Management of Spent Fuel from Nuclear Power Reactors

An Integrated Approach to the Back End of the Fuel Cycle

Proceedings of an International Conference
Vienna, Austria, 15–19 June 2015

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International Atomic Energy Agency

MANAGEMENT OF SPENT FUEL FROM NUCLEAR POWER REACTORS

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PROCEEDINGS SERIES

MANAGEMENT OF SPENT FUEL FROM NUCLEAR POWER REACTORS

AN INTEGRATED APPROACH TO THE BACK END OF THE FUEL CYCLE

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ORGANIZED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY,
IN COOPERATION WITH THE
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INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

Spent fuel management is one of the most important steps in the nuclear fuel cycle, and implementing the final step of the fuel cycle, through the development of deep geological disposal, remains a priority.

Finland, France, Sweden and other countries have made progress in developing geological disposal facilities for high level waste and spent fuel; the first such facility is expected to be operational in the coming decade. In the meantime, globally, spent fuel in storage continues to accumulate at a rate of approximately 7000 tonnes of heavy metal per year. Such a situation has serious consequences in terms of the decreasing existing storage capacity for spent fuel and the increasing duration of storage prior to direct disposal.

Developments at the front end of the fuel cycle and the requirements for either its recycling or its disposal can also have implications for spent fuel storage. With these issues in mind, the 2015 International Conference on Management of Spent Fuel from Nuclear Power Reactors raised awareness of need to take a holistic view of the nuclear fuel cycle. Through such an approach, the influences of, and impacts on, all phases of the nuclear fuel cycle are clearly understood and can facilitate effective decision making in the back end of the fuel cycle.

The objectives of the conference were to raise awareness of how developments in power generation and the availability of disposal can have an impact on spent fuel management; to highlight the progress achieved in connection with the back end of the nuclear fuel cycle as well as associated challenges; to present recent developments in technology, the regulatory framework and safety aspects; to evaluate the advances in management of spent fuel from power reactors since the inception of IAEA conferences on this topic; and to identify pending issues and anticipated future challenges.

To address these objectives, the conference was structured into seven sessions covering spent fuel management strategies, status and challenges of an integrated approach, safety aspects of spent fuel management, ageing management programmes, storage options in support of an integrated approach, the impact of the front end of the nuclear fuel cycle on the back end, and research and development required to deliver an integrated approach.

The IAEA wishes to acknowledge the contributions to this conference series of J. Bouchard, formerly of the French Alternative Energies and Atomic Energy Commission (CEA, France), who passed away in January 2015. J. Bouchard was the conference president in 2006 and was known in particular for his work on Generation IV reactors.

The IAEA officers responsible for this publication were P. Standring of the Division of Nuclear Fuel Cycle and Waste Technology and G. Bruno of the Division of Radiation, Transport and Waste Safety.

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1. EXECUTIVE SUMMARY

The IAEA, in cooperation with the Nuclear Energy Agency (NEA) of the Organization of Economic Co-operation and Development (OECD), held an International Conference on the Management of Spent Fuel from Nuclear Power Reactors: An Integrated Approach to the Back End of the Fuel Cycle, 15–19 June 2015 in Vienna. The conference was attended by more than 200 participants from 39 Member States and 5 International Organizations. The IAEA also supported the attendance of 9 young professionals.

Symposia or conferences on management of spent fuel from nuclear power reactors have been organized by the International Atomic Energy Agency (IAEA) every 3–5 years since 1987 [1–6]. The conferences are normally held in cooperation with the NEA of the OECD and the previous conference was held 31 May–4 June 2010.

At the 2010 conference the nuclear industry was full of optimism reflected by: the largest number of new nuclear power reactor constructions started in a single year since 1985; over 60 Member States had indicated an interest to the IAEA in considering the introduction of nuclear power; growing interest/activities in the development of advanced fuel cycles and fast breeder reactors. Around 9 months later the industry was impacted by the accident at the Fukushima Daiichi Nuclear Power Plant (NPP) which left three reactors with melted cores and a fourth reactor badly damaged from the effect of a hydrogen explosion from an adjacent reactor.

In the following years the Member States operating nuclear power plants introduced additional emergency response measures as well as undertook safety reviews of their facilities. Where required, modifications have been or are in the process of being incorporated. Some countries reviewed their nuclear programmes, and Belgium, Germany and Switzerland took additional steps to phase out nuclear power entirely. In the case of Germany, 8 NPPs were shut down immediately and the remaining 9 NPPs will be phased out by the end of 2022. Japan shut down all of its NPPs while safety reviews and modifications have been carried out; the 6 reactors at Fukushima Daiichi have been shut down permanently. The premature shut down of NPPs and the management of the resulting fresh and spent fuel presents additional spent fuel management challenges.

In terms of renewed interest in nuclear power generation, the response to the Fukushima accident was initially mixed with some countries continuing their programmes and others introducing delays while the situation was analysed. By the end of 2013 there was renewed growth with 72 new power reactors under construction, the largest number since 1989, including the construction of power reactors in two newcomer countries; Belarus and the United Arab Emirates.

Implementing the final step of fuel cycle still remains a priority. The geological disposal projects in Finland, Sweden and France are progressing towards licensing for construction and operation. Finland is expected to be the first country to have an operational geological disposal facility around 2020. Following the United States of America Government’s decision in 2009 not to proceed with the Yucca Mountain geological disposal facility, work in this area has been stopped and the U.S. Department of Energy is currently working on addressing the recommendations of the Blue Ribbon Commission.

The 2015 conference therefore was timely to reflect upon the changed operating environment in the nuclear industry since the last Conference in 2010, and to reflect upon how the industry and key stakeholders have responded to these changes.

The basis of the 2015 international conference was to take a holistic view of the nuclear fuel cycle in order to better understand how decisions taken in one phase of the fuel cycle can influence and/or impact other phases of the fuel cycle, and vice versa.

The conference addressed all aspects of spent fuel management with a focus on the approach to the back end of the fuel cycle. 78 presentations from 19 Member States and 4 International Organizations were delivered over seven sessions.

The objectives of the conference were to raise awareness on how developments in power generation and availability of disposal can impact on spent fuel management, to highlight the progress achieved in connection with the back end of the nuclear fuel cycle as well as associated challenges, to present recent developments in technology, regulatory framework and safety aspects, to evaluate the advances in management of spent fuel from power reactors since the inception of IAEA conferences on this topic in 1987, and to identify pending issues and anticipated future challenges.

The conference sessions were planned in order to address these objectives, and covered spent fuel management strategies, status and challenges in an integrated approach, safety aspects of spent fuel management, ageing management programmes, storage options in support of an integrated approach, impact of the front end of the nuclear fuel cycle on the back end and research and development required to deliver an integrated approach.

The sessions were complemented by four keynote speeches covering a holistic view of the nuclear fuel cycle, how spent fuel management options might affect geological disposal, safety and technological aspects of spent fuel management, the influence of fuel design and reactor operation on spent fuel management.

The opening session included opening remarks from the conference President Ms. Rayment (NNL, UK), Mr. Amano (Director General, IAEA) and a keynote speech from Mr. Magwood (Director General, NEA-OECD). The key message delivered by Mr. Magwood in considering what to do with spent nuclear fuel was that effective involvement will be key to enabling trust with key public stakeholders and will facilitate the implementation of spent fuel solutions.

One of the main messages taken away from this Conference, and it relates to the conference theme, is the need for an integrated back end of the fuel cycle; especially in the areas of processing, storage, transport and disposal as well as the necessity to adopt a holistic view for the management of spent fuel.

Spent fuel management strategies, at this conference, were directed more towards how each country is implementing its own sustainable spent fuel management strategy and less on considering or justifying whether spent fuel should be regarded as waste or as a resource and therefore which strategy should be adopted. DG Amano recalled the importance for embarking countries in nuclear energy to develop ‘cradle-to-grave’ plans for both spent fuel and radioactive waste, and strongly encouraged those with existing nuclear power programmes to share their experiences with newcomer countries.

There seem to still be two approaches to the integrated vision; the industry, who focus on addressing the near term need of storage to maintain power generation or to enable reactor decommissioning as a main element of the integrated approach, and the waste management organizations and regulatory bodies, who promote, in line with international positions, the need to have an integrated approach with disposal being the end point to achieve.

An integrated approach will also ensure that interdependencies between the different steps of spent fuel management are taken into account from safety, technical and organizational standpoints.

The conference recalled, should this be necessary, the importance of safety in the management of spent nuclear fuel. The importance of having the right scientific, technical and engineering skills and maintaining these competences are key to ensuring on-going safety and to deliver a comprehensive and safe fuel cycle. Examples presented included: the technology developments

for the recovery and management of damaged fuel; safety assessment modelling; storage developments in response to customers' needs; advanced fuel cycles.

With regards to timeframes, the issue of ageing of structures and materials remains an important element of a safe and integrated management of spent nuclear fuel. Since the last conference such an issue has become a priority for a few Member States which have been impacted by premature NPP shut downs and/or are unlikely to have an end point in place for decades. Research and development (R&D) is addressing this issue.

As far as reprocessing and recycling options are concerned, the reuse of plutonium in the absence of a fast reactor or alternative fuel cycle programme remains a limiting factor. A number of options for addressing this issue were presented.

Disposal safety remains a topic of concern in particular regarding the availability of geological disposal facility(ies) for high level waste and spent fuel, but emphasis was made on the progress of some countries in this regard. This also represents an opportunity to learn from one another as the fuel cycle is developed. The concept of multinational approaches was also discussed highlighting the views of pros and cons for this approach.

The last session of the conference highlighted the important role R&D plays to ensure safety in the back end of the fuel cycle. In particular many of the presentations focused on responding to the questions concerning what do we know in the long term? How should we manage ageing? Research and development have to be continued in these areas to address these issues.

2. OPENING ADDRESS

2.1. CONFERENCE PRESIDENT

Opening speech as provided, verbatim.

F. Rayment
National Nuclear Laboratory, United Kingdom

Good morning Ladies and gentlemen,

It gives me great pleasure to be here this week in Vienna and chairing this International Conference on Spent Fuel from Nuclear Power Reactors.

The last Conference on this topic was held in May 2010, and since then a number of challenges have happened across the world that have brought the importance of the management of spent fuel to the forefront of any nuclear energy programme, and nothing more so than the Fukushima Daiichi accident in 2011.

This has, in some cases, reshaped some countries thinking on their nuclear power programmes with early closures creeping onto their agendas. Germany is an example of this, where a planned phase out in now under way for energy generated from nuclear power. The Swiss Government, on the other hand, has taken a decision not to extend or replace their existing fleet.

In addition, and despite the accident at Fukushima, a number of countries are powering ahead with lifetime extensions to existing power plants, together with the implementation of some highly challenging new power plant construction programmes. This construction, being planned in places like China, the United Arab Emirates and even my country, the United Kingdom, will generate spent fuel challenges in their own right.

What is clear is that whether nuclear power is being phased out, being maintained at current levels, or undergoing expansion programmes, the management of spent fuel will be key to each country's success in their nuclear energy programme.

Whether a closed or an open fuel cycle is chosen, a demonstrable route must be implemented for the management of the spent nuclear fuel.

Countries considering closed fuel cycle options discuss benefits on the use of scarce resources like repositories through minimizing waste volumes and radiotoxicity content. However, we also hear about the considerations for non-proliferation of special nuclear materials like Plutonium and Uranium with these cycles. For a closed fuel cycle to be viable though, reprocessing services need to be more commercially attractive. Its areas like this that R&D can play a significant role through plant improvements, waste management and step changes in technology.

Countries considering open fuel cycle options are typically progressing on the short term economics of the fuel cycle. This is especially the case where smaller nuclear programmes are in place and the investment required for a reprocessing facility is too great in comparison with that nation's energy requirement.

Good progress was made at the recent meeting of the IAEA Joint Convention on the safety of spent fuel management and on the safety of radioactive waste management, and this will contribute and enable the continuation of higher levels of safety management.

In addition, the Euratom basic safety standards directive will make the focus on spent fuel even more important for newcomers to the industry and mature players alike. A key aspect is about having effective life cycle strategies in place for the management of both spent fuel and waste.

Within the U.S., The Blue Ribbon Commission on America's Nuclear Future was formed by the Secretary of Energy to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle. From this a new strategy emerged including key elements focus and engagement on waste management, storage, disposal, transportation and innovation.

In addition, the U.S. DOE have published a report on R&D investment priorities where programmes have been established to support scientific excellence and technological innovation.

A key aspect for effective spent fuel management is in developing and collecting the information required for successful delivery of the back end of the fuel cycle. This includes: the collection of data to support relicensing or continued operations safety assessments, this is especially important in relation to systems going decades beyond original design life; the collection of data to support recycling; and the collection of data to support high level waste (including fuel disposal).

Knowledge management is especially important here and the sharing of data globally through accessible databases is key to achieving this. Through R&D programmes these databases are kept up to date with validated information to assist in decision making.

Surveillance programmes are also important in confirming that both the spent fuel and storage system are safe which in turn provides evidence to key stakeholders.

As new enhanced safety standards are developed the focus will not only be on the reactor system of choice, but also on the fuel and associated fuel cycle. Accident Tolerant Fuels, for example, could make a significant impact on enhanced fuel safety under accident conditions. Much work is being carried out globally on the cladding and fuels which will enable further accident tolerance and understanding the behaviour of these fuels post irradiation will be key in any future decision making on their use.

Even where a country's key stakeholders perceive nuclear power as a positive energy source, when asked what their key area of concern would be, management of spent fuel and waste is always highlighted. Deferral of disposal will have an immediate consequence for storage safety through pushing storage beyond current license lifetimes, and so integrated approaches must be developed.

This Conference will bring a number of these key challenges here today for discussion and as such I'm so pleased to be here opening the debate on effective spent fuel management and bringing together the experience across many nations through sharing best practice.

I'd like to welcome all of you here to Vienna and I look forward to meeting with you throughout the event. I'm convinced that you will find this Conference as exciting and as thought provoking as the title suggests.....

2.2. INTERNATIONAL ATOMIC ENERGY AGENCY

Opening speech as provided, verbatim.

Y. Amano
Director General, IAEA

Thank you, Madam President.

Good morning, Ladies and Gentlemen.

I am pleased to welcome you to this International Conference on Management of Spent Fuel from Nuclear Power Reactors.

Spent fuel management is an essential component of the nuclear fuel cycle. Supporting the safe management of spent fuel, and of radioactive waste, is a key IAEA activity. We develop safety standards and guidance, publish technical reports and organize training courses, workshops and technical meetings.

Last September, we devoted our annual Scientific Forum to the subject of radioactive waste management. We are organizing an international Conference on the same subject in 2016.

Waste disposal is often cited as one of the major problems facing nuclear power. In fact, the nuclear industry has been managing waste disposal for more than half a century. Dozens of facilities for low level and intermediate level nuclear waste are in operation throughout the world.

As far as the management of high level radioactive waste and spent fuel is concerned, good progress has been made in recent years, especially in Finland, Sweden and France. I have had an opportunity to visit the ONKALO facility in Finland, where a repository for the final disposal of spent fuel is being built deep underground, and the Hard Rock Laboratory in Sweden. They are impressive sites.

I was also impressed by the briefing on the Cigéo project, which I received from the head of the French national radioactive waste management agency, Andra, during my recent visit to France. I understand that it is now at the license application stage.

It will still be some years before the first deep geological repositories for nuclear spent fuel become operational. But the progress being made in this area deserves to be better known.

Ladies and Gentlemen,

Since your last meeting five years ago, the most important event in the nuclear sector was the accident at the Fukushima Daiichi nuclear power plant in Japan in March 2011. Last week, I presented the IAEA report on the accident to our Board of Governors.

Extensive efforts have been made throughout the world in the last four years to improve safety at nuclear power plants and at facilities housing nuclear material.

I know that those of you working with the nuclear fuel cycle have extensively reviewed your practices and procedures since the accident and taken additional steps to improve safety.

This includes improving transparency and the exchange of information between countries. Conferences such as this have an important role to play.

Despite the Fukushima Daiichi accident, many countries continue to see an important role for nuclear power as part of their energy mix. They believe that nuclear power can help to improve energy security, mitigate the effects of climate change, and make economies more competitive.

IAEA projections indicate that the use of nuclear power throughout the world will continue to grow in the coming decades. The volume of spent fuel will also continue to grow, and it is essential that it is managed safely.

Since your last Conference, the IAEA has launched a programme to demonstrate the long term performance of dry stored spent fuel and related storage system components. We are also finalizing a new guidance document on the use of dual purpose casks for both transport and storage.

In 2012, we published a new safety guide on the storage of spent nuclear fuel. It is being revised to take into account the lessons learned from the Fukushima Daiichi accident.

As you may know, the IAEA provides extensive support to countries which are considering, or embarking upon, nuclear power programmes.

One of the points which I stress in my meetings with leaders from these newcomer countries is the vital importance of having 'cradle-to-grave' plans in place for both spent fuel and radioactive waste.

I strongly encourage countries with existing nuclear power programmes, and experience of the back end of the fuel cycle, to share their experience with newcomer countries to ensure that best practice is implemented everywhere.

Ladies and Gentlemen,

The sub-title of your Conference is "an integrated approach to the back end of the fuel cycle."

The IAEA considers it important for practitioners to take a holistic approach to the fuel cycle and remain aware of issues outside their particular speciality.

I wish you every success with this important Conference and I look forward to learning about the outcome.

Thank you.

2.3. ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT – NUCLEAR ENERGY AGENCY

B. Magwood
Director General, OECD–Nuclear Energy Agency

Mr. Magwood, Director General Nuclear Energy Agency (OECD), gave a presentation on "What to do with Used Nuclear Fuel: Considerations Regarding the Back End of the Fuel Cycle". The presentation can be downloaded from the IAEA meetings page on the IAEA web site: Meetings in 2015, code CN-226 [7].

3. SESSION SUMMARIES

3.1. SESSION 1: SPENT FUEL MANAGEMENT STRATEGIES

A wide range of papers was presented on spent fuel strategies illustrating both the common and individual challenges that countries face.

Some papers covered national strategies for the management of spent fuel with examples of reprocessing and recycling of plutonium (and other actinides) in thermal and fast reactors aligned to large scale and ambitious nuclear power programmes. Russia, India and France continue to push ahead successfully with recycling spent fuel and reusing plutonium in fuels for thermal and fast reactors.

Other papers described alternative approaches with a focus on extending the storage period of spent fuel followed by disposal in a repository. The papers explored the multitude of challenges and issues that exist whichever strategy is chosen, and the range of papers served to illustrate the relative position of each nation in its journey with nuclear power.

A third approach of "wait and see" was discussed where fuel was committed to storage because the decision was pending on either reprocessing or direct disposal. Some observers felt it was important that countries commit to a clear pathway (sometimes termed roadmap) with decision points mapped out with progress on a repository, for example, important to maintain industry credibility and public confidence.

Given the multitude and complexity of issues a systematic approach to developing spent fuel strategies is important. To these ends, progress made by an IAEA consultancy group to develop a methodology for establishing and assessing the interfaces at the various points in potential fuel cycle strategies was reported. This work, published as an IAEA TECDOC [8], emphasized the importance of establishing an integrated understanding to inform key decisions. One particular issue highlighted was the increasing importance of "record keeping" to support extended storage, future transport and potentially repackaging of spent fuel having been stored for long periods of time.

The session discussed the sustainability of both closed and open fuel cycle approaches. An industry-led World Nuclear Association Working Group has defined concepts for "sustainable" open (direct disposal) and closed (recycle) fuel cycles. The debate centred around the different challenges and uncertainties presented whichever path a country chooses. The challenges of extended fuel storage and direct disposal compared to reusing the products of reprocessing, especially plutonium, and the interim storage and disposal of vitrified HLW were discussed. The session illustrated different sustainable approaches taken by countries but did not seek to compare the approaches or arrive at recommendations on which approach suits which type of nuclear power programme.

The progress being made by some countries on centralized storage and disposal of spent fuel was described and discussed. Building and maintaining stakeholder trust throughout the duration of repository development, siting and licensing was seen as a key to success. The importance of technical issues that affect the safety case such as decay heat, criticality and radionuclide migration were discussed. However, views were expressed that stakeholder confidence is paramount and the technical issues while important are surmountable.

A clear delineation of accountabilities between the bodies responsible for delivering the repository and the regulatory authority, a sound R&D programme early on in the journey, and an engagement-led "volunteer process" were seen as contributing to stakeholder confidence and enabling real progress to be made on the direct disposal of spent fuel in some countries.

Looking back to the 2010 conference, papers at this 2015 conference were directed more towards how each country is implementing its own sustainable spent fuel management strategy and less on considering or justifying whether spent fuel should be regarded as waste or resource and therefore which strategy should be adopted.

3.2. SESSION 2: STATUS AND CHALLENGES IN AN INTEGRATED APPROACH

A keynote speaker gave a perspective on how spent fuel management options may affect geological disposal and drew conclusions on how to achieve isolation for both spent fuel and HLW. Based on extensive comparative analyses of detailed safety analyses that have been published, notably on concepts from France, Sweden, Switzerland and USA, the keynote speaker concluded that the joint optimization of spent fuel management and disposal criteria requires consideration of multiple factors to be evaluated across the entire fuel cycle, including front end, core management and reactor operation.

Sweden and Finland presented the current status towards the implementation of their respective geological repositories. Licensing of a 'first of its kind' facility, going from theory to industrial practice and maintaining public confidence were outlined as some of the challenges they face. The two countries are also looking to maximize the synergies between the two projects, using the same technical design, e.g. canister fabrication and shared bentonite block production were a couple of examples cited. This presents an exemplar for other countries which may draw benefit from cooperative work on projects.

The perspectives of international or regional geological disposal facilities were presented, and paradoxically, no progress towards the implementation of such project has been reported since it has been launched some time ago. The IAEA recommendation that regional and international cooperation should not relieve any Member State from developing actively its national geological disposal programme was reaffirmed [9].

Several countries are facing the situation that spent fuel pools are becoming saturated and additional storage facilities will become necessary to avoid stopping the power plant operation. The presence of defective fuel (damaged, leaking and debris fuels) accumulated during reactor operation is also an issue needing attention. Defective fuel is a challenge for both operating and shutdown reactors in retrieving and transporting such fuel and in the safe long term storage.

France and Russia provided reports on the successful experience in retrieving and transportation of defective fuel followed by reprocessing. Reprocessing of such type of fuel is seen by many experts as an efficient and decisive solution to manage this category of fuel. Nevertheless, solutions for long term storage and disposal of defective fuel were also presented. One service provider from the United Kingdom shared a number of examples of the bespoke solutions that had been provided for the retrieval of damaged and severely damaged fuel.

Should it be intended to dispose of defective fuel, Sweden confirmed that there is an acceptable limit to the amount of water in a disposal canister, since too much water from defective fuel may corrode the inside of the canister or create H_2 and, if air is present, may also cause the formation of NO_x that may lead to stress corrosion cracking of the container. This highlights that the potential for radiolysis due to the presence of water has to be addressed and demonstration of dryness in the presence of defective fuel or the implementation of other complementary measures to provide acceptable solutions.

France reported about long term solution for countries developing dry storage followed by direct disposal. The solutions presented rely primarily on a "unique capsule" for transport and storage of defective fuel. Confinement, radiolysis, criticality and shielding were specifically addressed in the safety assessment for transport and long term storage.

The storage of spent fuel for longer periods of time is facing new challenges. Due to the deferral of disposal facilities existing storage facilities will have to be in operation beyond their initial licensing period. Practical experience with the extension of licenses beyond, e.g. 40 years of dry storage is not yet available and the basis for such extension has to be developed.

Other challenges related to spent fuel management are related, e.g. to transport prohibition, extension of nuclear power plant operation and consequently spent fuel inventories, and upgrades of safety requirements following the Fukushima accident. All these changes have brought challenges in trying to adapt existing facilities to new technical specifications and safety requirements, in addition to operation of the storage system for long periods of time and without any link or comprehensive analysis to nuclear security.

3.3. SESSION 3: SAFETY ASPECTS OF SPENT FUEL MANAGEMENT

A broad range of topics was addressed, covering transport, storage and disposal. The operation of spent fuel management facilities over long time periods was of particular interest as it is of particular importance to address ageing issues, to perform periodic safety reviews and to provide feedback of experience.

It is necessary to have an integrated view on all steps of spent fuel management because choices at one stage may have strong influence on the following stages and therefore an overall strategy for the safe spent fuel management must be developed and implemented. All relevant stakeholders should be involved in the decision making process. Key safety aspects are a robust design, the definition of provisions to control ageing, periodic safety reviews, and the feedback of experience in order to avoid severe accidents or avoid their consequences should they occur. The importance of a holistic view on transport, storage and disposal was emphasized even though the disposal requirements for waste packages are not yet known.

The management of spent fuel at Fukushima after the earthquake / tsunami was addressed. After inspection and maintenance, the casks from the cask custody area were transferred to the new temporary cask storage area. It was reported that the spent fuel removal operations at Unit 4 were completed and that the spent fuel removal operations at Unit 3 were planned to start following the clean up of rubble and debris. The spent fuel removal from Units 1 and 2 was pending. Spent fuel that had been in contact with sea water was reported to be in stable conditions.

The progress in establishing a deep geological disposal facility in Finland was presented, including the licensing experience since project initiation to the inspection programme for the implementation of the disposal system. The application for a construction license was forwarded to the government and a decision was expected in 2015[1]. Consideration is also given to an alternative emplacement of spent fuel in ‘supercontainers’ (copper canister in titanium shell) in horizontal disposition drifts.

The development of dry spent fuel storage in Germany over the last 35 years was summarized jointly with an outline of future perspectives. An overview of transport and storage licensing issues was given including inspections for transport of ageing packages in a well-defined QA programme. Nevertheless, demonstrating compliance for a package that cannot be inspected completely (such as dual purpose casks) remained a challenge. A modified pre-shipment inspection was necessary after the storage period. It was recommended to amend the IAEA transport regulations to take ageing needs into account. Also simplified approaches to consider conservatively spent fuel behaviour were discussed, including plans for related R&D work.

[1] A construction license was granted to Posiva Oy on 12 November 2015 by the Finnish Government.

The OECD/NEA Working Group on Fuel Cycle Safety (WGFCS) reported it was preparing a Technical Opinion Paper (TOP) on safety of long term storage (wet and dry) requirements and technical needs [10].

The session included also other issues such as impact testing for aircraft crashes, upgrading of spent fuel transport casks, and the thermal behaviour of such casks.

The results of a review by the safety authority of the French reprocessing plant revealed risks poorly anticipated at the design stage and gave guidance for the design of new facilities. The lesson learned was the importance of both considering and monitoring ageing processes in plant design.

3.4. SESSION 4: AGEING MANAGEMENT PROGRAMMES

Ageing management programmes ensure that safety is maintained by detecting and correcting any age-related degradation before any loss of safety function or condition that may jeopardize the continued operations of fuel cycle facilities or the future transportability of spent fuel. They address both physical ageing and obsolescence of safety related structures, systems and components of the fuel cycle facility and periodic assessments are carried out to ensure the continued adequacy of ageing management plans and to help establish the technical basis for continued operations or license extensions. The session primarily focused on spent fuel storage facilities and extending storage periods beyond original design assumptions.

Technical issues related to managing ageing effects on spent fuel storage systems for extended long term storage were highlighted and the issue of a subsequent transportation of spent fuel was addressed. In addition, institutional information on license renewal of spent fuel storage facilities was introduced.

The need for enhanced and updated guidance on extending storage licenses was identified, i.e. for high burn up fuel (>45 $GW \cdot d \cdot t(HM)^{-1}$) performance, localized corrosion of welded stainless steel canisters and for reinforced concrete structures.

Information resulting from ageing management activities serves as a baseline for prioritizing needs and associated research and development objectives.

Specific test programmes were introduced. They covered a demonstration test for the storage of spent PWR fuel in dry metal cask over 60 years, the hydrogen effects on cladding, the corrosion issues associated with stainless steel canisters, the behaviour of elastomer seals for dual purpose casks, the behaviour of aluminium and alloys as structural material for cask basket, and the comprehensive, integrated data and analysis tool for spent fuel in existing dry cask storage systems. Finally, the results of the IAEA Coordinated Research Programme on 'Demonstrating Performance of Spent Fuel and Related Storage System Components during very Long Term Storage' (CRP T13014) were introduced.

3.5. SESSION 5: STORAGE OPTIONS IN SUPPORT OF AN INTEGRATED APPROACH (INDUSTRY)

The session highlighted how the vendors have been providing a range of storage options in response to customers' needs which are supporting an integrated approach. The growing importance of long term storage (maybe 100 years and beyond) in the back end of the nuclear fuel cycle was highlighted. The commercial dry storage inventory is diverse and growing worldwide. In addition, the first generation reactors which are being shut down or will be shut down in the coming years will lead to a growth of spent fuel inventories being transferred to away from reactor storage systems to facilitate reactor decommissioning. The diversity of cask

and canister designs poses a challenge in licensing. The storage systems need to be designed in such a way as to ensure the necessary safety functions during storage and subsequent transport after storage. Consideration needs to be given also to potential ageing deterioration of component materials that may occur during operation of the storage system. Several presentations elaborated on industrial experience and the numerous safety studies that have been carried out in recent years to incorporate and demonstrate the safety and security features into spent fuel storage facilities. Several innovative storage systems and innovative solutions were presented to monitor and mitigate any deterioration of casks and related systems. Integrated planning, involving robustness of storage and transport in dual purpose casks (DPCs) is of paramount importance to ensure safe and secured storage and transportability of spent fuel under normal and off-normal situations, including natural calamities (earthquake, flood, etc.) and terrorist attacks (aircraft crash).

Transport of spent fuel is the only activity in the back end of the nuclear fuel cycle which is within the public domain. Hence, radiation safety of the public has to be taken into consideration particularly during transport of casks after long storage periods.

The historical perspective of the various technologies, available in the market place, for spent fuel storage was presented. One example is the multipurpose canister which potentially could be used for the transport, storage and disposal of spent fuel. The disposal aspects are under investigation, but initial studies suggest that storage periods up to 300 years may be required; depending on canister size, inventory and repository design. In response to physical protection concerns, one vendor has developed an underground ventilated dry storage system in reinforced silos. The system is currently being deployed in some locations in the USA.

Metal-concrete casks were developed and licensed for dry long term storage and transport of spent fuel from RBMK–1000, BN–350, decommissioned nuclear powered submarines and nuclear ice breakers. New dual purpose casks are being developed for spent fuel from operating WWER–1000 and for the upcoming new generation WWER–1200.

The experience in Magnox fuel reprocessing at Sellafield for the last 50 years was highlighted. The modifications made in the plant over the years and the contingency plan for the management of residual spent fuel that would be left after the planned shutdown of the facility in 2020 were explained.

3.6. SESSION 6: IMPACT OF THE FRONT END OF THE NUCLEAR FUEL CYCLE ON THE BACK END

The design of a fuel assembly can have a significant impact on the subsequent spent fuel management. Different fuel characteristics were discussed: internal rod pressure, stress corrosion cracking of the top nozzle sleeves and zirconium oxide spalling. For high burnup uranium or mixed oxide (MOX) fuel (> 55 $GW \cdot d \cdot t(HM)^{-1}$) specific considerations have to be taken into account for dry storage which should be prioritized for future examination, in particular to monitor the reorientation of hydrogen precipitates in the cladding, the fission gas release and the degradation of the cladding by irradiation or chemical interaction with the fuel. The cladding material is of crucial importance for the further stages in the spent fuel management, i.e. reprocessing or storage. This emphasizes the necessity of a good knowledge of the fresh fuel characteristics. More than this, an increasing number of requirements is defined for the fuel through its entire life, i.e. in the reactor and for all the operations related to spent fuel management.

Operating conditions of the nuclear power plant were discussed (e.g. operating history, fuel burnup, coolant temperature, boron concentration). Also, a comparison of the calculated

performance of fuel assemblies from two different vendors in the same WWER–1000 reactor was presented. Slight differences were found in the isotopic composition of the spent fuel.

Several presentations addressed the reprocessing of spent fuel based on current industrial activities and alternatively for new developments. One of the main issues with reprocessing is how to manage plutonium in the absence of a fast breeder or alternative fuel cycle programme.

For instance, increasing of MOX fuel loaded in light water reactors could lead to a balance between plutonium production and plutonium recycling. One option for managing plutonium resulting from recycling to ensure there is no separated plutonium or fresh MOX fuel returned to the customer at the end of the reactor life is termed 'precycling'. This option consists of an anticipated use of MOX fuel from plutonium stock prior to the implementation of reprocessing of used fuel and recovering of plutonium for MOX fuel fabrication with the objective of a plutonium balance near zero at the end of the lifetime of a reactor.

Also, the multi-recycling of REMIX fuel in a WWER was presented. REMIX refers to a fuel containing around 1% of ^{239}Pu and around 4% of ^{235}U. This fuel is being prepared from an unseparated uranium / plutonium stream from reprocessing and it is blended with enriched uranium to get to the enrichment of about 4% ^{235}U. This is regarded as an option to reduce the amount of stored spent fuel. The technological development and the demonstration of safety and technology are being carried out.

A new concept with a lead cooled fast reactor and a metal based reprocessing to produce unseparated uranium and plutonium is under development. Questions on economic justifications of the different options have been raised.

The presentations and discussions showed that the whole fuel cycle must be coherent. This is a key issue to ensure a safe and consistent spent fuel management, independent of the option of an open or a closed cycle. Studies and analyses are necessary to pursue the definition of the main drivers of spent fuel management.

It was suggested that international organizations, e.g. INPRO (International Project on Innovative Nuclear Reactors and Fuel Cycles) should coordinate their actions regarding back end fuel cycle issues.

3.7. SESSION 7: RESEARCH AND DEVELOPMENT REQUIRED TO DELIVER AN INTEGRATED APPROACH

Research and development (R&D) plays a very important role in helping provide and ensure safety in the back end of the fuel cycle, in particular to respond to delays. The role of radial hydrides on the long term performance of Zircaloy based cladding and the effect of stress corrosion cracking (SCC) on the confinement ability of spent fuel canisters are two important issues to be addressed in safe storage for long time periods and for transport after storage.

Reported R&D included:

- A new model for radial hydride precipitation in Zircaloy–4 cladding taking the results from radial hydride precipitation under a constant applied stress and transforming it to a transient precipitation model.
- The mechanical behaviour of high burn up fuel rods under dynamic loading. A different failure mode and strength were observed in the lateral impact tests between segments tested without fuel and those with dummy pellets.
- The impact on ZIRLO clad ductility. Studies utilized un-irradiated clad pre-hydrided and tested at different temperatures. It was found that at lower temperatures, radial hydrides can make the cladding become brittle.

- The ability of high burn up cladding to maintain its integrity, especially under normal conditions of transport was measured on a shaker table and an over-the-road test using an instrumented dummy assembly where the strains and accelerations the cladding is expected to experience were measured. The results suggested that even with reoriented hydrides, high burn up fuel will maintain its integrity. The influence of irregularities and shocks during transport may need to be verified.
- SCC of spent fuel canisters, induced by salt depositions, as a function of time for various laboratory and field tests. Countermeasures to reduce or eliminate SCC. The monitoring of salt concentrations. Techniques to make the spent fuel canisters resistant to SCC; i.e. by looking to remove the tensile stress and to make the surface stress compressive. The method of zirconia peening of the entire canister surface and the burnishing of the lid weld and heat affected zone showed no cracking in the treated samples. Dust and salt layers on spent fuel canisters at three different sites were sampled with wet and dry sampling methods. The results can be used to determine the sampling and inspection frequency.

Other topics covered included long term performance of storage systems, both wet and dry.

For example, the long term storage (up to 80 years) of spent AGR oxide fuel in pool water; which has been dosed with sodium hydroxide to a pH of 11.4 to inhibit IGA (inter granular attack) of the sensitized cladding. Storage experience since 1989 and the current results provide substantial evidence that the intended length of storage is possible under these conditions.

The thermal, radiation protection and safety aspects, and the development of various sensors were emphasized that can be utilized for monitoring of spent fuel storage systems.

Reprocessing of UO_x fuel, vitrification of fission products and minor actinides for disposal and reusing plutonium in MOX fuel in the existing reactor fleet is an established technology. Even though the spent MOX fuel could be reprocessed, it is currently stored. The preference for future sustainability is to have the systematic recycle of both uranium and plutonium in fast reactors. A large R&D programme is under way to develop the fast reactor design, improved processing techniques, fuel fabrication techniques, and minor actinide partitioning and transmutation.

A summary of results from research programme spanning thirty years on the behaviour of spent fuel and components of a storage facility was presented. For zirconium based alloy cladding in both wet and dry storage, it was shown that performance during storage remains excellent with no generic failure mechanisms identified or experienced. Other cladding types, such as stainless steel and magnesium based alloys have good performance provided that optimum storage conditions are maintained.

4. SUMMARY AND CONCLUSIONS OF THE CONFERENCE

4.1. CONFERENCE PRESIDENT

Closing speech as provided, verbatim.

F. Rayment

National Nuclear Laboratory, United Kingdom

Ladies and gentlemen, this was an International Conference on Management of Spent Fuel from Nuclear Power Reactors, with a focus on An Integrated Approach to the Back End of the Fuel Cycle.

Over the last 5 days we have listened to 78 presentations from 19 Member States and 4 Organizations covering all steps of the back end of the fuel cycle and with particular attention being paid to the status of deep geological disposal.

So Ladies and Gentlemen what conclusions can we draw from our discussions over the last 5 days?

Effective public engagement will be key in our success, and in fact we may need a separate session on this at a future Conference. Bill Magwood, DG Nuclear Energy Agency highlighted the need to develop trust with key public stakeholders. He highlighted where trust is strong, spent fuel solutions are easier to implement. We need to be clear with our stakeholders that nuclear energy is a safe, clean, reliable and economic energy resource that has an optimized waste and spent fuel management solution.

Nuclear will play an important role in the world's energy mix, and with increases in nuclear power there will be similar increases in used fuel generated. As such we need to effectively manage our used fuel through recycle, direct disposal and the associated storage options. For many, there is little integration in the fuel cycle in terms of analysing how potential decisions made in one part of the fuel cycle may impact on another part. In fact, many decisions are made independently of the holistic fuel cycle and highlights the need to look at the fuel cycle in a holistic, fully integrated manner combining impacts on processing, storage, transport and disposal.

Target dates for the various national geological disposal programmes vary and as such there is a real opportunity here for us all to learn from each other as we develop our spent fuel solutions. The approaches highlighted by Sweden and Finland are applauded and results are eagerly awaited by all.

A number of vendors have shared their solutions for the management and recovery of failed or damaged fuel. Such technologies will be of great value for the defuelling at reactor pool storage and also for the recovery of damaged fuel from reactors; for example, at Fukushima.

Since the last Conference the importance of ageing management has become a priority for some Member States. This has been the case particularly for those Member States that have been affected by decisions which will impact the duration of spent fuel storage and take systems beyond their licensed or design life. Efforts are under way in a number of Member States to develop guidance for ageing management plans (AMP) and supporting R&D to ensure continued storage will continue to be safe**.**

Each country has specific polarized views on used fuel management; wet vs dry storage, centralized vs localized facilities and of course reprocessing vs direct disposal. We won't resolve the optimum approach this week, and in fact that optimum approach may be different

for each country, however having the discussion here enables the benefits and challenges for each option to be highlighted and discussed.

The approach of "wait and see" was discussed where fuel was committed to storage because the decision was pending on either reprocessing or direct disposal. Some observers felt it was important that countries commit to a clear pathway (sometimes termed roadmap) with decision points mapped out with progress on a repository, for example, important to maintain industry credibility and public confidence.

Managing capacity is also a key focus area internationally where spent fuel pools at reactor sites reach saturation point.

The management of spent fuel will be over very long timeframes. As such continued work is required to understand the behaviour of this fuel over these timeframes within storage and ultimately repository environments. Transportability of used fuel after storage is also an area that requires further work.

The question of effective Policy implementation has been discussed, specifically in relation to multi-national approaches to spent fuel management.

Having the right scientific, technical and engineering skills are extremely important to ensure we implement effective spent fuel management solutions. The nuclear industry must maintain these skills to ensure that we have a skilled workforce deliver these solutions in the future. For example, collection of experimental data to underpin and validate models and assumptions going forward will be key together with the facilities to enable this.

Benchmarking internationally is also important and international cooperation must be implemented to enable this. Knowledge management is essential with programmes lasting long periods of time, together with the ageing profile of our industry. This knowledge needs to be "future proofed".

Ladies and gentlemen, I'm impressed with the level of discussion that has occurred this week with a number of the key issues being debated in open forum. We have explored the interactions and relations in the back end of the fuel cycle, and in my view, have surpassed the overall Conference objective.

I would also like to mention the new approach in asking the co-chairs to give a summary of the poster presentations for each session. I welcome this as it gave the work being done more prominence within the relevant Conference session.

I'm convinced that you will all agree with me that this has been an excellent Conference, with very relevant topic areas being discussed through impactful presentations from key experts and senior leaders within our industry internationally. I also believe we have all convinced ourselves that an integrated approach to the back end of the nuclear fuel cycle is imperative for a successful international nuclear energy programme over the long term.

As such I would like to thank the IAEA secretariat in organizing and hosting such an excellent event, the speakers in making this event possible. Finally, I would like to thank all of you for your open and honest participation in this Conference throughout the week and indeed proving that an integrated approach for used fuel management is an imperative for our industry.

4.2. INTERNATIONAL ATOMIC ENERGY AGENCY

Closing speech as provided, verbatim

K. Mrabit
Director NS-NSS, IAEA

Dear Ladies and gentlemen,

Time has come to the closure of the Conference and on behalf of the Deputy Director General, Head of the Department of Nuclear Safety and Security I would like to bring a few observations, many of them have been discussed during this week.

This Conference was very successful with a high attendance and dynamic discussions involving a wide range of stakeholders in the management of spent nuclear fuel such as the industry, but also operators and regulators.

Such Conference recalls, should this be necessary, the importance of safety in the management of spent nuclear fuel and the IAEA through the development of safety standards and their application contributes reaching a higher level of safety worldwide.

Also, in line with the discussion that took place during this Conference, let me recall the messages given by the Director General of the IAEA as part of the last scientific forum on radioactive waste that "All Member States should embrace, from the start, their responsibility for radioactive waste management", and that "It is imperative that each country establish a comprehensive plan for waste disposal as soon as they begin to use nuclear technologies".

The IAEA is strongly attached to organizing such International Conference, bringing in a same place for exchange of information and communication, recognized experts from around the world.

In particular, for the IAEA such events are an essential contribution to the definition of programme and, as an example, I would mention the successful international project on Dual purpose casks which was initiated by the Department of NSS after the last Spent Fuel Conference, the results of which were presented during this week.

Let me thank you again for your participation and contribution to the success of this Conference and we all hope to see you again soon and at least for the next Conference on that topic.

Closing speech as provided, verbatim

J. C. Lentijo
Director NEFW-NE, IAEA

Dear Ladies and gentlemen,

On behalf of the Deputy Director General, Head of the Department of Nuclear Energy I would like to say a few words to close this Conference.

I would just like to build on the observations from our Conference President and my colleague from the Department of Nuclear Safety and Security.

One of the messages that I am taking away from the Conference and it relates to the Conference theme, which is the need for the back end of the fuel cycle to be integrated. We need to work hard to address this issue.

The importance of the technical skills required to deliver the fuel cycle has been evident this week. The Department of Nuclear Energy supports this requirement through knowledge management, the development of technical documents to capture knowledge and to provide technical guidance, coordinated research projects, training courses, networks and workshops.

I work like to join my colleague from the Department of Nuclear Safety and Security in reiterating the importance of such events for sharing information and it helps the IAEA in both setting our work programmes and acts as a vehicle for us to ensure our programmes are aligned to the industry needs. To provide better value to our Member States we have been working to strengthen our collaboration with the Department of Nuclear Safety and Security and this Conference is one example. Another example which has been outlined at this Conference has been the transfer of the task on dual purpose casks from providing a basis for developing both a storage and transport safety case to the necessary technical underpinning and ageing management programmes which will make this possible; a task which has been taken up by the Department of Nuclear Energy. Finally, I would like to mention our joint review process with the Department of Nuclear Safety and Security called ARTEMIS.

Lastly, I would like to thank all those involved in making this Conference a success: Our Conference President (Dr. Rayment), Session Chairs and co-chairs, keynote, invited and contributed papers speakers. In particular, I would like to thank Karen Morrison and Anastasia Lazykina who have been the main interface with Conference participants over the last 9 months, our Conference clerks and technicians which ensure everything moves smoothly and finally the Conference steering committee, Conference rapporteur and our scientific secretaries Mr. Bruno and Mr. Standring for putting together such an informative programme. I wish you all a safe journey back to your respective countries, I hope the Conference has been of value to you please give us feedback and I hope that you will support this Conference again when it is held next.

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ANNEX 1

CONTENTS OF THE ATTACHED CD-ROM

The following papers and posters presented at this Conference are available on the attached CD-ROM.

Retrieval of damaged fuel from wet and dry storage using innovative remote handling techniques
G. Ashworth, I.W. Smith

Ageing mechanisms influence on transport safety of dual purpose casks for spent nuclear fuel
B. Droste, F. Wille, S. Komann

Regional cooperation on spent fuel management: status and prospects in Europe, Arab regions and Asia
C. McCombie, N.A. Chapman

Industry experience on back end transport
B. Bonnardel-Azzarelli

Licensing of the deep geological disposal of spent nuclear fuel in Sweden
S.L. Engström, H. Åhsberg, A. Ström

Challenges in developing the basic design of the KBS-3 system into a qualified and industrially viable operation
J. Andersson, T. Jaonen

SESSION 3: SAFETY ASPECTS OF SPENT FUEL MANAGEMENT

Regulatory experiences from implementation of spent nuclear fuel disposal programme from site selection to construction of disposal facility – the Finnish case
J. Heinonen, K. Hämäläinen

Development of long term safety requirements for an alternative design variant (KBS-3H) for spent fuel disposal
A. Hagros, B. Pastina, M. Snellman, J.O. Selroos

Transport aspects of spent fuel management
I. Reiche, F.-M. Börst, F. Nitsche

Spent fuel transport container C-30 Part II: Using of the old type transport container C-30 for an improved fuel VVER-440
V. Chrapčiak, R. Zajac, P. Lipták

Thermal field modelling of spent fuel transport container C-30
J. Václav, M. Čarnogurská, T. Brestovič

Activities of the OECD/NEA/CSNI working group on fuel cycle safety in spent fuel and high level waste management
M. Bailey

Consequences of long term black out accident on spent fuel pool for VVER-1200
K. Doğan, C. Kocar

Interim storage of spent fuel in Germany - History, state and prospects
J. Palmes, C. Gastl

Lessons learned from a periodic safety review, applied to the design of new nuclear fuel cycle facilities
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Aspects of spent fuel behaviour assessment for transport packages
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Evaluation of sealing performance of metal gasket used in dual purpose metal cask subjected to an aircraft engine missile
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Fabrication thermal test: methodology for a safe cask thermal performance
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Managing ageing effects on dry cask storage systems for extended long term storage and transportation of used fuel
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Ageing management solutions to ensure safety of extended dry fuel storage
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Demonstration test programme for long term dry storage of pressurized water reactor spent fuel
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The high burnup confirmatory data project
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Performance of elastomer seals in transport and storage casks
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A unified spent nuclear fuel database and analysis system
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SESSION 5: STORAGE OPTIONS IN SUPPORT OF AN INTEGRATED APPROACH

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Multiple recycle of REMIX fuel based on reprocessed uranium and plutonium mixture in thermal reactors
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Comparative analysis of isotope composition of VVER-1000 WESTINGHOUSE and TVEL spent fuel
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A new model on radial hydride precipitation in Zircaloy-4 claddings under decaying stress and temperature transient
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An integrated approach to closing the technical data gap for high burnup spent fuel performance during normal conditions of transport (NCT)
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