual rate of lignite mining should be not more than 7–8 million t. With the stabilization of lignite production at this level, the reserves will be sufficient for about 220 years. Since the method of indirect coal liquefaction allows obtaining the final product of high purity, the application of CTL technology will allow using even the so-called complex (radioactive) coal which is unsuitable for use either in private households or in the energy sector because of its high radioactivity. 750 thousand t of such type of coal have already been produced at the Urtuyskoe field [IV.12].

The evaluations shown above allow concluding that the energy technological cluster that combines HTGR operation and liquid motor fuel production by processing coal may have the perspective of use of brown coal as the raw materials for the production of fuels for a long time.

Production of synthetic liquid fuel from lignite consumes heat energy which is provided by the combustion of raw materials, i.e. coal in the 'traditional technologies.' The use of nuclear reactors to supply heat for individual processes in the technology of synthetic liquid fuel production will save more than half of the traditionally consumed raw materials, as well as will prevent leakage of radioactivity content in the combustion products to the atmosphere.

The start-up of the energy-technological cluster (the start of first HTGR operation) is assumed for 2035. From this year the growth of capacity rate is expected to be about 1 reactor unit in 5 years. It is expected that by 2085, energy-technological clusters with two sites

(Urtuyskoe and Kutinskoe, which are the most radioactive coal deposits) will reach the maximum calculated capacity of 6 HTGR units on each site. Beyond 2085 the total installed capacity is assumed to remain constant. The relevant data for the considered scenario are presented in Table IV.5.

TABLE IV.5. MAIN PARAMETERS OF THE SCENARIO INVOLVING HTGR OPERATION

Year of beginning	2035	2040	2085(max)
Reactor capacity, GW(th)	0.6	1.2 (pilot cluster)	7.2 (12 modules)
Synthetic liquid fuel production, thousands t/year	416.1	832.2	4 993.2
Coal consumption for processing and high potential heat*, thousands t/year	1450	2900	17 400
Coal consumption for processing (with HTGR implementation to produce high potential heat) **, thousands t/year	725	1 450	8 700

* *without nuclear power*
** *with nuclear power*

Table IV.6 shows the results regarding the evaluations of the annual emissions of uranium and flying ashes into the atmosphere. Figure IV.2 and Table IV.6 also show the results of evaluations for the synthetic liquid fuel production. The results support the conclusion that it is possible to classify the energy technological complex with HTGRs and chemical processing of coal as a ‘green technology’.

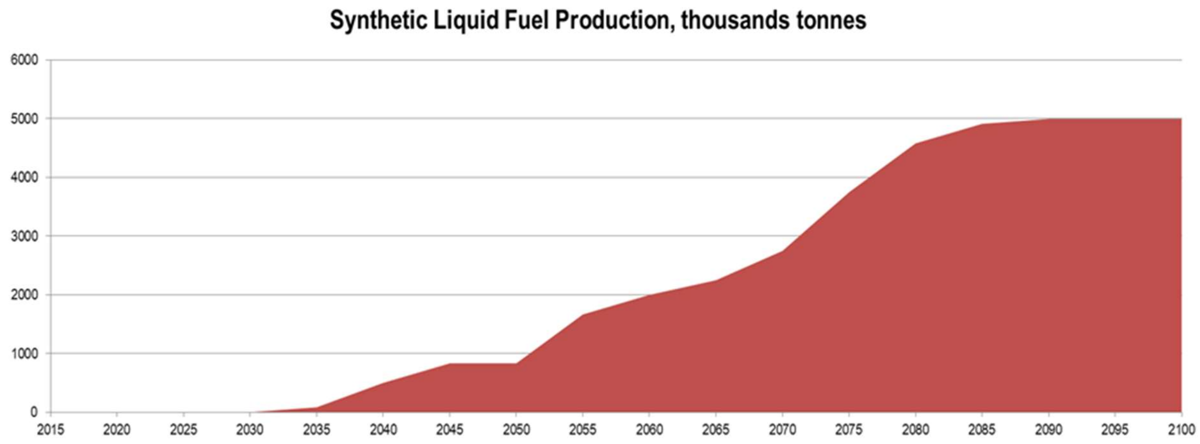

FIG. IV.1. Synthetic liquid fuel production

TABLE IV.6. *COAL BURNING WASTES AND PREVENTED EMISSION*

Year of beginning	2035	2040	2085(max)
Flying ashes*, thousands t/year	8.12	32.48	97.44

Slags**, thousands t	101.5	203	1218
CO_2 emission**, thousands t	2280	4580	27500
Uranium emission to atmosphere*, t	0.03	0.122	0.367
Uranium content in slags**, t	4	6.7	40.2

* *without nuclear power*
** *with nuclear power*

IV.2. CONCLUSION

A preliminary analysis of the CTL process competitiveness has been performed. It shows that the growth of this fuel production competitiveness will contribute to the incentive for an energy cluster combining HTGRs with the CTL process to potentially be classified as a 'green technology', which would provide the possibility to reduce the share of taxes and excise duties in the synthetic liquid fuel price.

An evaluation of HTGR application as a source of energy for synthetic liquid fuel production from coal was made. This would allow both the reduction of the impact on the environment during synthetic liquid fuel production and the reduction of the uranium emissions into the atmosphere. Therefore, the application of HTGR as a source of energy for synthetic liquid fuel production from coal allows reducing the impact on the environment.

Based on the literature regarding the prognosis of coal mining in the Trans-Baikal region, an assessment was performed regarding the radioactive coal resources available for conversion into synthetic liquid fuels on the site of a potential energy-technological cluster combining HTGRs and chemical production facility.

The possibility of using HTGRs to produce heat for the processing of lignite was shown under the limited reserves of natural uranium and provided minimum intervention in the structure of the specified scenario assuming that the production of electricity remains unchanged.

The results of the evaluation show that it would be possible to classify the energy-technological complex including HTGRs and chemical processing of coal as a 'green technology'.

The uranium deficiency problem can be solved in different ways:

- Increasing the number of fast reactors in the NES structure;
- Improvement of the breeding properties of a reactor BN-1200 –and partial transition to VVER-TOI reactors with MOX fuel; and
- Re-enriching recycled uranium.

Also, HTGRs have flexible fuel cycles and can be introduced with recycled uranium - plutonium fuel (GT-MHR – type reactors). In this case, the operation of the energy technology cluster will not depend on natural uranium resources at all.

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ANNEX V.

ANALYTICAL AND VISUALIZATION TOOLS IN ROAD MAPPING STUDIES

Performing comprehensive road mapping studies requires an extended application of different analytical tools to provide support for these activities and their meaningful application to assist experts. The set of these tools includes different advanced quantitative analytical software tools and visual qualitative tools, combined with subject-matter specialized codes that allow structuring and effective representation of the related information and data. This section provides some illustrations of tools which may be applied and discusses how they may be used within road mapping studies related to enhancement of NES sustainability.

V.1. ANALYTICAL TOOLS

Traditionally, tools which are widely used within road mapping studies may be categorized in the following groups: visualization tools; analytical tools; and software tools supporting data input, analysis and reporting. Tools can be categorized as: universal tools applicable within any road mapping studies which do not take into account subject areas for which a specific roadmap is being elaborated, and tools which reflect specifics of a subject area and can provide specific data and information.

Providing an appropriate qualitative visualization is especially important within road mapping activities, so long as it is a characteristic feature providing a demonstration of interconnections, system evolutions, time-dependences, etc. In general, a roadmap is a multi-layered and time-based chart. Suitable visualization may be performed using different techniques, such as trees, taxonomies, Gantt charts, mind maps, concept maps, etc. Among many possible visualization methods, Gantt charts are very popular in road mapping activities and other project management applications to illustrate project schedules and can serve as one of the planning methods which provides a chance to reflect qualitative and quantitative information and data.

Analytical tools are required to provide calculational support of the studies and produce needed data, to justify decisions which are finally to be made based on study results and may be carried out by a variety of analytical instruments (e.g. decisions trees, MCDA, cost-benefit analysis, etc.).

Different project management software tools are quite popular for technology road mapping: such software as MS Project or other Gantt software (Aha, ProductPlan, etc.) and other integrated project management tools (Vision Strategist, VersionOne, etc.) have found wide application in different areas, but such tools should be adapted in a proper manner for road mapping studies towards enhanced NES sustainability due to the specifics of the subject area.

Within NES oriented road mapping use nuclear material flows software tools are required to model the existing and planned reactor fleet and the requirements for goods and services of the NFC front-end and back-end for selected timeframes. Such tools allow the system response to changes in NES development strategy to be analysed to determine direct and indirect effects as well as to assess the feasibility of certain options for NES development.

Combined use of the mentioned toolkit facilitates elaboration and consideration of problems related to roadmap development and implementation making it possible to explore linkages, trade-offs and consequences, thereby helping to develop effective roadmaps supporting sustainable development goals. In such analysis experts representing essential stakeholders should be involved whose in-depth knowledge and experience are necessary to structure the examination correctly, compare the validity of multiple options, judge the credibility of conclusions, and explain the analysis and findings.

To carry out practical application it is necessary to have an analytical decision support tool for structuring and unifying data on issues related to a transition to NESs with enhanced sustainability, which has to be an open-source, flexible, universal and easy-to-use analytical instrument designed for analysing and presenting analytical results of NES deployment strategies at the global, regional and national levels integrating visualization, analytical and decision support capabilities.

V.2. DATA VISUALIZATION

Data visualization presents data in a graphical form which would ensure their perception, examination, comparison, and processing in the most efficient way. Data visualization is an important part of road mapping activities and data mining systems, especially those focused on the processing of massive datasets. Visualization can be used in all phases of data processing to visualize the initial data, a data sample loaded into the processing system, the primary processing results, and the intermediate and final results. A summary list of the most commonly used visualization methods including those which are needed for both process and structure visualizations is presented in Table V.1, being classified in groups according to the interactive resource [V.1].

High-quality visualization may accelerate the process of human perception and sorting of information, as it meets the following requirements:

- Concision, i.e. the ability to simultaneously display a large number of different-type data;
- Relativity and proximity, i.e. the ability to demonstrate clusters, relative group sizes, similarities and differences between groups, and outliers in the query results;
- Focus with context, i.e. interaction with a certain selected object with the ability to view its status and relations with the context;
- Zoomability, i.e. the ability to easily and quickly navigate between micro- and macro-representatives;
- ‘Right hemisphere orientation’, i.e. not only providing users with pre-established data processing methods (promoting their intended and planned approaches to searching for the necessary information), but also supporting their intuitive, improvisational cognitive processes of identifying conformities.

As applied to status monitoring and decision support, it has become common practice to use a ‘dashboard’ approach which represents a concise, illustrative, and interactive report per one sheet or screen. Dashboard is a visual representation of a set of essential data and indicators grouped and arranged in such a way that all the minimally necessary basic and key information is located on the same screen, thus allowing users to quickly and easily keep track of key changes in the system and its condition. Dashboard is focused on visualizing the most essential data or indicators so that an expert could quickly obtain necessary information about any part of the process (e.g., actual system state, key indicator time history, performance aggregated indicators, etc.).

TABLE V.1. THE MOST COMMONLY USED VISUALIZATION METHODS

Information visualization (visual representations of data to amplify cognition)
Sankey diagram (*structure visualization*)
Information lense (*structure visualization*)
Treemap (*structure visualization*)
Hyperbolic tree (*structure visualization*)
Entity relationship diagram (*structure visualization*)

Cone tree (*structure visualization*)
Cycle diagram (*process visualization*)
Petri net (*process visualization*)
System dynamics/simulation (*process visualization*)
Timeline (*process visualization*)
Flow chart (*process visualization*)
Data-flow diagram (*process visualization*)
Clustering (*structure visualization*)
Semantic network (*structure visualization*)
Concept visualization (visual representation of concepts, ideas, plans, and analyses)
Mindmap (*structure visualization*)
Layer chart (*structure visualization*)
Soft system modelling (*process visualization*)
Synergy map (*structure visualization*)
Cause-effect chains (*structure visualization*)
Force field diagram (*structure visualization*)
Tolmin map (*structure visualization*)
Ibis argumentation map (*structure visualization*)
Meeting trace (*process visualization*)
Communication diagram (*process visualization*)
Swim lane diagram (*process visualization*)
Decision tree (*process visualization*)
Process event chains (*process visualization*)
Flight plan (*process visualization*)
Gantt chart (*process visualization*)
Critical path method (*process visualization*)
Pert chart (*process visualization*)
Concept skeleton (*structure visualization*)
Perspectives diagram (*structure visualization*)
Concept fan (*structure visualization*)
Evocative knowledge map (*structure visualization*)
Concept map (*structure visualization*)
Vee diagram (*structure visualization*)
Strategy visualization (visual representation for analysis, development, formulation, communication, and implementation of strategies)
Performance charting (*structure visualization*)
Strategy map (*structure visualization*)
Organization chart (*structure visualization*)
House of quality (*structure visualization*)
Feedback diagram (*structure visualization*)
Failure tree (*structure visualization*)
Life-cycle diagram (*process visualization*)
Porter`s five forces (*structure visualization*)
S-cycle (*process visualization*)
Stakeholder map (*structure visualization*)

Ishikawa diagram (*structure visualization*)
Technology roadmap (*process visualization*)
Mintzberg`s organography (*structure visualization*)
Affinity diagram (*structure visualization*)
Decision discovery diagram (*process visualization*)
Strategy canvas (*structure visualization*)
Value chain (*process visualization*)
Hype-cycle (*process visualization*)
Tool for action plan selection (TAPS) (*structure visualization*)
Spray diagram (*structure visualization*)

REFERENCES TO ANNEX V

[V.1] PERIODIC TABLE OF VISUALIZATION METHODS, http://www.visual-literacy.org/periodic_table/periodic_table.html

ANNEX VI.

COLLABORATION AMONG COUNTRIES FOR NUCLEAR ENERGY SUSTAINABILITY

VI.1. DRIVERS AND IMPEDIMENTS FOR THE COLLABORATION AMONG COUNTRIES FOR NUCLEAR ENERGY SUSTAINABILITY

Multiple studies performed worldwide indicate that regional collaboration could help achieve deployment of the first nuclear power plant (NPP) for newcomer countries, and support maintenance and enhancement of sustainable NESs for technology holders and technology users to help to meet the 21st century energy needs. The following are potential benefits of collaboration among countries:

- Minimizing infrastructure effort for NESs of individual countries;
- Suggesting and implementing sound solutions for SNF utilization and disposal;
- Enabling optimum use of the available resources;
- Minimizing costs owing to the economy of scale and other factors;
- Ensuring that international commitments are met by all countries in a more easy and transparent way.

Such a collaborative effort to achieve deployment of the first NPP in a newcomer country and to establish, maintain and enhance a sustainable NES of technology holders and users would be possible by assuring that the related driving forces overcome the impediments.

Economic benefits are the most often conventionally considered drivers for collaboration between both the technology holders/suppliers and technology users and also the technology users and technology holders separately, but there are more factors, not less important, that could drive or impede such collaboration. As an example, considerations regarding the security of supply might be considered an impediment, while the aspiration to become a technology holder/provider may be a strong driver surpassing the cost considerations. Likewise, resource constraints in some countries could be a motivating factor for collaboration, while certain legal and institutional restrictions may impede/affect/obstruct the collaboration efforts.

Different synergies exist among the various current and innovative nuclear energy technologies and options to amplify them through collaboration among countries in NFC. Better understanding of the benefits and issues associated with regional collaboration in building a sustainable NES, and a clearer vision of the driving forces and impediments behind such collaboration would help to find practical collaborative approaches based on "win-win" strategies for all involved countries.

The various synergies among nuclear technologies and forms of collaboration among nuclear technology holders and technology users are available in order to identify mutually beneficial strategies for working together to promote the sustainable expansion of nuclear energy worldwide and also to identify the corresponding driving forces and possible impediments involved in achieving a globally sustainable NES such as: collaboration among countries holding different NPP technologies; collaboration among technology holder and user countries, including the option of international NFC vendors; regional approaches to interim SNF storages; international approaches to collaboration in NFC back-end etc.

To make the largest contribution to the growing energy needs in the 21st century, nuclear energy needs to be available and affordable for all countries. Some countries would afford or may prefer different sustainability options for their national nuclear energy programmes. Collaboration among countries is seen as a means of bringing the benefits of innovative nuclear energy technologies to all users of nuclear energy, enhancing the collective global sustainability of nuclear energy.

The legitimate question “How can a solid basis for collaboration be established?” can be addressed easier by considering the following approach elements:

- Identifying viable collaboration options, based on "win-win" approaches, to enhance national NESs sustainability in the regional and global context;
- Bringing together decision-makers and senior technical experts working in MS institutions, NGOs, nuclear industry, utilities, academia and R&D institutions involved in nuclear energy programmes planning or implementation, long term strategic planning and international collaboration to exchange views on all the aspects and issues; and
- Understanding the nuclear technology developer, user and newcomer countries’ standpoints regarding the driving forces and the impediments for collaboration.

The following general drivers or motivation factors for collaboration among countries can be highlighted[2].

(a) Energy policy

National policy should consider both energy security and the potential to become a regional provider of energy, once the national needs are fulfilled. In these regards, some countries could provide stable and secure base-load power leading to an increased and reliable regional electricity trade.

(b) Economics

Benefits related to costs and useful applications of nuclear technology have to be taken into account. Large energy markets would lead to increasing the potential of countries for benefits and reduction of financial burdens. Also, investment risk mitigation is important and needs to be considered, especially increased economic security/risks mitigation and stronger financial and technical basis for large investments involving collaborative and shared efforts.

(c) Sharing of facilities and resources

The following should be considered: R&D collaborations, sharing expertise on licensing, regulations, environmental assessment, exchange of specialized human resources, infrastructure sharing, training etc. The interest in sharing existing expertise and competency should be based on several factors, such as: comprehensive legislation and regulations, accumulated well-proven, successful experience and professional capability for nuclear capacities operation, proven expertise on licensing, regulations, radioprotection, environmental assessment, NFC management, highly skilled and specialized human resources, specialized R&D and engineering infrastructure, etc. A strong motivation could be given by sharing of common goals, similar challenges, common interests, mutual long-time benefits, and scientific interest.

(d) Security of supply

Both assurance of nuclear fuel supply (in direct connection to assurance of NPP operation) and used fuel management (including the longer term interim used fuel storage and also the reprocessing and recycling of the SNF) need to be considered. To assure security of supply, the averaged preferences of technology holder, technology user and newcomer countries indicate as reasonable a number of 3 suppliers (while the newcomer countries are satisfied with 2–3 suppliers, the technology holder and user countries prefer 2–4 suppliers, pointing to a higher desired degree of diversity of supply). Leasing of nuclear fuel is attractive for newcomers and could well be more acceptable to the public in these countries.

[2] SYNERGIES and ROADMAPS collaborative projects, the 4th and 11th INPRO Dialogue Forums.

(e) Radioactive waste management

The regional and international solutions for final disposal of SNF could become attractive for technology holder and user countries once the proven disposal technologies would be commercially available, taking also into account the possibility to optimize the geological repositories costs. The potential collaboration among countries becomes more convenient leading to “win-win” situations as the newcomer countries are optimistic regarding the reprocessing and recycling of SNF in supplier countries or international centres; most of the NPP providers take back the SNF for reprocessing, and only high-level waste is returned back to the NPP owner. In the meantime, it must be mentioned that the technology holder/user countries’ preference is to keep the SNF in controlled storage for a longer time for reprocessing and recycle (e.g. in future fast reactors). Joint solutions in long term management of SNF/HLW could provide a good basis for collaboration among countries.

(f) Best practice sharing

Collaboration among countries on the way to globally sustainable nuclear energy could be favoured and enhanced by the participation of international organizations for sharing best practices in safety, operational performance, science and technology, etc., with the assurance of the resource optimization and the transparency for non-proliferation and safeguards.

The general impediments/challenges for sustainable global expansion of nuclear energy and possible solutions were identified as follows:

(g) Regulations

National regulations are still essentially a national focus and sometimes prohibit synergistic collaborations with other countries. Legal prohibitions/ restrictions for the SNF return to suppliers from other countries or for trans-boundary transport impede implementation of collaborative NFC back-end options, be they a shared repository/disposal facility or a reprocessing service provided by a supplier or a regional or international NFC centre. The diversity of legal requirements existing in the national regulations could lead to open questions regarding the sharing responsibilities between partners, particularly related by radioactive waste management (e.g. transfer of ownership of SNF), competitiveness of NPP on the electricity market, abilities to cover project implementation risks, etc. The shared use of a NFC facility could be technically optimized by the development of technologies and also by improved efforts to share experience, skilled human resources and best practices. To make the process easier, the harmonization of the national regulations is strongly supported.

The multinational NFC is a concept (vision of a future world) that must be capable of including many countries. Still it requires instruments that allow reaching a high level of understanding and trust between partners. Major needs are represented by the harmonization of the national regulations, implying the comprehension and the conception of a regulatory system, mutual recognition agreement for the enforcement of regulations, use of a common nuclear liability regime, development of a common legal framework concerning the physical protection of nuclear installations, etc.

(h) High investment costs and long-term commitment

Nuclear energy is capital intensive and a high capital investment is required. Therefore, although fuel costs are very low, the overall cost of nuclear energy is high. This challenge apparently should be a driver for cooperation but the high capital intensiveness beginning with initiating plans to build a nuclear plant, through the whole licensing process and construction up to commercial operation, takes considerable time, typically up to 15 years. To turn it into a driver, it should be considered that while the absolute capital investment becomes very high, the high predictability in nuclear energy generation can render nuclear energy very attractive, especially combined with the total independence of carbon-tax impacts when applied. The long-term nature of nuclear energy projects spanning around 100 years or more is definitely an impediment for collaboration among countries as it requires a long term commitment in a changing socio-political and economic environment. The rate of national policy change can be much more rapid than the rate of technology deployment. Another issue is represented by the insufficient funding for development / demonstration with both aspects considered, namely: spreading insufficient funding across too many solutions would results in no progress; meantime, excessive focus on development of only one solution increases the risk of failure.

(i) Political environment

Several aspects which need to be taken into consideration are:

- Protective policy/national protectionism on technologies/approaches rejects solutions that are 'not invented here'. Nuclear technologies can be considered as having competitive advantage in the region and could impede establishment of collaboration among countries, mainly based on the tendency of dominance as a regional provider of energy. At the same time, unavailability of similar technologies can impede collaboration among countries as the integration with regional infrastructure might be costly for some countries;
- Political instability, lack of legal coherence and political willingness on long term development of nuclear energy; and
- Political and institutional monopoly needs to be mentioned; nuclear power remains essentially an energy source requiring Government commitment: industry involvement alone is not sufficient.

(j) Public concerns

'Radiation' is the common factor for the concerns associated with nuclear energy. Other concerns are proliferation risk related to non-civil use of nuclear materials, physical protection (e.g. avoidance of "dirty bombs"), and ultimate waste management challenges spanning centuries. The public concerns are reflected in the level of public acceptance and often have influenced the political considerations/political willingness of Governments toward nuclear energy development. Reducing the public's concerns will consequently lead to positive reactions and a better public acceptance for nuclear energy, based on the following issues:

- Resource sustainability, which could be improved by various options/solutions, such as: Uranium utilization improvement via thermal recycle (10–30%); Uranium/Thorium (U/Th) utilization improvement via fast spectrum breed and burn without recycle (improvement by a factor of 10); U/Th utilization improvement via breeding and closed NFC systems (improvement by a factor of 100).
- Waste disposal, which could be improved in steps by: Disposal of SNF, Disposal of minor actinides and fission products only, Disposal of fission products only.
- Proliferation resistance and security, which could be improved through collaboration among countries in sensitive stages of the NFC, based on advances in the scale of nuclear deployment and, specifically, in NFC technologies. In these regards, management of sensitive technologies and sensitive materials is mandatory, but the solutions still need to be developed.
- Nuclear energy cannot be considered without correct attention on the international level being devoted to the inherent dual nature of the potential use of some of the fissile materials and nuclear knowledge required in nuclear energy use. The international safeguards regime ensuring a non-proliferation nature of civil nuclear energy use is essential here. Safeguards agreements and verification help ensure a high degree of proliferation resistance for operating NPPs.
- The non-uniform socio-political stance on nuclear energy across some regions must be also considered. In this respect, neighbouring countries disliking nuclear power may

impact nuclear deployment in a country engaged in developing the nuclear power, where the stance is positive.

(k) Considerations of sovereignty

Sovereignty is well-defined as 'the supreme, absolute and uncontrollable power by which an independent country is governed and from which all specific political powers are derived; the intentional independence of the state, combined with the right and power of regulating its internal affairs without foreign interference'. Because of sovereignty of Member States, each Member State has the right to decide how to use nuclear technology.

(l) "Wait and hope for Generation IV" considerations

In this case, a factor influencing collaboration is the willingness of potential plant owners to make high capital investments for new Generation III nuclear plants and products considering the potential of Generation IV to provide better solutions in a number of years. The evolutionary projects, based on already proven technology, experience and highly skilled professional human resources are, to an extent, in competition with the innovative solutions, which promise better technological and safety features and economic benefits, but still face various challenges.

(m) Repeated severe accidents

Decreasing public acceptance for nuclear energy deployment, especially after the Fukushima accident (neighbouring countries apprehension), could be an impediment to the collaboration among countries. Development and introduction of NPPs with innovative nuclear reactors that rely more strongly on inherent safety features and reliable passive mechanisms and offer minimum amounts of non-nuclear energy (mechanical, chemical) stored in the reactor core with a release potential could help to practically exclude accidents with major release beyond plant boundaries in the future.

The challenges for collaboration in nuclear energy in comparison with other energy producing industries may be driven by: the strategic nature of nuclear energy for energy independence and technology development; long term liability issues; long term commitment for nuclear energy projects; non-proliferation; national pride and aspirations. Nuclear energy's credibility and availability are based mainly on the following:

- Safety and security should be guaranteed 'whenever' & 'wherever', thereby demanding proven technology and, thus, long qualification periods before industrial maturity;
- Industrial robustness and flexibility are accepted as essential; and
- Nuclear infrastructure investments are considered very important, both in value and in time.

VI.2. MODELS AND EXAMPLES OF COLLABORATION IN THE NFC FRONT-END AND BACK-END

World experience gives evidence that economic competitiveness is not a sufficient criterion for deciding to develop a particular energy source. Decisions of some governments on the deployment of renewable sources are sometimes based on safety and environment criteria in contrast to the low cost of electricity production.

International collaboration for enhancement of nuclear energy sustainability is especially important because a serious nuclear accident, global pollution or violation of the non-proliferation regime in any country would raise doubts worldwide on the potential of nuclear power to operate in a sustainable manner. The IAEA took over the mission to develop the requirements for sustainable development of nuclear power and to create a representative forum to determine the mechanisms for meeting these requirements. The IAEA carries out this mission based on joint research of its Member States through the international INPRO project [VI.1], and through interaction and coordination with other international energy organizations.

While requirements of the NES sustainable development have been recognized by many IAEA Member States as a common goal, the national approaches to reaching the goal are various in many respects because of specific social and macroeconomic conditions in the countries of the world. The countries have different preferences regarding the nuclear power objectives, and the pace and scope of its development.

Collaboration is an inevitable part of the world nuclear power industry at all stages of the production chain including natural uranium mining, uranium enrichment, fuel fabrication, SNF reprocessing and storage. The nuclear power industry is subject to various arrangements for cooperation among utilities, and internationally, among United Nations and government nuclear agencies and organizations. The main forms of partnership on nuclear fuel supply and NFC services are market mechanisms, bi-lateral agreements and contracts, multi-lateral entities/consortia, and inter-governmental arrangements. A few examples related to this broad topic are presented below.

VI.2.1. Collaboration at the NFC front-end

A healthy market exists at the front end of the NFC. For instance, in the course of only two years, a nuclear power plant operating in Finland has bought uranium originating from mines in seven different countries, conversion has been done in three different countries, and enrichment services have been bought from three different companies [VI.2].

The worldwide production of uranium in 2015 was 60,496 tonnes. Kazakhstan, Canada, and Australia are the top three producers and together account for 70% of the world uranium production. Other countries producing in excess of 1,000 tonnes per year are Niger, the Russian Federation, Namibia, Uzbekistan, China, the United States of America and the Ukraine.

The largest uranium mining companies are KazAtomProm, ORANO (former AREVA), Cameco, ARMZ, and Uranium One. Many of them jointly hold significant stakes in uranium mines around the world. Cameco holds a 69.8 percent stake in the McArthur River mine and ORANO holds the remaining 30.2 percent. Cameco also holds a 50 percent ownership in the Cigar Lake mine while the remaining ownership is divided between ORANO, Idemitsu Uranium Exploration Canada and TEPCO Resources. Several mines in Kazakhstan are operated through a joint venture between the state-owned nuclear energy company Kazatomprom, ORANO and Uranium One. The Priargunsky mine is owned and operated by the Russian ARMZ Uranium Holding Company.

Services for uranium conversion and enrichment are provided by national and international supply companies. The major companies providing enrichment services are TENEX (Russian Federation), URENCO (United Kingdom, Germany, Netherlands), ORANO (France), USEC (USA), and CNNC (China). The uranium enrichment consortia URENCO and ORANO are institutional expressions of the movement towards a European indigenous enrichment capability.

The IAEA activities on providing assurance of supply and services resulted in creation of several banks of low enriched uranium managed by the IAEA. In 2006, a proposal was brought forward by a US organization, the Nuclear Threat Initiative, for an international nuclear fuel bank under IAEA supervision [VI.3]. It would essentially form supply guarantees based on a stockpile of low-enriched uranium managed by the IAEA. In November 2009 the IAEA Board approved a Russian proposal to create an international guaranteed reserve or 'fuel bank' of low-enriched uranium under IAEA control at the IUEC at Angarsk. This was established a year later and comprises 123 tonnes of low-enriched uranium as UF_6, enriched to 2.0–4.95% U235 (with 40t of latter), and is available to any IAEA Member State in good standing which is unable to procure fuel for political reasons. In June 2015, the IAEA Board approved plans for the IAEA

LEU Bank to be located at the Ulba Metallurgical Plant at Oskemen in northeast Kazakhstan, which has 60 years of experience in handling UF_6.

Currently, the commercial market satisfies the demand for fresh fuel services. There is a diversity of commercial enrichment companies and enrichment capacity exceeds demand Based on current plans for the substitution of diffusion technology by centrifugation, enrichment capacity is likely to comfortably keep abreast of projected increases in demand in the medium term (e.g. until the end of the US/Russian agreement on HEU conversion to LEU) [VI.2]. For other front-end processes (such as conversion and fuel fabrication) the situation is similar. This equilibrium in the uranium market is likely to change only if the deployment of nuclear power increases significantly.

VI.2.2. Collaboration at the NFC back-end

The forms of international collaboration at the final stages of the NFC are rather diverse. At present, an open NFC prevails in the countries with nuclear power. SNF is stored either in storage pools of NPPs or is transferred to special storage facilities.

There are two main alternatives for further development of the international collaboration at the final stage of the NFC. A number of countries and international organizations are exploring the possibility of the final isolation of SNF in international repositories. This form of collaboration is at the stage of preliminary discussions and evaluations. The second alternative is SNF transfer to the countries that have the technology of a closed NFC for reprocessing and further use of the extracted fissile materials. This alternative is in the stage of practical implementation. The industrial facilities of the closed NFC technology for reprocessing SNF from thermal reactors have been created since the 1970s and now have reached a sufficiently high level of maturity in several countries.

For PWR type nuclear fuel, France has 1700 tonnes per year of reprocessing capacities at La Hague owned and operated by ORANO; the UK has 600 tonnes per year at Sellafield (THORP), the Russian Federation has one reprocessing plant of 400 tonnes per year at Osersk (MAYK site of ROSATOM), and a reprocessing plant in Japan of 800 tonnes per year at Rokkasho is expected to start operation in 2021. There are also reprocessing facilities for fuels of reactor types other than PWRs. These include the facilities for reprocessing used fuel of MAGNOX reactors at Sellafield, UK (Reprocessing of Magnox fuel is expected to end in 2017); small facilities for reprocessing of fuel of PHWR at the BARC site as well as one facility for thorium separation in India; and one for reprocessing of MOX fuel in Tokai, Japan (JNC). The total nominal capacity available for reprocessing civilian SNF is about 5000 tonnes of heavy metal per year (t HM/a). All reprocessing facilities are owned directly by governments or by companies controlled by governments.

Thus, reprocessing is an international business with facilities in France, the Russian Federation and the United Kingdom willing to accept foreign SNF for reprocessing. Taking into account present capacities to reprocess SNF for light water reactors and the reprocessing facilities under construction, there will be sufficient reprocessing capacity globally for all expected demands for plutonium-recycle fuel during some two decades [VI.2].

However, international collaboration on the reuse of extracted fissile materials is making first steps at the global level, and growth in reprocessing capacity worldwide has been limited. The main reason for the low scale of collaboration based on optimization of fuel use in partner countries is the fact that the second essential part of a closed NFC, namely, installations intended for use of fuels containing reprocessed fissile materials have not yet become an essential part of the global NES.

In some EU countries and Japan, a partial closure of the NFC is implemented, where plutonium separated from SNF of thermal reactors is used to make MOX fuel for partial loading of the cores of thermal reactors. Partial closure of the NFC in relation to uranium from spent fuel is implemented in the Russian Federation. The same option in parallel with MOX is implemented in France. The strategy of the full NFC closure with the use of fast reactors is a priority in the Russian Federation, France, India, China, and Japan. Currently, a technological platform for this strategy is in the stage of research, development and demonstration. The IAEA Technical Report [VI.3] has documented significant progress of the fast reactor technology and a trend to decrease the investment cost for their construction down to the cost of thermal reactors. It is expected that this technology will allow to more effectively solve the tasks arising at the final stage of the closed NFC, such as SNF accumulation, handling minor actinides, safe final disposal of the long-lived radionuclides, some issues of proliferation resistance, etc.

The deployment of fast reactors and a closed NFC would inevitably enhance the level of collaboration at the back end of the NFC worldwide. In particular, increased use of fissile materials resources could be arranged at the global level. At present, there is an uneven distribution of the amount of plutonium accumulated in SNF in countries with nuclear power. Some countries consider plutonium accumulated in SNF as waste material and develop programmes for its disposal as high-level waste or for 'burning' in dedicated facilities. At the same time China and India which develop fast reactors to cover high nuclear energy demand have to limit the rates of introduction of these reactors because of a lack of plutonium. Enhancing the international collaboration at the back end the NFC is a key condition for the increased use of fissile materials resources and reduction of the volume of material to be disposed of as high-level waste at the global level.

The partnership between a supplier country and a recipient country in the nuclear technology sector may be based on different forms, depending on the terms of delivery of nuclear fuel stipulated in the contract:

- Supply (sale) of fresh fuel with further storage of SNF in the recipient country;
- Supply (sale) of fresh fuel on terms of leasing, take back of SNF to the country of origin, reprocess SNF and return reprocessing products (nuclear materials in the form of new MOX, uranium from reprocessed uranium, or REMIX fuel and radioactive waste) to the recipient country;
- Supply (sale) of fresh fuel on terms of leasing, take back SNF to the country of origin for subsequent long-term storage, reprocessing and final disposal of the reprocessed products.
- Supply (sale) of separate services from the back-end options. The examples of this kind of collaboration are shipment of uranium from reprocessed spent fuel from France to the Russian Federation, re-enrichment of French reprocessed uranium at Russian enrichment enterprises and shipment of re-enriched uranium in the form of fuel pellets or fuel rods back to AREVA (formerly COGEMA or FRAMATOM). (Management of Reprocessed Uranium Current Status and Future Prospects - IAEA-TECDOC-1529).

With the exception of reprocessing of Russian origin SNF, current laws require that all final waste be eventually returned to the countries of origin. The challenging task for enhancing international collaboration at the back end of NFC is to provide more flexible legislative framework in order to help many countries in solving the problem of SNF in a sustainable manner.

Another important part of back-end options is depleted uranium tails management – a very prospective field from the point of view of international collaboration. A good example of such collaboration is enrichment of depleted uranium, mainly from European uranium enrichers URENCO and EURODIF, in the Russian Federation.

VI.2.3. Package of services

The nuclear energy markets provide various opportunities for services. The recipient can minimize their costs by selecting different suppliers in a competitive market, as shown above in the case of Finland. Another possibility is to obtain a package of services from one provider. Examples of companies that provide the sale of NPP units with a wide package of NFC services are ORANO [VI.4] and ROSATOM [VI.5].

The front-end services from both ORANO and ROSATOM combine the services of uranium conversion and enrichment along with the manufacturing of fuel assemblies for nuclear reactors. The fuel services cover every aspect of the fuel design and fuel production, from the technology to the finished fuel assembly.

The reactors and services operations of ORANO and ROSATOM bring together the design and construction of the nuclear reactors. The business also offers the products and services needed for the maintenance, modernization and control of all types of nuclear reactors. ROSATOM implements a new model of collaboration at the NPP market: BOO – build, own, operate.

ORANO offers back-end management solutions for used fuel: recycling, logistics clean-up and site rehabilitation. A specific feature of ROSATOM's package at the back-end management is the experience in implementation of the SNF take back option.

International conferences and meetings, including INPRO Cooperative Projects and Dialogue Forums, indicate that a package of services is a type of collaboration quite in demand by many nuclear power users and will no doubt be addressed by many country partners in the future.

VI.2.4. An analytical model of collaboration among supplying and recipient countries

An analytical model of interaction among supplying and recipient countries that underlies the approach implemented in the template is shown in Fig. VI.1. The collaboration simulated in the model covers all three dimensions shown in Fig. VI.1: technology improvements, development of infrastructure, and social-economic & environment area.

The flowchart in the Fig. VI.1 illustrates the role of international cooperation for the case when the group of the technology user countries implements a programme of nuclear power advancement by purchasing NPPs and minimizing the cost of nuclear fuel physical infrastructure by means of receiving services at the front and back end of the NFC from a technology holder country or from an International NFC Centre capable to provide services of recycling strategies. This synergistic NES based on thermal and fast reactors makes it possible to arrange win-win collaboration for both supplying and receiving partners.

The supplying partners can improve economics and, thus, sustainability of the NES by increasing their export business. The recipient countries receive the necessary components of the NFC without excessive burden to their domestic infrastructure. Thus, all collaborating countries can improve indicators in different sustainability areas of their NESs.

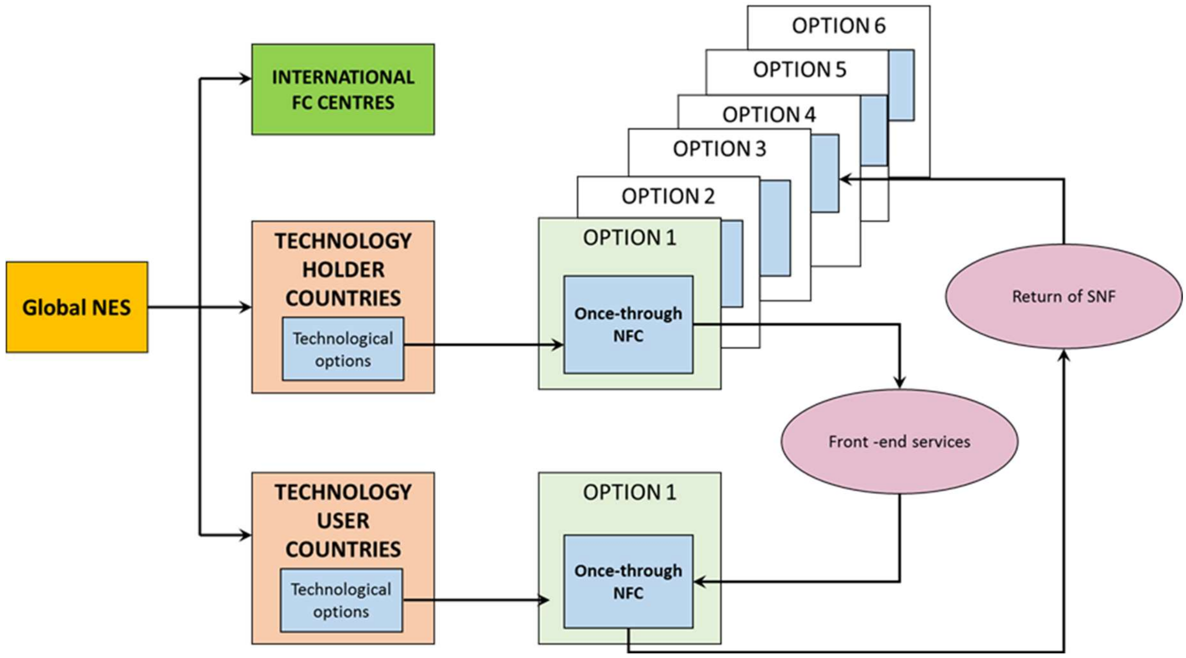

FIG. VI.1. The flowchart of services provided by supplying countries to recipient countries.

REFERENCES TO ANNEX VI

[VI.1] INTERNATIONAL ATOMIC ENERGY AGENCY, web page of INPRO section: http://www.iaea.org/INPRO

[VI.2] INTERNATIONAL ATOMIC ENERGY AGENCY, Multilateral Approaches to the Nuclear Fuel Cycle, IAEA, Vienna (2005).

[VI.3] INTERNATIONAL ATOMIC ENERGY AGENCY, Assessment of Nuclear Energy Systems based on a Closed Nuclear Fuel Cycle with Fast Reactors, IAEA-TECDOC-1639 (Rev.1), IAEA, Vienna (2012).

[VI.4] AREVA: GLOBAL LEADER IN NUCLEAR-ENERGY: http://www.areva.com/EN/home-57/global-leader-in-nuclear-energy-and-major-player-in-renewable-energies.html

[VI.5] ROSATOM STATE NUCLEAR ENERGY CORPORATION: http://www.rosatom.ru/en/

ANNEX VII.

GROUNDWORK FOR ROAD MAPPING TOWARDS SUSTAINABLE NUCLEAR ENERGY AT THE 11TH INPRO DIALOGUE FORUM

This Annex provides the discussion of a vision of road mapping conducted at the 11th INPRO Dialogue Forum “Roadmaps for a transition to globally sustainable nuclear energy systems” in October 2015. About 40 participants from 23 Member States discussed the key subjects important to achieve globally sustainable nuclear energy. Participants from Member States expressed their opinions on:

- Nuclear energy sustainability;
- Cooperation among countries as a pathway to long term sustainability;
- Synergies among nuclear technologies and options to amplify the resulting benefits through collaboration;
- Innovative nuclear technologies;
- Preferences of countries regarding the NFC;
- Cooperation of countries in the NFC;
- Safeguards and security implications for SNF disposal;
- Cooperative solutions for waste repositories; and
- Plans and studies related to national nuclear energy strategies.

Participants identified what they find interesting in ROADMAPS and proposed suggestions for the ROADMAPS project scope and on targeted audience for the ROADMAPS final report.

VII.1. NUCLEAR ENERGY SUSTAINABILITY

Many discussions at 11th INPRO Dialogue Forum addressed the issues of nuclear energy sustainability. It was noted that the main problem is that nuclear is not considered by many as a sustainable energy option in the long term.

It was mentioned that while the nuclear community representatives tend to position nuclear as sustainable, or even more sustainable than other energy options, the stakeholders involved with renewables argue that nuclear is not sustainable due to severe accidents with consequences beyond the plant boundary, and the final disposal solutions of high-level wastes are still not implemented in practice. In this context, the on-going INPRO collaborative project Review of Innovative Reactor concepts for prevention of Severe accidents and mitigation of their Consequences (RISC) addresses safety issues of innovative reactor designs with a focus on excluding accident consequences beyond the plant boundary. The new INPRO collaborative project on Cooperative Approaches to the Back End of the Nuclear Fuel Cycle: Drivers and Institutional, Economic and Legal Impediments, will address legal and institutional issues of cooperation among countries in the NFC back end with a focus on sustainable solutions for final disposal of high-level wastes.

The current situation was characterized as challenging for the nuclear industry and particularly suppliers, with multiple observed project delays, problems with financing, etc. According to the meeting Chairman, in Europe nuclear utilities have lost 500 billion Euros within the past decades. At the same time, countries have spent 600 billion Euros to support the introduction of renewables. The result is that nuclear utilities no longer have money to invest in research and development (R&D) and the suppliers have no options to grow. The investment horizons in many countries are limited to approximately 5 years, while some countries have long term R&D investments.

At the same time, it was noted that people tend to accept nuclear more and more because they see the challenges of non-nuclear options, as well as the benefits of the nuclear option – low carbon emissions and clean air, energy independence, stable prices, job preservation, etc. It was also suggested that people are missing a united voice from the nuclear community, internationally. A lot of money has been spent on finding solutions for radiotoxicity issues. The suggestion is to emphasize that the solutions to tackle radiotoxicity issues are known and can be implemented.

Other participants noted that, while it is not clear how exactly to collaborate towards sustainability, such collaboration appears urgent and cannot be postponed anymore. In their view, nuclear is consuming too much uranium resources, and the accumulated waste has to be disposed, while it may be impractical to reprocess all of the waste.

On the contrary, some participants noted that uranium consumption has been optimized over the last decades thanks to mixed oxide (MOX) fuel use and higher burn-up in thermal reactors. They also pointed to the current stepwise approach toward Generation IV reactors. Final disposal of SNF was challenged in view of pending long term safeguards and security issues, while recycling options were mentioned as potentially more sustainable.

Other participants indicated that there are two areas where revolutionary technologies have already enhanced sustainability: (1) Enrichment, where a truly revolutionary process emerged, from gaseous diffusion to gas centrifuge; and (2) Mining – in-situ leaching instead of digging holes.

Regarding in-situ leaching some participants argued this is not really sustainable. Although it provides access to more resources, which is positive, it may also have environmental consequences if not done properly.

Several participants indicated that economic issues are also an important area, including the cost of nuclear systems and incentives for other types of energy sources that impact nuclear competitiveness.

VII.2. COOPERATION AMONG COUNTRIES AS A PATHWAY TO LONG TERM SUSTAINABILITY

Cooperation among countries was mentioned as a vital tool for enhancing nuclear energy sustainability that applies to many topics, including NPP design, construction and financing, front-end and back-end of the NFC, plant operations, etc. There are certain issues that might prevent expanded cooperation, and many of these issues are related to national legal norms currently in place. The issue of intellectual property sharing was mentioned in this context as well as impediments related to nuclear waste disposal.

Participants from some technology holder countries noted that currently it is hard to imagine foreign-designed NPPs in their countries. However, future reactor and NFC technologies could be collaboratively developed, and the costs of the relevant R&D definitely need to be shared.

Regarding closed NFCs and fast reactors in technology holder countries, some participants noted that when fast reactors with plutonium fuel are deployed, the excess of reprocessed MOX fuel could go to thermal reactors of other countries. Others mentioned issues with MOX fuel exporting and plutonium insufficiency for high demand national programmes as possible obstacles for such cooperation.

It was also noted that nuclear still remains a small market, where very few suppliers are protecting and trying to recoup their investments. There are national short-term interests giving preference to the use of own designs and technologies, which don't help in establishing useful cooperative approaches. For example, it was suggested that what is needed is the ability of multiple vendors to be able to fabricate each type of fuel assembly, but it was also noted that certain limitations exist. If the designs are shared such that they become more generic, standardization could help everyone.

VII.3. SYNERGIES AMONG NUCLEAR TECHNOLOGIES AND OPTIONS TO AMPLIFY THE RESULTING BENEFITS THROUGH COLLABORATION

Some participants encouraged technology developers to pursue the options with collaboration among countries in the NFC (hereafter, synergistic options), specifically, as it helps to clarify how to manage SNF.

Some participants mentioned they don't consider international collaboration to be difficult when all have the same problems to solve. What is needed is mutual trust between countries. This could be easier to achieve if technology owners provide good examples on how to manage SNF.

It was also noted that to foster international cooperation the existing national and international instruments and liabilities under bilateral agreements for cooperation, which can sometimes be a drawback for cooperation, should be examined.

Some participants supported further application of the GAINS analytical framework for global and regional nuclear energy scenario analysis, within which countries are classified into three non-geographical groups, representing technology holders, technology users and newcomers. They suggested that potential cooperation between groups could be considered further.

VII.4. INNOVATIVE NUCLEAR TECHNOLOGIES

A variety of preferences regarding innovative nuclear reactors and NFCs were expressed. Many representatives of newcomer countries made a point that small and medium sized reactors (SMRs) can be very popular to smaller countries and countries with smaller economies, which cannot afford to build an NPP with a large reactor. Several participants mentioned SMRs as more attractive than large NPPs; in this context the need to improve their economics to make them competitive was emphasized. It was also noted that many of the innovative technologies being developed are considered to be implemented within small, potentially, modular reactors.

Participants from a number of technology user countries highlighted their cooperation with technology holders in development of the Generation IV reactors and in improvement of the Generation III/III+ designs.

Participants from a number of technology holder countries highlighted their interest in, and developments for, fast reactors. Some participants mentioned that fast reactors per se are not the objective, but are the means to meet certain objectives related to maintaining fissile resource availability and minimization of waste, including its volume, radiotoxicity and effective lifetime. In conjunction with large fast reactor programmes it was also mentioned that the demand for plutonium for their first loads may be quite high, hampering the possibility to produce MOX fuel loads for thermal reactors, depending on different parameters including, especially, the schedule of fast reactor deployment.

Participants from other technology holder countries highlighted alternative innovative technologies that, while still requiring plenty of research and development (R&D), might eventually help achieve sustainability benefits within a once-through NFC. Among them are breed-and-burn concepts, very high temperature reactors with high burn-up fuel, etc. Other participants noted that such an approach still does not achieve the same objectives as fast neutron reactors in a closed NFC.

Several participants expressed interest in the thorium NFC, in some cases in conjunction with SMRs.

Regarding innovation in general, it was noted that if one wants the best option he might be waiting forever. Newcomers have very reliable services available through the market today. Newcomers should start now in collaboration with experienced technology holder countries.

Regarding transition to innovative reactor fleets, it was emphasized that governments and industry should act together; however, it was noted that both corporations and governments often change, which is a factor that can limit long term cooperation.

VII.5. PREFERENCES OF COUNTRIES REGARDING THE NFC

Security of supply was typically mentioned in conjunction with the NFC front end, while long term storage pending the technology and political approval for final disposal was often mentioned regarding the NFC back end. Time spans for safe dry storage of SNF were discussed and one stance was that current technologies secure ~50 years of dry storage facility operation, based on neutronic calculations and deterministic safety analysis.

Participants manifested various preferences for ultimate high-level waste disposal, ranging from direct disposal of SNF to various reprocessing and recycling options, involving uranium, thorium, plutonium and minor actinides, sometimes based on different reprocessing technologies (aqueous, dry) for different types of fuel.

Participants from some technology user countries emphasized that a full NFC is not an option for them; therefore, international cooperation on options for disposal are sought.

Reflecting upon synergies among various nuclear technologies, NFC solutions with recycle of SNF from reactors of particular types into reactors of other types were considered, including recycle with only physical reprocessing options (e.g., DUPIC [VII.1]).

VII.6. COOPERATION OF COUNTRIES IN THE NFC

For many newcomer countries, SNF management is a difficult topic to address and a potential roadblock to their nuclear power development.

Participants from many countries expressed their interest in international cooperation on SNF and noted the benefits of fuel ‘leasing’ or take back of SNF in this respect.

One participant asked if the IAEA could be in a position to develop a convention for SNF take back. The secretariat has clarified that the Agency could provide some recommendation and advice, but most efforts, either national or regional, should be carried out by the Member States. IAEA is not in a position to develop such a convention.

Some participants have suggested that fuel ‘leasing’ may be quite useful for many newcomer and technology user countries. The secretariat noted that the term ‘leasing’ may be misguiding as operations with the supply of fresh fuel and take back of the spent (used) fuel may not fit under the notion of ‘leasing’ as adopted in national legislations. This in no way means such operations are not possible; and positive experience exists. It was also suggested that in the future ‘take back’ services could probably be provided internationally, although achieving this may not be simple and will depend strongly on public opinion. Nevertheless, it could be a very helpful approach for newcomer countries.

Other participants argued that take-back proposals may also have potential challenges, e.g., it is necessary to have conditions for countries to deliver these services safely. Especially, the service of SNF take-back is not and must not be related to the capacity of producing fuel, but instead should rely on SNF management capability, for example through recycling. These participants believe that keeping the responsibility for the nuclear waste with the producer, in accordance with existing international agreements, is necessary to assure that the waste producing country will actually choose responsible solutions (vs. selecting low bid proposals with no actual guarantees). They suggest taking back SNF for reprocessing with the return of the ultimate high-level waste to the producer could be a good example here, backed by multi-decade experience on an international scale.

A question was raised on which institutional steps and timeframes should be followed for SNF management. Experts from some technology holder countries clarified that for countries with large planned nuclear power programmes it is reasonable to develop a SNF management approach 2–3 years before starting a new NPP. For a newcomer country, it would be reasonable to develop at least a general strategy for dealing with the SNF before it starts the construction of a first NPP.

Regarding NFC services, according to some of the meeting participants, at least three different suppliers for each service are needed to exclude a monopoly. At the same time the degree of standardization of NPPs and, in particular, nuclear fuel, is at the moment insufficient, so that the choice of fuel supplier often defines the choice of an NPP and vice versa.

Other participants disagreed with this by noting one can have competition with only 2 market competitors and hardly any competition with several competitors.

The participants noted there is no real spent (sometimes also referred to as used) fuel market at the moment and pointed to the need to develop such markets to enable more choices for reprocessing and high-level waste disposal.

Some participants noted that international collaboration or internationalization of SNF or high-level waste repositories are attractive solutions, but could be quite difficult to achieve, not for technical issues, but because of public acceptance and political issues. Therefore, reprocessing options should not be postponed. Also, in conjunction with this, some countries could construct a pilot repository as a good practice example and this may help overcome public rejection.

VII.7. SAFEGUARDS AND SECURITY IMPLICATIONS FOR SNF DISPOSAL

A presentation from IAEA's Department of Safeguards highlighted the safeguards approach to the SNF disposal facilities under construction or planned in Finland and Sweden respectively. Prior to the facility closure there will be a 100-year trial operation period with the safeguards approach for this period already defined. Regarding this presentation the following question was raised: There would be a 100-year period when the facility would be filled, and after this it would be closed; what would be done when the facility would be closed?

The answer to this question was as follows: According to provisions of comprehensive safeguards agreements, safeguards on nuclear material can only be terminated if it is unrecoverable, but that's not going to be the case. We have 100 years to figure out exactly how we will apply safeguards for the very long term. There is no agreement on how to proceed.

A presentation from IAEA's Division of Nuclear Security of the Department of Nuclear Safety and Security highlighted security approaches to the NFC back end. It was clarified that the original Convention on the physical protection of nuclear material (CPPNM) only covers international transport. The provisions in the original CPPNM are requirements of all parties. The Amendment to the Convention will put requirements on domestic use, storage and transport – currently about 15 more ratifications are necessary for the Amendment to be adopted.

VII.8. COOPERATIVE SOLUTIONS FOR WASTE REPOSITORIES

A presentation from IAEA's Division of Fuel Cycle and Waste Technology (NEFW) of the Department of Nuclear Energy highlighted the progress towards multinational waste repositories. A question was asked whether any two countries ever seriously considered building a shared geological repository on their border. The answer was no, but some have proposed an artificial island in the North Sea as an international repository.

Regarding fuel take back, some countries noted they have a lot of experience in taking back research reactor fuel.

The NEFW presentation, inter alia, noted that the public attitude to waste repositories has evolved over time, e.g., in the early years of nuclear power there was less public opposition and radioactive waste storage was not seen as a major obstacle.

The NEFW presentation also highlighted certain optimism towards high-level waste repositories, since there are over 100 low-level waste (LLW) facilities operating around the world. The high-level waste repository can, therefore, be set up carefully by drawing upon lessons learned from the countries that pioneered disposal activities, with no major obstacles foreseen.

With reference to geological disposal, it was emphasized that up-front R&D can be conducted cooperatively; countries which are interested in starting a nuclear energy programme or developing innovative technologies have a lot of opportunities to do so.

It was also noted that important milestones were passing just at the time of the meeting, as certain countries (Finland, Sweden) have submitted robust applications to license long-term facilities; regulator reviews will help to communicate the safety features to the public.

VII.9. PLANS AND STUDIES RELATED TO NATIONAL NUCLEAR ENERGY STRATEGY

Some participants noted that, regarding plans and strategies for nuclear energy, it is important to distinguish clearly between official plans and studies. These are the official plans that make national strategies credible, and not just how much research and studies are being done.

In most of the presentations at the meeting official country strategies were defined up to 2030–2035. It was observed that nearly all participants had filled out the meeting questionnaire in parts related to longer term national projections, up to the end of the century. Some countries noted that they are planning longer time periods for their national strategies.

VII.10. POINTS OF INTERESTS ON THE ROADMAPS PROJECT

The following considerations reflect the interest of the Dialogue Forum participant in the ROADMAPS collaborative project:

- Outcomes of the ROADMAPS project can be used to learn more about what technology developers are doing and how countries are evaluating plans for SNF management; many technologies will be available in this century, e.g., it is interesting to learn, what is the probability that the fast breeder reactors (FBRs) will be commercialized? It could be helpful to many technology user countries if this information is available in roadmaps;
- The nuclear market is unique; it is widely known that if something happens to nuclear power in one country, it will affect all others; this should be a driver, an incentive for countries to collaborate; and by identifying options for collaboration the ROADMAPS project can facilitate actual collaboration;
- From the standpoint of a newcomer country, the roadmap approach should encourage standardization of nuclear technology; this would bring more customers on board;
- Regarding technology, decision makers in newcomer countries may use the developed roadmaps to support more strategic planning, including how to prepare for budgets. Technology suppliers may have different objectives including the need to standardize technologies;

- The ROADMAPS project may offer good ideas on how to advance from a business-as-usual option to a NES with enhanced sustainability, and it is very useful to have comments on how to do this.

It was noted that demands for proven technologies are real; hence, there is a need to balance development of proven technology with development of more radical R&D. It is important to understand the precondition of new markets – and the roadmaps approach offers the opportunity to begin examining this.

VII.11. SUGGESTIONS FOR THE ROADMAPS PROJECT SCOPE AND SCHEDULE

During the discussions at the meeting, the following suggestions for the ROADMAPS project scope and schedule were produced, including specification of requirements for the roadmap template:

- The roadmap template should not only address long term issues; a lot of countries need to examine options in the short and medium term as well, based on existing technologies;
- The roadmap template needs to take consideration of industrial availability, and how countries can collaborate on the enhanced sustainability options;
- The ROADMAPS project has been described as an umbrella project that would incorporate a lot of other projects; it can also be an umbrella for the projects that still can occur – the ROADMAPS project could provide more detail and forward looking information to queue up future projects;
- The roadmap template needs to consider options for waste disposal;
- The roadmap template could identify stumbling blocks of timelines, including those for thorium based application technologies, small and medium sized reactors (SMRs), as well as options for collaboration in some technical areas;
- The roadmap template could emphasize the harmonisation of different countries' intentions and resources;
- The bottom-up approach of the roadmap template can provide credibility; when considering evolutionary vs. innovative technologies, one needs to be more realistic and keep in mind this is a bottom-up process;
- Short term actions need to have a priority; that doesn't mean the long term will be forgotten; the questions is, if one looks strictly at economics, is wait-and-see the best option?
- The roadmap template should help define short term actions to prepare for long term innovative NESs;
- The problem is how to aggregate the questionnaire within the roadmap template so that dimensions are not lost; one can't start the questionnaire with assumptions about the available NFC options;
- With reference to the OECD-NEA and GIF technology roadmaps, it is necessary to make sure that these are useful overlaps; for example, NEA is much more focused on R&D and R&D funding as compared to INPRO;
- Regarding the roadmap template scope, one needs to make sure the uncertainties including possible technological and cooperative forks are considered;
- The roadmap template may contribute to developing a global public awareness programme regarding sustainability and safety; a strong programme would help to address a lot of questions and speed up implementation of NESs that are actually needed now;

- The roadmap template could record the status of current available technologies, including those that are becoming available on the market in future;
- The timeframe uncertainties are large, so it may be better to concentrate on documenting the status of evolutionary technologies rather than putting a timeframe on them; similar strategies are being used in the Generation-IV International Forum;
- Technologies with similar names can be different in different countries, so in addition to naming them, the aims and objectives and enabling technologies could also be listed;
- It is important to include non-electric applications, and such should consider transport in addition to district heating, etc.;
- The ROADMAPS project could provide recommendations and suggestions to governments as well as international organizations to consider nuclear energy development in a sustainable manner;
- The roadmap template could indicate clearly what kind of actions by governments and other organizations are needed and at which time; also, actions by international organizations and other stakeholders like universities, research institutes, nuclear communities, could be highlighted; this includes structure and skill of human resources, public education, economics and financing, 3-S (safety, security and safeguards), SNF management, and R&D on innovative technology for future NESs;
- With reference to non-proliferation issues some participants suggested to adapt a roadmap for thorium as future fuel;
- The roadmap template needs to consider three important points: actual forecasts of development, milestones and frameworks for forecasting, and prospects for collaboration among countries;
- The roadmap template could also consider regional roadmaps in addition to the national and global ones; this could facilitate harmonization towards sustainability;
- The roadmap template needs to provide answers on how competitive nuclear generation could be achieved and how spent fuel could be managed;
- The roadmap template needs to consider options for standardization;
- The roadmap template needs to allow for flexibility of technology development without locking in on particular designs or concepts; one needs to appreciate the diversity of designs, opinions, and accommodate this in relevant roadmaps;
- Global crosscut can be developed further using the roadmap template;
- The ROADMAPS collaborative project needs to further review the roadmap template to enhance development of individual country' roadmaps;
- With umbrella project vision the IAEA secretariat could encourage more countries to sign up for the ROADMAPS collaborative project.
- The ROADMAPS collaborative project is to be conducted in close collaboration with the other divisions of the IAEA; how this collaboration is going to take place needs to be better explained to / and discussed with Member States.

VII.12. ROADMAP TEMPLATE

Some participants of the meeting expressed the opinion that the presented ROADMAPS project framework and roadmap template provide a very good basis to move forward with the ROADMAPS collaborative project. Other suggested a more graphical representation may be helpful, which should also include institutional information.

VII.13. TARGETED AUDIENCE FOR THE ROADMAPS FINAL REPORT

During the meeting a discussion was convened on whether the public should be involved in the development of the roadmaps towards nuclear energy with enhanced sustainability. A few participants have supported this point, while others did not agree that it can be productive to involve the public in early stages on elaborating such roadmaps, because it requires special expertise to consider relevant deployment scenarios, communication with the public should be realized based on the well-elaborated and clear platform for sustainable nuclear energy development.

The participants generally supported the definition of targeted audience to include policymakers, decision makers, industry, R&D organizations and academia.

VII.14. SUMMARY

In the course of the discussions at the Dialogue Forum the participants agreed that one of the effective solutions to bring the benefits of enhanced nuclear energy sustainability to a broader variety of users is through cooperation between countries on the NFC. They identified national prospects for nuclear energy collaboration strategy until the end of the century based on the current patterns of nuclear trade, which may include bilateral agreements, multiple bilateral agreements and multilateral agreements.

REFERENCES TO ANNEX VII

[VII.1] MYUNG SEUNG YANG et al, The Status and Prospect of DUPIC Fuel Technology, Nuclear Engineering and Technology **38**, No. 4 (June 2006)