IAEA BULLETIN

QUARTERLY JOURNAL OF THE INTERNATIONAL ATOMIC ENERGY AGENCY

INSIDE THIS EDITION

IAEA BULLETIN 40/1/1998 (March 1998) Vienna, Austria ISSN 0020-6067

COMPARING ENERGY OPTIONS

THE INTER-AGENCY DECADES PROJECT

BY HANS-HOLGER ROGNER AND ARSHAD KHAN

Supplying adequate and affordable energy services is an essential element of sustainable development. The challenge is to develop those energy services that best support development and improve the quality of life, especially in developing countries, while simultaneously minimizing health and environmental impacts of anthropogenic activities.

The need to design and implement sustainable strategies in the electricity sector has been repeatedly stressed during international fora. Cases in point are the Senior Expert Symposium on Electricity and the Environment (Helsinki, 1991), the United Nations Conference on Environment and Development (UNCED, Rio de Janeiro, 1992), the 16th Conference of the World Energy Council (Tokyo, 1995), and, most recently, the Third Conference of Parties to the United Nations Framework Convention on Climate Change (December 1997 in Kyoto, Japan).

Agenda 21, adopted by UNCED, emphasizes that environmental and development concerns should be integrated into the decision making process. The Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) emphasizes that mitigation options for alleviating the risks of global climate change should be comprehensively assessed and adequate policies be implemented to promote the installation of the most environmentally benign energy conversion technologies.

At the Kyoto Conference, States adopted a Protocol to the Climate Change Convention that aims to lower overall emissions of a group of six greenhouse gases by the years 2008-2012. The Protocol will entail industrialized countries reducing their collective emissions of greenhouse gases by 5.2%.

In the early 1990s within this global context, the IAEA and eight international partners initiated an inter-agency project, called DECADES. *(See box, page 4.)* It aims to enhance databases and methodologies for comparative assessment of different energy sources and conversion technologies.

This article highlights the project's progress to date, providing some illustrative applications of its computer tools and overviews of comparative case studies that have been carried out in IAEA Member States.

COMPUTER TOOLS

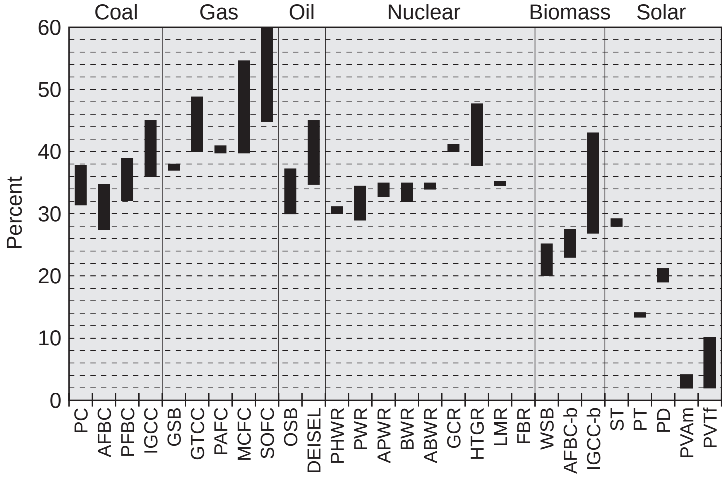
Databases and software developed in the DECADES project have been effectively applied in a number of comparative assessment studies.

Comparison of Power Plants. The net generating efficiency values of several types of power plants (conventional as well as those under development) were compared. (*See graph, next page.*) It may be noted that while significant improvements in the generating efficiency may be obtained for the conventional technologies based on gas, the expected efficiency improvements for the other conventional technologies appear to be only marginal. However, new technologies, with different combustion processes and advanced power cycles, will eventually surpass the best performance of current technologies.

The generating efficiency data are strongly influenced by the characteristics of the fuel used, maintenance of the power plant, and other local conditions. Plant efficiencies vary from country to country and in many countries are lower than the values presented here for electricity generation technologies fueled by coal, oil, and gas.

Mr. Rogner is Head of the Planning and Economic Studies Section, IAEA Department of Nuclear Energy, and Mr. Khan is a staff member of the Section. Also contributing to this article were Mr. Florin Vladu and Mr. Vladimir Kagramanian of the Section.

COMPARISON OF NET GENERATING EFFICIENCY FOR ELECTRICITY TECHNOLOGIES



Fossil Fuels: **PC**=Pulverized Coal **AFBC**=Atmospheric Fluidized Bed Combustion **PFBC**=Pressurized Fluidized Bed Combustion **IGCC**=Integrated Gasification Combined Cycle **GSB**=Gas Steam Boiler **GTCC**=Gas Turbine Combined Cycle **PAFC**=Phosphoric Acid Fuel Cell **MCFC**=Molten Carbonate Fuel Cell **SOFC**=Solid Oxide Fuel Cell **OSB**=Oil Steam Boiler **DIESEL**=Diesel Engine

Nuclear Power: **PHWR**=Pressurized Heavy Water Reactor **PWR**=Pressurized Water Reactor **APWR**=Advanced PWR **BWR**=Boiling Water Reactor **ABWR**=Advanced BWR **GCR**=Gas Cooled Reactor **HGCR**=High Temperature GCR **LMR**=Liquid Metal Reactor **FBR**=Fast Breeder Reactor

Biomass & Solar: **WSB**=Wood Steam Boiler **AFBC-b**=Atmospheric Fluidized Bed Combustion using Biomass **IGCC-b**=Integrated Gasification Combined Cycle using Biomass **ST**=Solar Thermal **PT**=Parabolic Trough **PD**=Parabolic Dish/Sterling **PVAm**=Photovoltaic Amorphous **PVTf**=Photovoltaic Thin Film

Also compared were the CO_2 emission factors for various types of fossil-fuelled power plants. The power plants have the same size (500 megawatts) and the coal-fired plants use similar coals. The highest CO_2 emissions result from the coal-fired options. These technologies display a considerable range of CO_2 emissions as a result of variations in the efficiency of power generation.

The CO_2 emissions depend on the fuel's carbon content (highest for coal, lowest for natural gas), generating efficiencies, pollution control measures included in different designs, and other factors. The emission factors assume the use of the best available technologies and good quality fuels. Similar comparisons can be carried out for other pollutants, including SO_2, NOx, and particulates.

Economic comparative assessments carried out at the power plant level using the DECADES database show that nuclear power is a competitive option for generating electricity in many countries. The total capital requirements were compared for different types of plants in several countries. *(See graph next page.)* As expected, the total capital requirements per unit capacity vary from country to country, but the range is not large for similar technologies.

Comparison of Energy Chains. Maximum and minimum greenhouse gas emissions were compared for solid, liquid, gaseous, hydro, nuclear, wind, solar and renewable electricity generation pathways. Taking into account the entire up-stream and down-stream energy chains for electricity generation, nuclear power emits 40 to 100 times less carbon dioxide than currently used fossil-fuel chains. *(See graph page 5.)* Greenhouse gas emissions from the nuclear chain are due mainly to the use of fossil fuels in the extraction, processing, and enrichment of uranium and to fuels used in the production of steel and cement for the construction of reactors and fuel cycle facilities. These emissions, which are negligible relative to those from the direct use of fossil fuels for electricity generation, can be reduced even further by energy efficiency improvements. Such improvements at the enrichment step include, for example, replacing the gaseous diffusion process by less energy-intensive processes such as centrifugation or laser isotope separation. Among the fossil fuel chains, natural gas has the widest uncertainty, mainly due to different assumptions concerning methane releases to the atmosphere during drilling, extraction, and transportation of natural gas.

It may be pointed out that in the case of nuclear power, the costs arising from ensuring safety, and for radioactive waste management and decommissioning of facilities, are internalized. This means that they are included in the price of electricity generated by nuclear power. On the other hand, the costs arising from the adverse environmental and health impacts of other electricity generating pathways remain to be fully internalized, in part because of the difficulty in their quantification.

Power System Expansion. DECADES computer tools can be used to determine environmentally sound least-cost expansion plans for electricity generation systems or to analyze whether a particular project fits into the robust long-range least-cost development plan for a country or region. It can also be used in an iterative manner to investigate least-cost methods to reduce environmental burdens (e.g., minimum system costs to meet targets for reducing SO_2 or greenhouse gas emissions).

The optimization of the expansion plan is performed taking into consideration the capital investment costs, the operation and maintenance cost, the fuel cost, the fuel inventory cost and the cost of energy not served. Once the optimum expansion plan has been developed, the software allows for the calculation of air emissions, land requirements and production of solid wastes, year-by-year and step-by-step, for every energy chain included in the system, so that the totals for the entire electricity system are calculated.

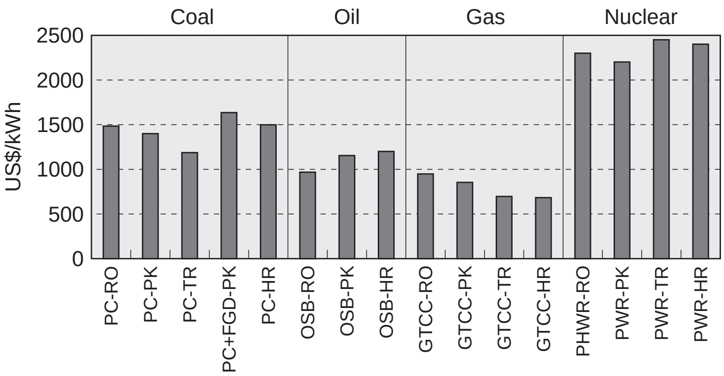
CASE STUDIES

In the first phase of the DECADES project, 22 country case studies on comparative assessment of alternative strategies and policies for the electrical power sector were carried out, supported by the IAEA through a coordinated research project (CRP).

The case studies sought to identify electricity generation strategies that would meet the objectives of environmental protection, in particular reduction of atmospheric emissions at acceptable cost. A broad range of issues have been addressed. They include assessing the potential role of nuclear power in reducing the greenhouse gas emissions; effects of CO_2 taxation and/or emission constraints on the future generation mix; and the impact of privatization and deregulation of the electricity sector on electricity system expansion strategies.

Significant reductions of emissions and other environmental burdens can be obtained by improving the efficiency of existing facilities at different levels of the energy chains. The rehabilitation of existing power plants, in particular by adding pollution control technologies, was often found a cost effective measure for mitigating local air quality and regional acidification impacts. Improving the overall efficiency of energy systems by promoting co-generation was identified as a cost-effective option in many countries, especially where heat

INVESTMENT COSTS AT POWER PLANT LEVEL



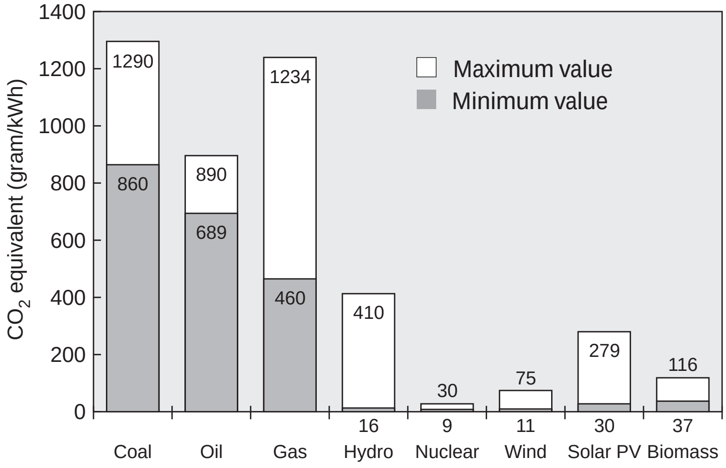
Note: RO=Romania; PK=Pakistan; TR=Turkey; HR=Croatia

For abbreviations of technologies, see note for graphs on page 3. *Source: CSDB*

JOINING FORCES FOR

Nine international organizations joined together in 1992 to launch the inter-agency project on Databases and Methodologies for Comparative Assessment of Different Energy Sources for electricity generation, in short DECADES. They are the IAEA, the European Commission (EC), United Nations Economic and Social Council for Asia and the Pacific (ESCAP), Institute for Applied Systems Analysis (IIASA), World Bank (IBRD), Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD/NEA), Organization of Petroleum Exporting Countries (OPEC), United Nations Industrial Development Organization (UNIDO), and World Meteorological Organization (WMO). The project's aim is to facilitate the development of sustainable energy strategies as an integral part of planning and decision making in the electricity sector. The project has established technology databases, developed analytical tools, and provided training and support to developing countries in conducting comparative assessment studies. The

CO_2 EQUIVALENT EMISSIONS FOR FULL ENERGY CHAIN



distribution networks already exist for district heating.

In most of the studies addressing capacity expansion, nuclear power proved cost-effective for reducing emissions of SO_2, NOx, and CO_2 and other greenhouse gases. In Romania, for example, the case study examined a gas expansion scenario versus a nuclear expansion scenario. The study found that a large reduction of CO_2 emissions may be obtained by using nuclear power plants in the power system expansion without any significant increase in the total system expansion cost. For the gas scenario, although the CO_2 emissions are reduced in comparison with coal-dominated scenarios, they are significantly increasing over the study period. SO_2 emissions decrease in both scenarios but, in the nuclear expansion scenario, the decrease is approximately 30% more than in the gas scenario.

Some studies also showed that, although CO_2 emission reduction targets could be achieved without nuclear power, its use would lead to significantly lower costs. It may be pointed out that the implementation of environmental protection measures and policies are likely to increase the cost of electricity from fossil-fueled power plants that will have to comply with these regulations. Furthermore, global climate change concerns are leading many countries to consider policies, such as carbon taxes, that would affect the competitiveness of fossil fuels for electricity generation. In the Romanian case, CO_2 abatement costs based on the accelerated use of nuclear power are approximately US$5/ton CO_2 or US$18/ton-carbon, which is at the bottom end of the range (US$0 to US$120/ton-carbon reported in the IPCC Second Assessment Report).

In most of the case studies, power plants using the natural gas combined cycle — which are very attractive from the point of view of generating efficiency (55% or higher), capital requirements, and short construction periods — were considered as candidates for electric system expansion. Other factors also need to be taken into account when considering this option. These factors include security of supply for countries relying on imports, the potential for gas price fluctuations, and the contribution to greenhouse gas emissions from carbon dioxide during combustion and methane during gas production and transmission.

The cooperation that has been established through this CRP — involving experts hav-

ENERGY PLANNING

DECADES computer cools consist of databases and analytical software. They can be used for evaluating the always existing trade-offs between technical, economic and environmental features of different electricity generation technologies, chains and systems at the national, regional and international levels.

Two types of technology databases were developed: the Reference Technology Database (RTDB) and Country Specific Databases (CSDBs). The RTDB provides a comprehensive, harmonized set of technical, economic and environmental data for energy chains that use fossil fuels, nuclear power, and renewable energy sources for electricity generation. It contains data for about 300 technologies, characterized according to their level of maturity. The CSDBs store data on electricity generation technologies for various countries or regions for the purpose of carrying out case studies with the DECADES analytical software or other national planning tools. More than 25 countries have developed a CSDB, containing a total of more than 2500 technologies.

ing different scientific backgrounds and coming from different countries — has proved extremely valuable and effective.

In particular, the cooperation and exchange of information and experience between different teams that are confronted with similar difficulties — such as data collection, technology description, fuel chain definition and comparison, and electric generation system analysis — resulted in identifying and implementing common approaches for solving such problems. The participation of experts in the fields of electricity system analysis, macro-economics and environmental impact assessment led to a recognition of the need to reconcile various concerns and priorities — for example, alleviating local and global environmental impacts and addressing economic, social and security of supply issues — within a comprehensive assessment of alternatives.

DECADES PHASE II

The second phase of the DECADES project (1996-2000) focuses on disseminating the current computer tools, providing user training in their application, supporting country studies, and developing new analytical capabilities.

The DECADES computer tools will be extended to address more comprehensively the issues of impact assessment and integration of impact indicators in the decision-making process. Enhancements currently under way include an improved representation of the health and environmental damages as well as external costs, enhanced capability for regulatory analyses, demand-side management options, multi-fuel units, and combined heat/power systems.

The comparative assessment of comprehensive source-to-service pathways of different energy sources and conversion technologies is key to the development of sustainable energy supply strategies. The DECADES project provides the necessary methodology and tools for performing such assessments, and the dissemination of activities and results to IAEA Member States is an ongoing process. Interregional workshops on the use of the DECADES computer tools were held at Argonne National Laboratory in the United States (1995 and 1996), in Poland (1996) and in Brazil (1997). Also, seminars and workshops were held in Canada, the United States, the United Kingdom, Brazil, and the Republic of Korea. The high interest manifested by institutes, organizations, and universities in Member States participating in these events is a good indicator for the usefulness of the DECADES approach.

The comparative assessment studies based on DECADES show that nuclear power can be economically competitive with other baseload generation options and that it generates significantly lower emissions of SO_2, NOx and CO_2 than any fossil-sourced option. In countries having the right infrastructure in place, natural gas is the preferred option for electricity option, even if the gas is imported. In the case of coal-fired power plants, they may be attractive in countries having access to inexpensive sources of supply. However, their economic competitiveness might become questionable in the context of more stringent environmental protection regulations and standards requiring the implementation of pollution control devices and limitations to greenhouse gas emissions. Most renewable energy sources offer interesting prospects for environmentally friendly electricity generation systems. However, their potential role for large-scale electricity generation, other than conventional hydropower, may be limited by physical constraints in some regions. Moreover, they are unlikely to be economically competitive with fossil fuels for baseload electricity generation and nuclear power in the short and medium term.

To assist more countries interested in conducting their own studies, the Agency intends to strengthen its capacity for objective analysis in the area of comparative energy assessments. Foreseen is closer cooperation with other organizations in the energy field, including the Nuclear Energy Agency, European Commission, World Bank, Organization of Petroleum Exporting Countries, and the International Energy Agency, among others. The Agency also will continue to work within the UN system on an objective examination of all energy options.

Based on results of its comparative assessment analyses, the IAEA plans to participate actively in the preparation of the Third Assessment Report of the IPCC. During the next two to three years, the report will provide an important scientific platform for policy approaches to the issues of climate change and the mitigation of greenhouse gases. ❐

CHANGING
GLOBAL PERSPECTIVES
NUCLEAR FUEL CYCLE TRENDS INTO THE NEXT CENTURY

BY NOBORU OI AND LOTHAR WEDEKIND

At a time when more countries are facing rising energy demands and environmental challenges, the role that nuclear power can play in the safe and clean production of electricity is receiving closer attention. At the same time, changing conditions are affecting the plans of the world's nuclear power industries and redefining the technology's future development.

Over the past twenty years, the question of how nuclear power should be technically and commercially developed has changed significantly. It was once widely believed among scientific and technical experts that a closed fuel cycle would be the most desirable option – in other words, the fuel from power reactors would be reprocessed after its initial use, and plutonium would be recovered from the spent fuel for recycling as fuel in "fast-breeder" reactors. In turn, these reactors would produce more plutonium that could be used for fuel in other reactors. So closed, the nuclear fuel cycle offered the promise of a long-term and competitive energy technology.

But conditions changed, and the past two decades have brought a set of "new realities" to the table. They include the fact that the generation of electricity from nuclear power has grown at a far slower rate than expected. Second, there currently is limited interest in fast-breeder reactors and delay in their commercialization where they are being developed. Third, the adoption of a closed nuclear fuel cycle has not taken hold as once envisaged, and where it is the chosen option, it has been only partially achieved. These new realities have contributed to the accumulation of plutonium in civilian programmes, and a rising inventory of spent fuel in storage. In addition, as the result of the end of Cold War, there may soon be a large amount of plutonium from dismantled warheads transferred into the civilian sector, thus adding to these inventories.

At the global level, countries are working together to address specific policy and technical issues that these changing conditions have raised, and to more clearly define common areas for global cooperation. One major forum was the International Symposium on Nuclear Fuel Cycle and Reactor Strategies: Adjusting to New Realities, convened in June 1997. More that 300 experts from 40 countries and five international organizations took part. It was organized by the IAEA in cooperation with the European Commission (EC), the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD/NEA), and the Uranium Institute (UI). *(See box, page 11.)*

This article highlights selected aspects of the major topics examined at the symposium. The topics were considered in depth by six symposium working groups, each of which presented conclusions reflecting the international common understanding of the status and trends affecting the development of the nuclear fuel cycle well into the next century.

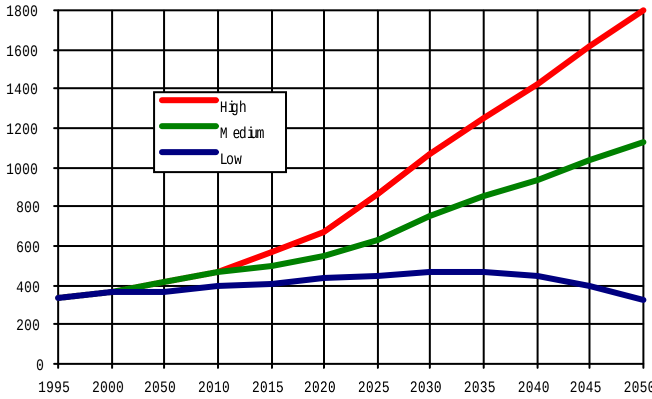
THE GLOBAL ENERGY OUTLOOK

This working group, under the chairmanship of Mr. H. F. Wagner of Germany, examined nuclear energy over the long term. Their key conclusions included:

- The supply of uranium for nuclear power reactors will probably be sufficient to satisfy

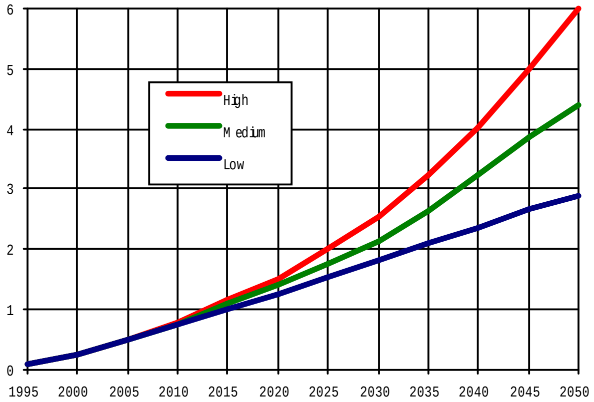
Mr. Oi is a senior staff member in the IAEA Department of Nuclear Energy. He and Mr. Peter Jelinek-Fink of the Department served as Scientific Secretaries of the International Symposium on Nuclear Fuel Cycle and Reactor Strategies. Mr. Wedekind is Chief Editor of IAEA Periodicals and Electronic Information Services, Division of Public Information.

WORLD NUCLEAR CAPACITY SCENARIOS

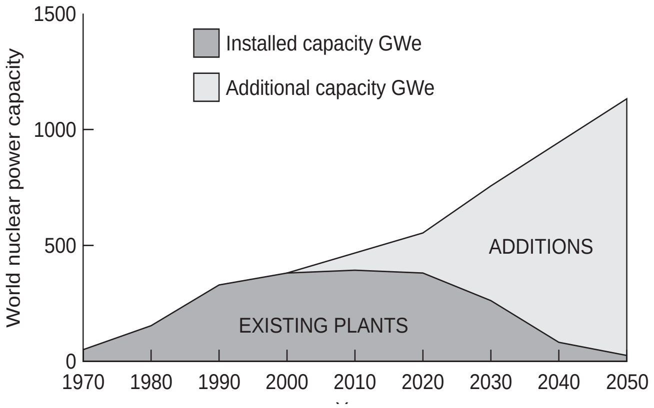


Source: IIASA; WEC

PROJECTED CUMULATIVE NATURAL URANIUM REQUIREMENTS UP TO THE YEAR 2050



PROJECTED NUCLEAR CAPACITY REQUIRED UNDER IIASA/WEC MEDIUM VARIANT



worldwide programme needs up to the year 2050. Three nuclear energy scenarios were considered, based on studies by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC), and they were characterized as "contrasting but not extreme". *(See graphs.)* Projected cumulative natural uranium requirements for the years 1995-2000 were compared with published levels of resources in the publication *Uranium Resources, Production and Demand*, commonly known as the "Red Book". In the case of the medium variant, the group found there may not be sufficient uranium resources to cover the years after 2050 for reactors existing then if one assumes that these reactors will have a total lifetime of up to 40, perhaps up to 60 years. Therefore, the ways and means to make better use of uranium resources, and the potential influence of steps taken, are of importance.

■ A number of technical measures offer promising options for the better utilization of uranium resources. They include increasing the burnup of nuclear fuel during reactor operations, the lowering of tails assays in the depleted stream of fuel enrichment operations, and recycling plutonium. About 25% of all uranium resources can be saved by reducing the tails assay from 0.3% to 0.15%, compared with a saving of about 17% by recycling all plutonium in light-water reactors. Both options are achievable from a technical and industrial viewpoint.

■ Over the long term from a worldwide perspective, strategies and technologies targeted at more efficient uses of uranium resources will probably have to be considered before 2050.

PLUTONIUM MANAGEMENT

The second working group, chaired by Mr. A Gloaguen of France, considered the present status and immediate prospects of plutonium management.

The production, storage and use of plutonium have been the subject of international concerns but there is no common international understanding on what policies should be adopted. In the late 1970s, the International Fuel Cycle Evaluation (INFCE) was conducted with the participation of 40 countries and four international organizations to examine non-proliferation aspects of different fuel cycles. The review showed that effective measures can and should be taken both at the national and global levels and agreements worked out to minimize the danger of proliferation of nuclear weapons – without jeopardizing energy supplies or the development of nuclear energy for peaceful purposes.

OCCUPATIONAL COLLECTIVE DOSES OF THE THREE FUEL CYCLE OPTIONS (PER 400 TERAWATT-HOURS), EXCLUDING RADIOACTIVE WASTE DISPOSAL

	Occupational Exposure	Main Contributors
Once-Through Fuel Cycle	153 man.Sv	Reactors 69%; mining/milling 29%
Mixed-oxide (MOX) (Recycling in thermal reactors)	147 man.Sv	Reactors 72%; mining/milling 26%
MOX-FR (Recycling in thermal and fast reactors)	139 man. Sv	Reactors 76%; mining/milling 22%

Key conclusions of the symposium working group include:

- Since INFCE some 20 years ago, not very much seems to have changed as far as policy is concerned. Most countries that decided to pursue reprocessing/recycling programmes have not changed their positions since then. A large and viable recycling industry has been established in Europe and is being developed in Japan.
- Key technologies are available for the effective management of both the closed and open nuclear fuel cycles, and for the disposition of surplus military plutonium. Many of these technologies have been implemented.
- At the end of 1996, the inventory of separated civil plutonium amounted to about 150 tonnes, and it is expected to increase to about 170 tonnes by the end of 1999 before dropping to about 150 tonnes by the year 2015. Under free market conditions for plutonium, the inventory could be reduced to about 50 tonnes by 2013. This does not include the amounts of plutonium that Russia and the United States have in excess of their defense needs and may release into the civilian sector.
- The inventories of separated plutonium are expected to be reduced by the use of modern fuel fabrication plants for producing mixed-oxide fuel (MOX) and the licensing of light-water reactors to burn MOX fuel.
- Medium- and long-term spent fuel storage can be carried out at both "at-reactor" sites and "away-from-reactor" sites.
- International transparency measures in the management of plutonium are important to provide accurate information to the public and build international confidence.

FUEL CYCLE AND REACTOR STRATEGIES

Chaired by Mr. D. Meneley of Canada, this working group examined the timeframe up to the year 2050 for fuel cycle and reactor strategies. Key conclusions include:

- The dominant trend in the commercial market for nuclear power plants will be characterized by a slow evolution of present reactor types and designs. The background for this conclusion is that high investment costs, a strict regulatory climate, and the need for high performance over a long period of time dictate a very conservative approach for most nuclear plant buyers.
- The expansion of nuclear power will depend on three basic issues: governmental and public interest, economic competitiveness, and the beneficial role which nuclear energy might be called upon to play in sustaining the world's healthy environment.
- Water reactors will continue to play a significant role during the next 50 years and beyond.
- In the case of recycling plutonium in thermal reactors, there are limits to the number of possible recycles. Multiple recycling produces degraded plutonium which limits the number of recycles in thermal reactors to two or three. Such degraded plutonium can, however, be used as a fuel in fast-breeder reactors. If such reactors, or other effective plutonium burners, do not materialize, spent fuel will still end up in final repositories.
- Although the goal of sustainable nuclear energy production can be achieved most

effectively by fast-breeder reactors, their introduction may not be seen in the competitive electricity market until after the year 2030, when they could account for only about one to two percent of projected nuclear energy capacity.

HEALTH & ENVIRONMENTAL IMPLICATIONS

A fourth working group, chaired by Mr. J. Lochard of France and Mr. B. Loewendahl of Sweden, examined the health and environmental implications of the different fuel cycle options. Key conclusions include:

- In normal operation, there are no significant differences in terms of human health and environmental safety impacts among the nuclear fuel cycle options considered. *(See table, page 9.)*
- A remaining issue common to all three fuel cycles is the potential for major accidents which may have significant health and environmental consequences. The prevention of such accidents calls for a high level of vigilance and an ongoing improvement of safety.
- Long-term storage and disposal of spent fuel or radioactive waste do not raise any particular problems in terms of health. Individual exposure remains at extremely low levels as long as no intrusions into the disposal sites occur.
- Plutonium toxicity is not a major factor in the context of normal operational impacts. Certainly, however, there is much misconception about this issue, which has been often used as a strong argument against the fuel cycle, including reprocessing of nuclear fuel.

ASPECTS OF NON-PROLIFERATION & SAFEGUARDS

Under the chairmanship of Mr. H. Kurihara of Japan, this working group considered non-proliferation and safeguards aspects related to the nuclear fuel cycle. Its key conclusions included:

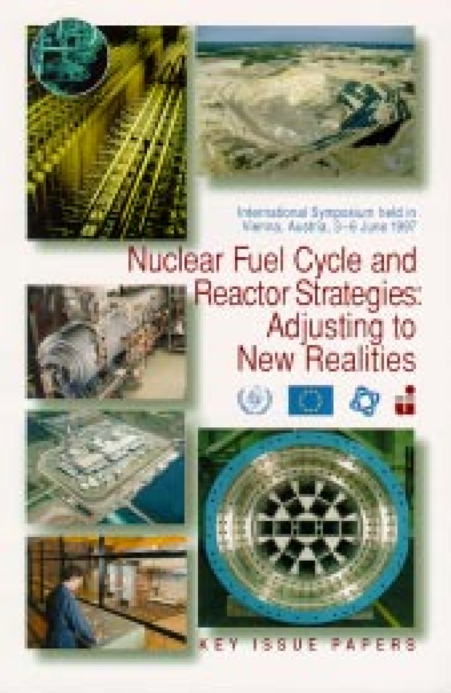
- The nuclear non-proliferation regime is becoming increasingly effective. Additional demands placed upon the regime must be adequately funded by the international community.
- The nuclear non-proliferation regime needs continuous adaptation to “new realities” affecting nuclear power development. Two good examples are the IAEA’s safeguards development programme through which the verification system was strengthened, and initiatives for the verification of surplus military materials transferred into the civilian sector.
- A main issue facing the nuclear non-proliferation regime over the next decades is the extent to which the IAEA will be involved in the verification of surplus military material and how this, and other demands on the safeguards systems, will be resourced. New technical and institutional approaches will be required.
- In the context of reactor and fuel-cycle choices and future technological development in the civil nuclear power sector, the nuclear non-proliferation regime should be able to provide the necessary assurances, irrespective of the nuclear technology chosen, and should not constrain future choices.

INTERNATIONAL COOPERATION

Chaired by Mr. M. Kratzer of the United States and Mr. I. Kouleshov of Russia, the sixth working group considered aspects of international cooperation. Its key conclusions included:

- International co-operation has been an essential factor and a principal driving force in the development and application of nuclear power. The most distinctive feature of this co-operation — the nuclear non-proliferation regime — has successfully limited the spread of nuclear weapons to a level far below those once predicted.
- The supply of nuclear materials, equipment, and technology for peaceful uses by States possessing them to other States has been one of the major and most impressive successes of international co-operation.
- The arrangements and mechanisms in place for international co-operation are generally adequate to meet current and future needs. However, improvements are desirable in a number of areas, such as the disposition of surplus military plutonium, development of fast-breeder reactors, regional fuel cycle centres, international plutonium storage, and the transparency of plutonium management.
- The IAEA should explore appropriate steps to ensure the exchange of basic information on major developments, and economic and programmatic information on the fuel cycle, possibly through establishing a regular mechanism of such exchange in close cooperation with other international organizations.

SYMPOSIUM OVERVIEW



The International Symposium on Nuclear Fuel Cycle and Reactor Strategies: Adjusting to New Realities provided an in-depth picture of energy, economic, and technological developments shaping the future.

A Steering Group of senior experts from twelve IAEA Member States and two international organizations directed the Symposium's organization over a number of years; it was chaired by Mr. M. Kratzer of the United States. Additionally, six Working Groups prepared six key issue papers with the participation of over 70 experts from 12 States —Argentine, Canada, China, France, Germany, India, Japan, Russia, South Africa, Sweden, the United Kingdom and the United States — and the Nuclear Energy Agency of the Organization for Economic Cooperation and Development, the European Commission, the International Energy Agency, and the Uranium Institute. These papers represented the common international understanding on various aspects of nuclear fuel cycle and reactor strategy, with particular reference to the issue of plutonium, up to the year 2050, and were the result of two years of intensive work by the experts.

Altogether, more than 300 experts from 44 countries and five international organizations participated in the symposium, which received extrabudgetary financial support from Japan. In addition to the six issue papers, 24 invited papers were presented and 45 poster presentations were made. Also featured were addresses by leading experts and policy makers in the field, and the key issues were explored in discussions by the participants and a panel of experts from India, Republic of Korea, Japan, France, Germany, Russia, the United Kingdom, and the United States.

The IAEA recently published the symposium's key issue papers in its Proceedings Series and, in December 1997, issued the orally presented papers as a Technical Document (IAEA-TECDOC-990).

CONTINUING THE DIALOGUE

In summary, the symposium served as a valuable forum for examining the new realities and choices facing countries utilizing nuclear energy. The six key issue papers presented at the symposium summarized the common international understanding of the various fuel cycle issues, including those related to technology, safety, safeguards, environmental and institutional developments.

The symposium also served to heighten interest in continuing the dialogue at the global level, in light of the importance of issues being faced and nuclear power's established and potential role in contributing to world electricity supplies. Toward this end, the IAEA in early 1998 set up the International Working Group on Nuclear Fuel Cycle Options. Among topics that the Group will cover are the advantages and disadvantages of different fuel-cycle strategies of plutonium and waste management, which will play a key role in the future development of nuclear energy.

In the final analysis, the ongoing evolution of Agency programmes related to the nuclear fuel cycle must reflect the realities confronting the international community today, including the security and commercial impacts of ex-weapons material. Moreover, the activities will have to be geared to promoting further the reliability, safety, and economic viability of nuclear power to help interested countries meet electricity demands well into the next century. ❑

PLUTONIUM CHALLENGES

CHANGING DIMENSIONS OF GLOBAL COOPERATION

BY NOBORU OI

Global developments in the 1990s have presented the international community with a new and serious challenge: a growing accumulation of plutonium originating from both civilian and military nuclear programmes. It arises from a number of developments. They include the end of the Cold War — notably the steps toward dismantling nuclear weapons and transferring surplus plutonium once used in warheads to the civilian sector — and changes affecting the nuclear industry, specifically delays in the commercialization of fast-breeder reactors that can burn plutonium as fuel. In response to these developments, among others, new realities are influencing the safe and effective management of plutonium and countries are defining associated policies and programmes.

At the end of 1997, more than 130,000 tonnes of spent fuel from power reactors were estimated to be stored worldwide containing about 1000 tonnes of plutonium. Another 170 tonnes of separated plutonium were in storage from civilian reprocessing operations, and about 100 tonnes of excess plutonium from dismantled warheads no longer required for defense purposes were scheduled to be released from the military sector by Russia and the United States.

The dual challenge is that plutonium is a valuable energy source (generally speaking, one gram of plutonium is equivalent to about one tonne of oil) and a matter of global concern because of its potential health hazards and possible use for the production of nuclear weapons. In this article, selected aspects of the issue of plutonium management in civilian nuclear programmes are discussed over a longer term perspective in the context of global cooperation and the IAEA's own role, which is evolving in response to the interests of its Member States. It draws upon discussions at international fora, including the International Symposium on Nuclear Fuel Cycle and Reactor Strategies in June 1997 *(see related article, page 7)*. The article does not address non-proliferation aspects of the issue, including the IAEA's established safeguards and verification activities.

STATUS & TRENDS

Plutonium from civilian programmes. Plutonium is one element formed in the fuel of nuclear reactors during their operation. It can be separated, stored, and subsequently used in recycled fuel for nuclear power plants. (Parenthetically, the use of plutonium for energy generation is not something new. Nearly 40% of the electricity produced by each thermal reactor fuelled by uranium is due to fission of plutonium isotopes accumulated during the burning of uranium.) Altogether 443 power reactors were operating in 1997 with a total electricity output of about 350 gigawatts-electric. All these power reactors produced plutonium; for example, spent fuel from light-water reactors contains about 1% of plutonium.

The IAEA estimates that in 1997 about 10,500 tonnes of spent fuel was discharged from nuclear power reactors worldwide; this amount contains about 75 tonnes of plutonium. It is estimated that the annual production figure will remain more or less the same until 2010. The cumulative amount of plutonium in spent fuel from nuclear power reactors worldwide is predicted to increase to about 1700 tonnes by 2010.

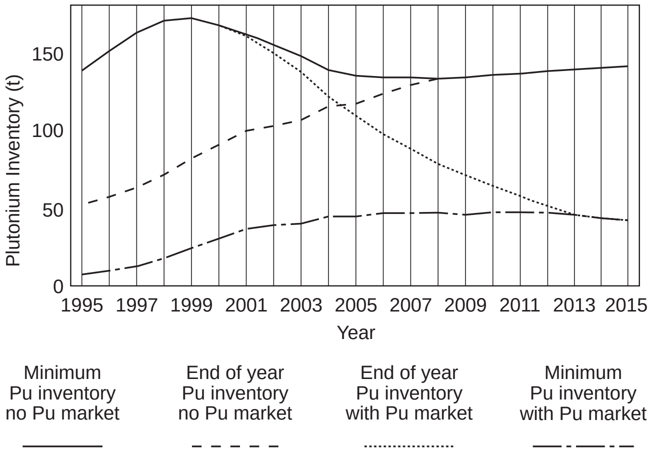
It is estimated that about 3000 tonnes of spent fuel discharged from power reactors were reprocessed in 1997, which corresponds to about 30% of the total. About 24

Mr. Oi is a senior staff member of the IAEA Department of Nuclear Energy.

tonnes of plutonium were separated in reprocessing plants and nine tonnes of plutonium were used mainly as mixed uranium-plutonium oxide fuel (MOX) in light-water reactors. The imbalance between the separation and use of plutonium had resulted in an accumulated inventory of separated civil plutonium of about 170 tonnes at the end of 1997.

IAEA projections of plutonium inventories show that the rate of separation of civil plutonium and its rate of use will fall into balance in a few years. This is due to an enhanced capacity of MOX fuel production which will amount to 360 tonnes of heavy metal (tHM) per year in 2000. Beyond this period, the inventory is expected to decrease modestly and level off at around 130 tonnes. Despite the efforts to reduce the current inventories of separated civil plutonium, the worldwide inventories still remain at a substantial level. *(See graph.)*

PROJECTED WORLDWIDE CIVIL INVENTORIES OF SEPARATED PLUTONIUM



Plutonium designated as no longer required for defense purposes. In addition to the amounts of civil plutonium, plutonium is being released from dismantled warheads. Under the START-I and -II Treaties, many thousands of US and Russian nuclear warheads are slated to be retired within the next decade. As a result, at least 50 tonnes of plutonium from each side are expected to be removed from military programmes.

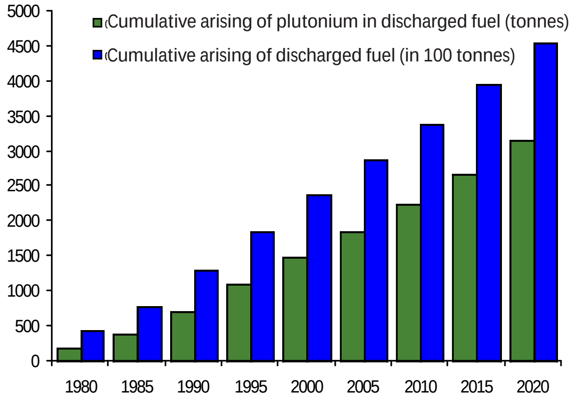
PLUTONIUM MANAGEMENT

The question arises as to what to do with plutonium either in a separated form or contained in spent fuel. A number of issues arise because of plutonium's potential use as an energy source and for the production of nuclear weapons. The US Academy of Sciences has proposed the conversion of ex-military plutonium into a form which is protected from theft and seizure by intense radioactivity (the "spent fuel standard"). Such proposals, however, would only be applicable for a rather short term. Within 200 years, the protection afforded by intense radioactivity will disappear as the result of the decay of most radioactive nuclides. If the spent fuel is buried in a geological formation, it might be regarded as a potential "plutonium mine", meaning that at some later point in time the buried plutonium could be mined and extracted.

Burning excess plutonium. Presently, plutonium is used in light-water reactors as MOX fuel and also in a small amounts for the development of fast-breeder reactors. Currently 22 power reactors in five countries (France, Germany, Switzerland, Belgium, Japan) are loaded with MOX fuel and this number is expected to rise to between 36 and 48 by 2000. The use of MOX reduces the inventory of separated plutonium and is regarded as an interim measure before plutonium's possible full-scale use in fast reactors later in the next century. It is known that multiple recycling in light-water reactors degrades plutonium, which in turn limits the number of times it can be recycled to two or three. Such degraded plutonium can, however, be used as fuel in fast reactors. Without such reactors, spent MOX fuels will still end up in a final depository or in storage facilities.

It may take another several decades before extensive use of plutonium as an energy source will become a reality. The commercialization of fast reactors has been delayed. The main reasons are economics and non-proliferation concerns. Any fast reactor being designed/constructed today appears to have no economic advantages over light-water reactors, which profit from rather abundant low-priced

CUMULATIVE ARISING OF DISCHARGED FUEL AND OF PLUTONIUM IN DISCHARGED FUELS



uranium. Although sustainable nuclear energy production can be achieved effectively by fast reactors, its introduction into the competitive electricity market is not expected before 2030 (about one to two percent of predicted nuclear energy capacity in 2030). This prediction may still be optimistic. The possibility cannot be denied that other energy sources may compete with fast reactors. Even so, the problems of managing spent fuel and plutonium will persist.

Are there any other methods for burning excess plutonium? Accelerator driven systems, burning in inert matrices, and the use of thorium to burn plutonium are being studied. But these technologies are still in an early development stage.

Disposition of plutonium from the defense sector. In the case of plutonium released from the defense sector, both the USA and Russia have taken steps addressing the problem. The United States decided in January 1997 on a "dual-track" strategy, namely to use the major portion of plutonium in light-water reactors as MOX fuel and to immobilize the rest. Russia has not formally declared its policy but the emphasis is to use plutonium as fuel in reactors. Once basically a bilateral concern between the USA and Russia, the demilitarization and disposition of plutonium once used in weapons is one of most important new realities facing the international community. The resolution of issues will require political will, sufficient funds, and effective international cooperation.

It is worthwhile noting that disposition of 50 tonnes of plutonium can be technically completed in the timeframe of 20 to 40 years. The amount of ex-military plutonium, therefore, does not change the nature of the overall plutonium-related problems facing the nuclear community. It should be emphasized, however, that the disposition of plutonium from the defense sector is a great step towards disarmament and should be carried out with highest priority.

Storing spent fuel. For plutonium from civilian programmes, the logical scenario is either to store spent fuel for a long time or to dispose of it in geological formations. The same applies to the reprocessing option because spent MOX fuel will end up in storage or geological disposal after being recycled two or three times.

The long-term storage of spent fuel and separated plutonium is a rather mature technology and poses no significant technical problems. The technology for geological disposal of spent fuel is still to be demonstrated. To date no disposal site has been licensed in any country.

A large amount of spent fuel can be stored rather easily. The volumes are far smaller and more compact than other types of wastes being produced by modern industries. Spent fuel can be more easily isolated from the environment than waste from fossil fuel plants which is mostly released into the atmosphere. Spent fuels are inherently chemically stable and compact and the thermal condition of storage improves over time due to the decay of fission products.

Two examples illustrate that the space necessary for spent fuel storage is very modest. The "CLAB" facility in Sweden is a system of water pools 120 meters long, 20 meters wide, and 27 meters deep. It is located in an underground rock cavern which can store 5000 tonnes of spent fuel. Operation started in 1985 and by 1997, a total of 2600 tonnes of spent fuel from boiling-water reactors and pressurized-water reactors have been stored.

An example of dry storage is at Point Lepreau nuclear power plant, in Canada, where 1026 tonnes of spent fuel from Candu reactors have been stored in 100 silos since 1991. Each silo is a concrete canister, 3.07 meters in diameter and 6.1 meters in length. Dry storage can be a preferred option, especially for long-term storage following extended underwater storage, from the standpoint of ease of operation and maintenance and inherent safety features. Almost 20 years of favorable experience exists with the dry storage of spent fuel. The dry storage systems can be concrete canisters, steel-lined concrete storage containers, and vaults. Even though dry storage is a younger technology compared to wet storage, it has become a mature technology and the quantities being placed into dry storage are beginning to increase significantly. At the end of 1997, about 3600 tonnes of spent fuel (about 3% of the total in storage worldwide) have been placed into dry storage in eight countries.

In the past, the storage of spent fuel has been regarded as an interim step in the management of spent fuel. But this perception will have to change as long-term storage over many decades will become a necessary measure.

In summary, today's nuclear fuel cycle issues seem to boil down to considerations of the use of mixed-oxide fuel (to the extent States are committed to reprocessing) and of separated plutonium, and the long-term storage/disposal of spent fuel foreseeably in geological repositories. As plutonium is released from the military sector, the issue of its direct disposal adds to these considerations.

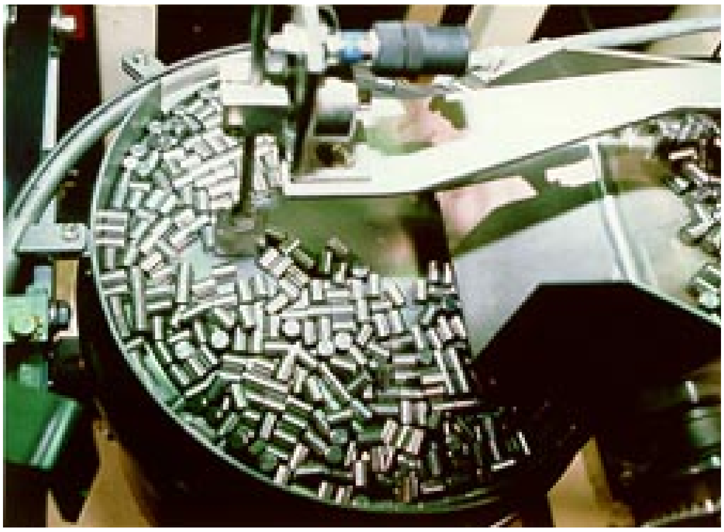


Photo: *Mixed-oxide fuel pellets containing about 5% plutonium. (Credit: Cogema)*

INTERNATIONAL CONTEXT

Since the early 1990s, plutonium-related issues have received greater international attention.

- In 1992-93, the IAEA held two meetings to discuss the the issues connected with the accumulation of separated plutonium from civilian programmes. In this connection, the concept of an international plutonium storage, dormant since mid-1980, was touched upon. In the following years, discussions on plutonium management were carried out by nine states (Belgium, China, France, Germany, Japan, Russia, Switzerland, the United Kingdom, and the United States) who formed a Working Group independent of the IAEA. The Group has recently completed International Guidelines for the Management of Plutonium (published March 1998 in INFCIRC/549). The guidelines set out the policies which each government has decided to apply to the management of plutonium in peaceful nuclear use. With a view to increasing the transparency and public understanding of the management of plutonium, the States have agreed to publish occasional statements explaining their national strategies for nuclear power and the fuel cycle, and their general plans for managing national holdings of plutonium. In addition, the States also committed themselves to publishing an annual statement of holdings of plutonium subject to the Guidelines.
- In 1994, an ad hoc expert group under auspices of the Nuclear Energy Agency was formed to study the broad technical questions related to plutonium management. Its report, published in May 1997, covered technical options for management of civil plutonium. The group had a membership drawn from fifteen countries and three international organizations, including the NEA, IAEA, and European Commission.
- In 1995, the Review and Extension Conference of the

Treaty on the Non-Proliferation of Nuclear Weapons (NPT) called for greater transparency in the management of plutonium for civil purposes, including stock levels and their relationship to national nuclear fuel cycles. One of the main Conference Committees also called for continued international examination of policy options concerning the management and use of stocks of plutonium, including the option of an arrangement for deposits with the IAEA, and the options for a regional fuel cycle centre.

- In 1996, the participants in the Moscow Summit on Nuclear Safety also underscored the importance of global cooperation. While recognizing that the primary responsibility for the safe management of weapons fissile materials rests with those States which have produced and possess it, they stated that “other States and international organizations are welcome to assist where desired”.
- Later in 1996, following up on the Moscow Summit, an “International Experts Meeting on Safe and Effective Management of Weapons Fissionable Materials Designated as No Longer Required for Defense Purposes” was held in Paris. The IAEA was represented together with ten countries and the European Commission. This was the first meeting at which a current and primarily bilateral plutonium issue was discussed in an international forum. The IAEA used the occasion to describe its experiences and expertise in matters relevant to international plutonium management.
- In September 1996, the so-called Trilateral Initiative of the USA, Russia and IAEA was established during the IAEA General Conference on the verification of nuclear materials removed from the defense sector. It was agreed jointly to explore the technical, legal, and financial issues connected with the verification of such materials.
- From a global perspective, the IAEA “International Symposium on Nuclear Fuel Cycle and Reactor Strategies: Adjusting to New Realities” examined major issues and developments in June 1997. The objectives of the Symposium were to prepare for decision makers and the public a scientific assessment of different fuel cycle and reactor strategies with particular reference to the production, use, and disposal of plutonium.
- In 1997, States adopted international safety norms for spent fuel management. The Joint Convention on the Safety of Radioactive Waste Management and the Safety of Spent Fuel Management was opened for signature at the Agency’s General Conference in September 1997.

The IAEA’s role. The IAEA’s role in this area is evolving in response to the interests of its Member States. In addition to carrying out its established nuclear safeguards and verification activities, the Agency’s existing and planned activities related to civil plutonium management involve:

- *Serving as a forum for information exchange.* This entails providing an impartial perspective for a common understanding of various important aspects of the nuclear fuel cycle; the regular publication of the estimated world inventories of plutonium; assisting efforts to enhance transparency to increase public confidence through periodic objective reports and studies; and promoting necessary research and development, including possible international co-operation related to fast reactors, to contribute to the reduction of inventories of plutonium.
- *Assisting countries in formulation of infrastructures for the safe and secure handling of plutonium and spent fuel.* As an example, the IAEA has published Safety Guides for the safe storage of spent fuel from power reactors, and recently prepared for publication a Safety Report on safe handling and storage of plutonium.
- *Formulation of necessary international arrangements.* This includes activities addressing the possibility of international plutonium management or storage from safety and security perspectives, as well as arrangements for regional and international co-operation to find economically effective ways of resolving plutonium and spent fuel management issues.

As a result of the IAEA’s 1997 Nuclear Fuel Cycle Symposium, the International Working Group on Nuclear Fuel Cycle Options was established in 1998 to maintain a dialogue among States on important issues in the field. The Working Group is intended to be a major forum for discussion of cooperative tasks, including the IAEA’s role in the disposition of spent fuel and plutonium, international storage of spent fuel from power and research reactors, and international plutonium management. ❑

BALANCING NEEDS

GLOBAL TRENDS IN URANIUM PRODUCTION AND DEMAND

BY JEAN-PAUL NICOLET AND DOUGLAS UNDERHILL

In many countries, uranium is a major energy resource, fueling nuclear power plants that collectively generate about 17% of the world's electricity. With global demand for energy, especially electricity, projected to grow rapidly over the coming decades, the price and availability of all energy sources, including uranium, are key components in the process of energy planning and decision-making. Over the past decade, changing political and economic conditions left their marks on the civilian uranium market, as they did throughout the energy industry.

Particularly affecting the uranium market were changing projections about nuclear power's growth and the consequent demand for nuclear fuel; the emergence of a more integrated free market system including former centrally planned economies; and the emergence into the civilian market of uranium released from dismantled nuclear weapons. All these factors contributed to uncertainties in the commercial uranium market that raised questions about future fuel supplies for nuclear power plants.

Signs today indicate that the situation is changing. The world uranium market is moving towards a more balanced relationship between supply and demand. After falling nearly 50% from 1988-94, world uranium production increased in 1995, 1996 and 1997. The estimated 1997 production was up about 20% over 1994. While the uranium spot market price has followed an erratic trend since recovering from its all time low in mid-1994, prices in early 1998 were up by more than 30%.

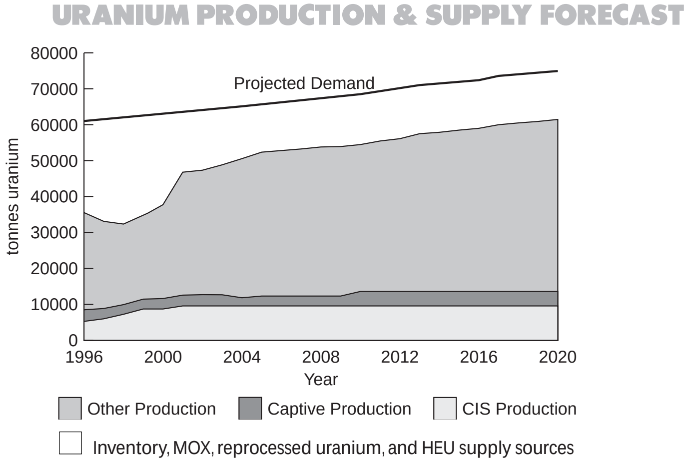
Important production-related developments have been taking place in some countries, including Australia, Canada, Kazakhstan, Mongolia, the United States, and Uzbekistan. Additional progress was made in 1997 regarding the market introduction of low-enriched uranium (LEU) derived from blending down of 500 tonnes of high-enriched uranium (HEU) purchased by the United States from Russia. The first deliveries under this agreement were made by Russia to the United States in 1996 and 1997.

World uranium production has been below uranium requirements since 1990. Only about 60% of total world requirements for nuclear reactors – about 63,800 tonnes-uranium (tU) — was met by production in 1997. This undersupply situation has caused a cumulative drawdown of world inventories of about 160,000 tU since 1990. *(See graphs next page.)* The drawdown is expected to continue at more than 20,000 tU in 1998. The rapid drawdown has depleted the civilian uranium stockpile to a level where some market analysts concluded that there are only limited amounts of excess material available for sale. Although inventories remain substantial, the increase in spot uranium prices during 1995-96 was a sign that inventories are getting much closer to desired levels.

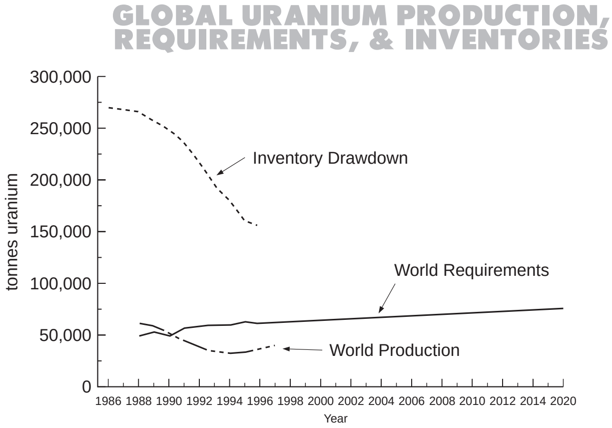
SUPPLY & DEMAND PROJECTIONS

Analysis of the availability of supplemental uranium supplies to meet reactor demand leads to the conclusion that uranium production will continue as the predominant source of nuclear fuel. Therefore, the question arises as to the adequacy of both uranium resources and production capacity to meet demand on a timely basis. To address these questions, the IAEA invited specialists to analyze the available information and prepare a report of projections through the year 2020. This article highlights the principle findings of this report and describes selected IAEA activities related to uranium exploration and production activities. *(See box, page 20.)*

Mr. Nicolet and Mr. Underhill are staff members in the IAEA Division of Nuclear Fuel Cycle and Waste Technology.



URANIUM PRODUCTION & SUPPLY FORECAST



GLOBAL URANIUM PRODUCTION, REQUIREMENTS, & INVENTORIES

Note: Data does not include civilian stocks from the CIS or high-enriched uranium from the United States and CIS.

Demand Projections. World uranium demand is reasonably well known up to 2005. After 2005 there is increasing uncertainty in projections resulting from potential nuclear plant closures, variable construction schedules, and a lack of new plant orders. In this analysis, the annual uranium requirements are projected to increase from 61,500 tU in 1997 to 75,000 tU in 2020.

This projection was developed as an approximate "best fit" of the middle of the demand range based on the analysis of several published projections of requirements. In this projection, reactor demand increases by about 600 tU/year over the period through 2020, equivalent to a growth rate of under 1% per year. The total cumulative requirements for the period stand at about 1.638 million tU.

Supply Projections. Sources of uranium supply that are expected to be available to satisfy reactor requirements include:

■ ***Utility and producer inventories.*** Two types of inventory are accounted for: excess inventory in Western countries and estimated inventory held by the Russian Federation. The majority of non-Russian inventories are held by utilities for security of supply reasons. There are also smaller amounts owned by producers, uranium traders and the US Department of Energy. Discretionary utility inventory (inventory held by utilities in excess of preferred or mandated levels) at the beginning of 1997 was estimated to total about 50,000 tU. The last amount of discretionary inventory is projected to be sold in the year 2000. The inventory of natural uranium and/or LEU held by the Russian Federation at the beginning of 1997 was estimated to total about 30,000 tU. This inventory is projected to be drawn down gradually through 2004.

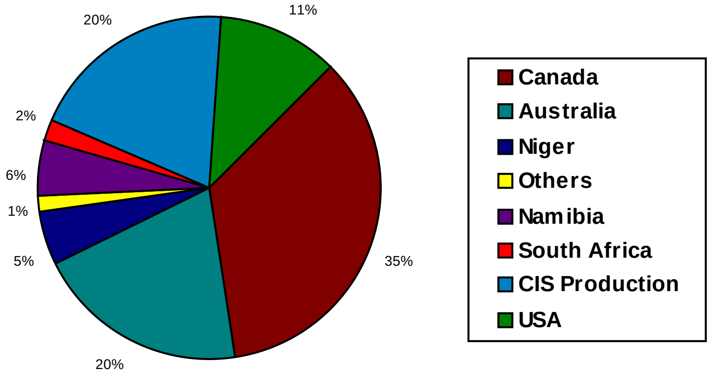
■ ***500 tonnes of HEU from Russian nuclear weapons.*** Probably no other supply source is surrounded by more uncertainty than HEU held by the Russian Federation. Politics, economics, and technology will all play a role in determining the availability of uranium from this source. A total of 500 tonnes HEU, equivalent to 153,000 tonnes natural uranium, is scheduled for delivery. There are, however, political and technical uncertainties as to whether the proposed delivery schedule can be maintained. The assumption used in this projection is that the LEU from the Russian HEU will be made available to the market at the rate the LEU's delivery is scheduled to the United States. The prevailing schedule calls for the delivery of 18 tonnes, 24 tonnes, and 30 tonnes HEU equivalent (5733 tonnes, 7644 tonnes and 9555 tonnes, respectively, of natural uranium) in 1997, 1998 and 1999. Delivery at the rate of 30 tonnes HEU equivalent then continues through 2012. In this projection, it is assumed that additional LEU blended from HEU from Russian and the United States will continue to be delivered through 2020.

Mixed uranium-plutonium oxide fuel (MOX) and reprocessed uranium. Assuming that countries maintain existing policies regarding the reprocessing of spent nuclear fuel versus opting for direct disposal, the future market for these options will be limited. Reprocessed uranium and plutonium for MOX fuel is an important component of the supply in only a limited number of countries. The contribution of MOX and reprocessed uranium is not expected to exceed about 6% of total annual requirements through 2020. The requirements not filled by these sources will have to be met from production of natural uranium from the sources noted below.

Mined and processed natural uranium from the Commonwealth of Independent States (CIS). With an estimated 1997 production of 6285 tU, the CIS supply is forecast to increase to 9785 tU in 2001 and remain at this level through 2020. This represent 15% of world requirements. There are, however, uncertainties about the capability of the CIS to produce this amount of uranium.

Captive Production. This refers to national programmes in which production is dedicated to domestic nuclear power programmes. The production schedule for the captive programmes is balanced with reactor demand in Argentina, Brazil, India, Pakistan, Romania, and Spain. Also included in this category are the production industries of France (projected to produce through 1999); the Czech Republic (projected to produce through 2003); Hungary (production scheduled to terminate in 1997); and Portugal (projected to continue production through 2020). Captive production equals about 5% of requirements or 3200 tU per year.

CUMULATIVE WORLD URANIUM PRODUCTION
1997-2020 (total = 1.245 million tU)



"All Other" Mined and Processed Natural Uranium. This category represents uranium production from North America, Africa, Australia and Europe. It meets 57% of requirements, and increases from 28,000 tU in 1997 to 38,500 tU by 2001. It then gradually increases to 47,700 tU in 2020. Production from projects with well-defined uranium reserves is adequate to fulfill requirements through the year 2012. Beyond that time, resources defined with lower confidence will be required to fill demand. Canada is expected to be the dominant producer throughout the study period. Canada's production is expected to peak at 20,400 tU in the year 2002 and then decline to about 38% of total supply in this category by the year 2020. This is expected to occur as reserves are depleted and as low-cost production capacity increases elsewhere in the world. In 1997, production in Australia and the United States in this category was expected to increase from about 21% to 29% and from 10% to 16% respectively, of total natural uranium. Cumulative output from Niger and Namibia is expected to meet between 5% and 10% of demand through 2020. *(See graph.)*

As reported in the 1997 edition of *Uranium Resources, Production and Demand* (the Red Book, jointly produced by the IAEA and Nuclear Energy Agency of the Organization for Economic Cooperation and Development), the world annual production capability on 1 January 1997 was 43,000 tU. This is comprised of 8050, 2600 and 32, 350 tU/year, respectively, of the production capability in the CIS, Captive and "All Other" categories.

In 1996, uranium production was 36,195 tU, representing a utilization rate of about 84% of the world's production capability. (Production capability utilization is defined as production divided by available production capacity.) Of the total production, 6275, 2440, and 27,450 tU, respectively, came from the CIS, Captive and "All Other" categories. In terms of production capability utilization, this represented 78%, 93% and 85%, respectively for these three categories.

In 2005, the estimated production is about 52,500 tU, about 44% higher than the 1996 level. To produce this amount, the production capability has to increase between 22% and 26% from the existing level of 43,000 tU. Under this projection, only seven years remain to plan, license, construct and bring uranium projects into production. Additional capacity will be required to produce about 61,500 tU/year by 2020, as well as to replace capacity that closes as resources are depleted.

BALANCING NEEDS

Based on a projected, modest 1% annual growth rate, world uranium requirements are estimated to grow from 61 500 tU in 1997 to 75 000 tU in 2020. Cumulative demand over the period is 1.638 million tU.

In 1996, production met about 60% of world requirements, with most of the balance coming from inventory. This source, which has been supplying an average of about 23,000 tU per year since 1992, is coming to an end. With the end of excess inventory in sight, uranium supplies from other sources will have to increase to meet requirements. What supply sources are available to meet requirements through 2020?

Uranium mine production will continue to be the primary source of supply, meeting 76% to 78% of cumulative requirements through 2020. Alternative sources supplying the balance, in order of relative importance, are LEU blended from HEU released from weapons programmes (11% to 13%), reprocessing of spent nuclear fuel (6%), and excess inventory (5%). The contribution of US government and other Russian strategic stockpiles is not known at this time.

To meet these projected uranium requirements, all sources of supply will have to increase as planned. Otherwise, shortages could result early in the next century from one or more types of producers. ❐

TARGETING SUPPORT

Thirty-four IAEA Member States are involved in exploration for and/or production of uranium resources. Twenty-two of these Member States are developing or emerging countries that are benefitting from specific types of IAEA support. Major Agency activities include:

Preparation of the global status report Uranium Resources, Production and Demand, also known as the "Red Book" on a biannual basis. The report is jointly prepared with the Nuclear Energy Agency of the Organization for Economic Cooperation and Development. The 1997 edition is the most complete ever with reports from 59 countries. It includes for the first time reports from all uranium producing countries, including official submissions from Russian Federation and Uzbekistan. It is useful to planners and policy makers involved with both uranium supply and demand.

The World Atlas Database. This world map of uranium deposits and accompanying guidebook is the first worldwide compilation of all uranium deposits featuring technical descriptions of their geologic setting, tonnage, grade, mine type and status. It supports national strategic planning, including decisions about economically developing indigenous uranium resources.

Transfer of Experience. During the past 15 years, the declining uranium price and increasing safety and environmental concerns about uranium mining operations has led to more complex regulations and the closing of uneconomic operations. At the same time exploration and mining technology has advanced substantially, bringing methods that are environmentally friendly and economically more efficient. The Agency is actively involved in transferring associated technologies and technical experience. Drawing more interest in many countries is in-situ leach mining, which recovers uranium from water-saturated, permeable sandstone deposits. Leaching solutions are injected through wells that are then pumped to recover uranium-bearing solutions for further processing. The method, which doesn't require breaking rocks and transporting them to a mill, has economic, environmental and safety benefits if projects are well planned and operated and deposits are carefully selected. It is used or being planned in Australia, China, Czech Republic, Kazakhstan, Mongolia, Pakistan, the Russian Federation, the United States, and Uzbekistan. About 13% of total world uranium production in 1996 came from in-situ leach mining. As part of its activities in this field, the IAEA is carrying out several technical cooperation projects and recently convened a technical meeting for developing countries on this subject.

HIGHER GOALS

NUCLEAR FUEL TECHNOLOGY & PERFORMANCE

BY VLADIMIR ONOUFRIEV AND PATRICK MENUT

Nuclear power plants have high initial investment costs but low fuel costs compared to electricity-generating plants burning fossil fuels. A 1000-megawatt nuclear plant, for example, uses about 30 tonnes of uranium a year, whereas a coal-fired plant of the same size requires about 2.6 million tonnes of coal and an oil-fired plant about 2 million tonnes of oil.

In today's changing energy marketplace, more countries are moving to introduce competition into formerly regulated electricity markets. For nuclear power development, this means, among other things, that fuel-related costs will have to be kept lower than the corresponding costs for fossil-fuelled plants to remain competitive. Economic pressures, alongside environmental demands, accordingly have become driving forces behind efforts to improve nuclear fuel technology and performance without compromising plant safety levels.

The search for better fuel economy at nuclear power plants involves extensive and detailed studies. They include evaluations of the design, behaviour, performance, and reliability of fuel elements under various operational conditions and at different types of power reactors. Particular interest has gone to extending the lifetime of nuclear fuels, and over the past decades there has been an upward trend in the achievement of "higher burnup" levels in most types of reactors. This has resulted in overall fuel-related savings and in the reduction of the amount of discharged spent fuel that must be managed. At the same time, high burnup also places greater demands on fuel performance. Therefore, research is in progress to assess fuel behaviour at different projected levels of burnup. The step-by-step increase in burnup is authorized only when evidence has been presented to licensing authorities that it can be achieved without compromising safety or fuel reliability. Research is focused on a number of phenomena that could potentially limit the lifetime of the fuel under different types of operating conditions.

Within the framework of the International Working Group on Water Reactor Fuel Performance and Technology, the IAEA has been supporting collaborative efforts of national and international experts in this field. It additionally organizes coordinated research projects involving national institutes investigating specific technical aspects, and conducts technical cooperation projects for transferring technologies and expertise. This article presents an overview of selected activities, particularly focusing on those related to the goals of achieving higher burnup of nuclear fuel.

FUEL EXPERIENCE

Under operating conditions, nuclear fuel assemblies are subjected to aggressive environments characterized by synergistic effects of stress, heat, coolant water chemistry, and irradiation. The effects lead to progressive degradation of the mechanical and physical properties of fuel cladding materials and other structural components of the fuel and control rod assemblies. Higher levels of fuel burnup add to these physical and mechanical demands, and much research and development is directed at developing advanced materials, including those that, for example, are more resistant to corrosion.

Overall, the reliability of nuclear fuel has been improving steadily over recent years. For light-water reactors, the main type in service worldwide, fuel failure rates have been 10^{-5}, which is about ten per year per million fuel rods in service. The mitigation and control of fuel defects are driven by economic and safety considerations. The goal of "zero fuel failures", which means in practice a reduction of the fuel failure rate to 10^{-6}, has

---

Mr. Onoufriev and Mr. Menut are staff members in the IAEA Division of Nuclear Fuel Cycle and Waste Technology.

been the target of utilities and fuel vendors over the near term.

Major causes of fuel failures to date have been mainly related to initial design and fabrication problems. New fuel rod and assembly designs are being developed and implemented in response. For example, at light-water reactors, metallic debris in the primary coolant system of the plant is known to cause a significant fraction, about 40% to 50%, of the fuel failures. As a result, utilities have developed programmes to identify and eliminate the sources of debris, and fuel vendors are offering "debris resistant" fuel designs.

To monitor fuel performance at higher burnup and to supply data for validating predictive computer codes, studies known as post-irradiation examinations are done. They apply to both surveillance-type, non-destructive examinations and to more sophisticated destructive examinations and measurements. Validation is needed for both new fuel concepts and for new cladding materials.

Fuel modelling studies are important from economic and safety perspectives. A reliable prediction of fuel behaviour in all conditions is required for safety calculations during design. Computer codes have been developed for this purpose. From a knowledge of fuel behaviour in both normal and abnormal conditions, operating rules are derived to prevent fuel failures and the possible release of fission products to the environment, or in extreme cases, to prevent serious fuel and core damage and any subsequent hazard. In this methodology, the fuel cladding is the first safety barrier.

Even with the simplest computer codes, adequate operating limits can be derived to ensure safe operation provided that conservative limits are set. The modelling of fuel performance, and inclusion of that knowledge in the codes, also are important to achieving more realistic predictions of fuel behaviour that will contribute to improving the economics of reactor operations.

JOINT RESEARCH

Through the IAEA's working group, experts have reviewed research results and operational experience, agreeing that fuel performance is satisfactory for current operational requirements at water reactors. Further research, however, is needed in several areas in light of ongoing efforts to achieve even higher burnup of nuclear fuels. They include studies related to:

Control of Water Chemistry. At high temperatures, water is an aggressive medium when in contact with structural materials. This means that the reliability of fuel assemblies, among other nuclear power plants systems, depends on the chemistry of water flowing in cooling systems. Corrosion is one of the most important processes leading to the degradation of fuel rods. During the 1980s, water chemistry specifications were gradually tightened, and this "purer is better" approach resulted in significant improvements, though it remained clear that corrosion had to be further reduced. More recently, chemists have been modifying specifications, usually by adding chemicals to the coolant. Investigations further allowed a better understanding of the mechanism of corrosion. Today, water chemistry regimes are getting more plant specific — for example, plant operators have new tools (calculation codes and programmes) to optimize water chemistry parameters and regimes within the specification, but taking into account the peculiarities of the plant. These issues further are being examined through two IAEA coordinated research projects.

Operational Anomalies. In the 1990s, several countries have reported problems with the bowing of fuel assemblies and lowering of control rods during plant shutdown operations. Although the drop time in these cases was still within the limits of technical specifications for the reactors involved, these anomalies were carefully analyzed and investigated. Studies of the anomalies, including the phenomenon of water gaps between fuel assemblies, are continuing. Some countermeasures have been implemented to prevent problems from recurring.

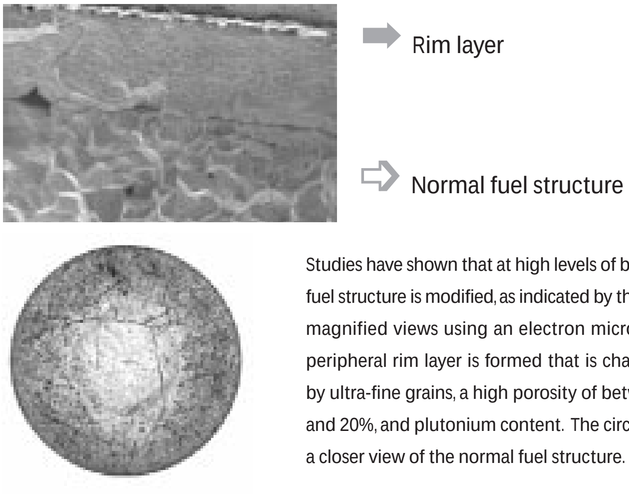
Irradiation and Other Effects. A number of phenomena related to the irradiation of nuclear fuel at higher levels of burnup are being investigated. Detailed characterization of the evolution of microstructures caused by irradiation is the key to understanding and predicting the degradation of physical and mechanical properties induced by radiation damage. *(See figure.)* Improvements in the fundamental theories of certain radiation-induced phenomena, among other developments, continue to improve the accuracy of predictions about the deformation of pressure tubes, and the knowledge is contributing to the development of tubes having longer lifetimes.

The formation of fission gases is directly related to the length of time fuel is irradiated. At high levels of burnup, these gases can lead to undesirable consequences, including the buildup of internal pressure in rods. Studies of this phenomenon are identifying factors that need to be taken into account to improve predictions about fuel behaviour at high burnup. Contributing to this work are researchers participating in an IAEA coordinated research project on fuel modelling. Nineteen different codes were studied, resulting in the improvement and validation of elementary models and codes.

In parallel, a more advanced modelling code for fuel performance has been transferred to ten Eastern European countries, together with guidance on its application to reactor operation and safety assessments. This code's adaptation to predict the behaviour of fuel used in WWER-type reactors under normal and transient conditions is now being done within the framework of an IAEA technical cooperation project. Also being studied is another cause of structural modifications of fuel that is related to the formation of plutonium during irradiation. A number of countries are investigating this phenomenon as part of safety studies.

Fuel Behaviour under Accident Conditions. To improve knowledge about fuel behaviour under different types of conditions, tests of fuel are being conducted through simulated accident scenarios. Two scenarios under investigation are reactivity insertion accidents and loss-of-coolant accidents; both scenarios involve testing the performance of fuel at extended levels of burn-up. Early results of these research programmes in some countries were reported in May 1997 to the IAEA's working group. The final outcome of these programmes is expected to be a decisive factor in the achievement of the desired higher levels of fuel burnup over the coming years.

STUDIES OF FUEL BEHAVIOUR & STRUCTURE



Studies have shown that at high levels of burnup, the fuel structure is modified, as indicated by these highly magnified views using an electron microscope. A peripheral rim layer is formed that is characterized by ultra-fine grains, a high porosity of between 10% and 20%, and plutonium content. The circle at left is a closer view of the normal fuel structure.

TECHNICAL CHALLENGES

Over the next decade, the trend of higher burnup levels for nuclear fuels is projected to continue, largely driven by economic incentives. Levels are expected to increase by 32% or more by the year 2010 for different types of fuels burned in water reactors. These incrementally higher levels will have to be tested and qualified before the use of the fuels can be licensed. In some areas, considerable research and development is required, as the cause of some fuel failures, even after examination, is not yet fully understood. Additionally, while there have been few fuel failures of mixed-oxide fuels, more experimental data are needed to study the behaviour of defective mixed-oxide fuel rods, especially at high burnups and for longer irradiation times.

The IAEA's Working Group on Water Reactor Fuel Performance and Technology includes experts from 26 countries and three international organizations. Through this group, among other avenues, the IAEA is assisting countries to benefit from each other's experience and technological development by focusing efforts on specific topics and needs. For example, jointly with the Nuclear Energy Agency of the Organization for Economic Cooperation and Development, the IAEA has established the International Fuel Performance Experiment Database, which includes data from experiments involving more than 300 fuel rods, that supports research in participating countries. These and other initiatives are contributing to collective efforts for meeting the technical challenges ahead and for improving the efficient operation of nuclear power plants. ❐

RISING DEMANDS

MANAGEMENT OF SPENT FUEL FROM NUCLEAR POWER PLANTS

BY PETER H. DYCK AND MARTIN J. CRIJNS

Last year about 10,000 tonnes of heavy metal were discharged as spent fuel from the world's nuclear power plants after use for the production of electricity. This spent fuel was placed in storage at specially designed facilities, kept and monitored for later retrieval either for reprocessing or later disposal in repositories.

In the coming years, the storage of greater quantities of spent fuel for longer periods of time is projected. As a result, the world's nuclear industries are building new storage facilities, expanding existing ones, and putting into practice technologies to ensure more effective long-term storage.

This article presents an overview of approaches that countries are following for the management of spent fuel from nuclear power plants, and briefly describes selected IAEA activities in the field.

BASIC APPROACHES

Spent fuel management encompasses an integrated series of technical operations. They begin with the discharge of spent fuel assemblies from a power reactor and end either with their direct disposal (open, or "once-through" fuel cycle); or with their reprocessing and the final disposal of the associated high-level wastes (closed fuel cycle). Direct disposal involves steps that would place the spent fuel in a location, such as a geological repository, under conditions which would not permit its later removal. Reprocessing operations separate the fissile plutonium and uranium from the waste materials for reuse as recycled fuel in reactors.

Originally the intention behind the closed fuel cycle concept was to recycle the separated plutonium and uranium in fast-breeder reactors. However, delays and cancellations of breeder programmes have led to the recycling of the separated fissile materials in thermal reactors already operating. Presently, thermal recycling of plutonium (as mixed-oxide, or MOX, fuel) is being carried out mainly in Belgium, France, Germany, Japan, and Switzerland. Thermal recyling of uranium is being carried out in the Russian Federation and in the United Kingdom, and is planned in Germany.

A third option for managing spent fuel is the deferral of decisions and involves interim storage. The approach enables operators to monitor the stored spent fuel continuously and to retrieve it later for either direct disposal or reprocessing. Most countries with nuclear power programmes follow this option. *(See table, next page.)* The selection of a spent fuel strategy is a complex decision with many factors to be taken into account, including aspects of policies, economics, safeguards, and environmental protection. A common feature in most countries, independent of the spent fuel management strategy being followed, is the ongoing need for additional storage capacity.

CHANGING PRACTICES

In earlier days of nuclear power development, countries following the closed fuel cycle generally stored spent fuel at the reactor in storage pools, in which the assemblies are submerged underwater in racks or contained in canisters, and, after transportation, in storage pools at a reprocessing plant.

However, the lack of enough storage capacity at reprocessing plants altered the picture. At the same time, not all countries selected the closed fuel cycle option and instead chose to store the spent fuel pending decisions as to its final disposal. As a result, nuclear utilities started expanding their storage pool capacity for spent fuel. Additionally, pool-type storage facilities were built either on the reactor site or elsewhere. Since then, no final disposal sites for spent fuel have been built, and the

---

Mr. Dyck is a staff member in the IAEA Division of Nuclear Fuel Cycle and Waste Technology, and Mr. Crijns is a consultant in the Division.

demands for long-term storage have intensified. In response, other storage technologies, involving emplacement of spent fuel in dry gaseous environments using casks, silos or vaults, have been developed and are typically located at sites away from the reactor (AFR).

Various types of wet and dry storage facilities now are in operation or under construction in different countries. Spent fuel can be safely stored for long time periods, and some has been stored for more than 30 years.

Overall, a variety of different technologies and systems are in use or planned. In most countries, storage pools at reactors are or will be reracked with high-density neutron absorber racks, to make more efficient use of available storage space. In some cases, ultra high-density racks (for example, in Slovenia and South Africa) will be used to store the spent fuel for the planned lifetime of the reactor. For AFR storage pools, improved steel containers and canisters are used to store the fuel more compactly so as to increase storage capacity.

In 1997, the annual spent fuel arisings from all types of reactors in nuclear power plants amounted to about 10,500 tonnes of heavy metal (tHM). The total amount of spent fuel accumulated worldwide at the end of 1997 was about 200,000 tHM and projections indicate that the cumulative amount generated by the year 2010 may surpass 340,000 tHM. About 130,000 tHM of spent fuel is presently being stored in at-reactor or AFR storage facilities awaiting either reprocessing or final disposal. *(See table, next page.)*

SPENT FUEL MANAGEMENT APPROACHES IN DIFFERENT COUNTRIES

Country	Deferred Decision	Direct Disposal	Reprocessing
Argentina	◆		
Belgium	◆		●
Brazil	◆		
Bulgaria	◆		●
Canada		■	
China			●
Czech Republic	◆	■	●
Finland		■	
France			●
Germany		■	●
Hungary	◆		●
India			●
Italy	◆		●
Japan			●
Korea Rep. of	◆		
Lithuania		■	
Mexico	◆		
Netherlands			●
Pakistan	◆		
Romania		■	
Russian Fed.		■	●
Slovakia		■	●
Slovenia	◆		
South Africa		■	
Spain		■	
Sweden		■	
Switzerland	◆		●
UK			●
Ukraine	◆	■	●
USA		■	

Note*: Some countries use different approaches for different types of fuel. Additionally, some countries follow one approach while evaluating different approaches that might be applied in the future.*

The quantity of accumulated spent fuel is over twenty times the present total annual reprocessing capacity. Assuming that part of the spent fuel to be generated in the future will be reprocessed, the amount to be stored by the year 2010 is projected to be about 230,000 tHM. Since the first large-scale repositories for final disposal of spent fuel are not expected to be in operation before then, the indications are that interim storage will be the primary option well into the next century.

NATIONAL DEVELOPMENTS

Over the past three years, countries have taken important steps to improve their capabilities for effectively managing spent fuel. They include:

■ In Canada, two AFR dry interim storage facilities were put into operation during 1995 and 1996.

■ In the Czech Republic, the dry storage facility at Dukovany, with a capacity of 600 tHM, was licensed in January 1997 for a 10-year period. By the end of 1997, it was loaded with 232 tHM.

STORAGE CAPACITIES AND INVENTORIES IN SOME COUNTRIES IN 1997

(tonnes of heavy metal)

Country	At Reactor Capacity	At Reactor Inventory	Away-from-Reactor (AFR) Capacity			AFR Inventory
			In Operation	**Being Built**	**Planned**	
Brazil	576	130				
Bulgaria	828	387	600			356
Canada	31,407	22,555	8567		14,496	1930
China		177		550		
Czech Republic	480	306	600			232
Finland	676	204	1047			684
France	11,290	5795	14,400			9159
Germany	4561	2756	7767	585		594
Hungary	480	357	160			54
Japan	9920	5800	213	3000		169
Korea Rep. of	5251	3072	609	812		609
Lithuania	2093	1380		352		
Romania	940	100				
Russian Fed.	5230	3480	13,800	1900	13,000	6046
Slovakia	480	150	600			523
South Africa	670	392				
Spain	4390	2000				
Sweden	1500	730	5000		3000	2703
UK	3345	1035	11,153			7157
Ukraine	3051	1650	2000			1695
USA	60,700	35,300	2164	2000	43,000	2164
Total	**147,868**	**87,756**	**68,680**	**9199**	**73,496**	**34,075**

■ In France, the MELOX plant for mixed-oxide fuel reached the licensed throughput of 120 tHM. It was also decided to load MOX fuel in 28 reactors, including twelve that already were using it.

■ In Hungary, a modular vault dry storage facility was put into operation in 1997 and loaded with 54 tHM by the end of the year.

■ In India, the new reprocessing plant at Kalpakkam completed trial runs required for licensing.

■ In Japan, the 3000 tHM wet storage facility at Rokkasho Mura is waiting for local approval to start operation. A programme is planned for using MOX fuel in light-water reactors beginning in 1999.

■ The Republic of Korea is reviewing future options after the cancellation, due to geological reasons, of the central interim storage site it selected earlier. At Wolsung, a 609 tHM dry store facility has been built and a 812 tHM dry store facility is under construction. Additionally, plans proceed for the construction of an experimental facility for the reuse (refabrication) of spent fuel from light-water reactors in a pressurized heavy-water reactor.

■ In the Russian Federation, an interim wet storage facility for 2000 tHM of spent fuel from RBMK reactors has been put in operation at the Smolensk nuclear plant.

■ Sweden continues with the design of a plant for encapsulation of spent fuel prior to final disposal. Completion of a license application is planned early in the next century. Also, licensing steps have been taken to expand the central storage facility (CLAB) with an additional capacity of 3000 tHM for operations by 2004.

■ In the United Kingdom, an operating license for the Thermal Oxide Reprocessing Plant (THORP) has been granted by the regulatory authority after a period of public consultation. The planning application by NIREX for the construction of a rock characterization facility at Sellafield was denied. Future options are under review.

■ In Ukraine, a dry cask storage facility for use at the Zaporozhe site is under review by the regulatory authority.

■ In the USA, three new dry storage facilities were placed in operation at nuclear power plant sites. Several dry storage systems are under review by the US Nuclear Regulatory Commission for use at reactor sites and at other sites.

GLOBAL COOPERATION & THE IAEA

Together with an advisory group of experts from its Member States, the IAEA regularly reviews the status and prospects of spent fuel management for power reactors, studying important developments and trends and identifying technical areas requiring greater cooperative efforts.

One aspect of the Agency's work has focused on the interest of countries in the greater use of remote technologies for handling spent fuel elements. Such technologies are used when spent fuel is discharged from the reactor, as well as for activities related to reprocessing and final packaging in the case of the spent fuel's direct disposal.

High interest also is being shown in the technology and safety aspects of a regional spent fuel storage facility. Several countries having small nuclear programmes face the problem of storing and disposing of their used fuel. From an economical point of view, they see little sense in building their own storage facilities. Experts working through the IAEA have started to collect and evaluate information on a regional spent fuel storage facility, a concept which in principle seems feasible.

The IAEA is assisting countries of Central and Eastern Europe operating the main types of nuclear power plants that were built there (WWER and RBMK reactors). This is being done through an extrabudgetary programme on the safety of WWER and RBMK nuclear power plants initiated in 1995 and funded by the Japanese government. In October 1997, experts attended a technical committee meeting and workshop on the commissioning of dry storage facilities. They discussed in depth the major steps involved in the commissioning of facilities; resource requirements; licensing procedures; radiological protection objectives; safety fundamentals; and standards and practices. In 1998, the IAEA is planning a workshop, among other activities, on the safety of long-term spent fuel storage, with emphasis on spent fuel from WWER and RBMK reactors.

As part of this extrabudgetary programme, several countries have completed computer code and modeling studies on spent fuel behaviour. The KFKI Atomic Research Institute in Hungary, for example, has done thermo-hydraulic calculations of spent fuel behaviour during long-term dry storage conditions using the COBRA-SFS code. The model description and manual were documented, and relevant handbooks were prepared. One result is that this code is now available to all IAEA Member States operating WWER nuclear plants to improve the safety of spent fuel storage.

One particular area that is drawing increasing interest from countries is the concept of "burnup credit" as it applies to the licensing of spent fuel management systems. The term refers to the reduction in reactivity of burned nuclear fuel that occurs from the change in its composition during irradiation inside the core; the data are established through physics calculations of the fuel. For spent fuel storage and transport systems, the use of the burnup credit holds the promise of achieving greater efficiencies. For example, it would allow closer packing of spent fuel, thereby increasing the storage capacity, and it can be applied to increase the capacities of transport casks for spent fuel to reduce the number of shipments needed. There are other applications as well, related to transportation, storage, disposal, and reprocessing operations. While the major incentive for the concept's use is economic, it also holds advantages in terms of public health and safety and environmental protection. Experts convened by the IAEA recently examined this subject, and the Agency will be publishing a technical document covering the status of national practices and the implementation of burnup credit in spent fuel management systems.

The IAEA additionally has published three safety documents on spent fuel management from nuclear power plants. They include a guide on the safe storage of spent fuel from power reactors; a guide on the operation of these facilities; and a document on the preparation of safety analysis reports for spent fuel storage.

These and other activities are directed at helping countries to effectively respond to the emerging technical challenges of spent fuel management. So far, about 40 years of experience exists in the long-term storage of spent fuel from nuclear power plants. However, much longer storage periods are expected, and further steps will be needed to improve storage technologies and methods. ❐

GROWING DIMENSIONS

SPENT FUEL MANAGEMENT AT RESEARCH REACTORS

BY IAIN G. RITCHIE

More than 550 nuclear research reactors are operating or shutdown around the world. At many of these reactors, spent fuel from their operations is stored, pending decisions on its final disposition. In recent years, problems associated with this spent fuel storage have loomed larger in the international nuclear community. Concerns principally focus on the ageing fuel storage facilities, their life extension, and the ultimate disposal of spent fuel assemblies. At both research and test reactors, spent fuel is being stored for longer periods than originally planned and in larger quantities.

In efforts to determine the overall scope of problems and to develop a database on the subject, the IAEA has surveyed research reactor operators in its Member States. Information for the Research Reactor Spent Fuel Database (RRSFDB) so far has been obtained from a limited but representative number of research reactors. It supplements data already on hand in the Agency's more established Research Reactor Database (RRDB).

Drawing upon these database resources, this article presents an overall picture of spent fuel management and storage at the world's research reactors, in the context of associated national and international programmes in the field.

GLOBAL CONTEXT

Two main programmes dominate activities for management, interim storage, and ultimate disposal of spent nuclear fuel from research and test reactors:

The Reduced Enrichment for Research and Test Reactors (RERTR) Programme. Initiated in the United States in support of its nuclear non-proliferation policy, this programme is directed at the conversion of research reactors from the burning of high-enriched uranium (HEU) to low-enriched uranium (LEU). It is now nearly a worldwide programme with the full support of the Russian Federation and ongoing discussions with China. The RERTR programme has already limited and will, if it becomes global, eventually eliminate all trade in HEU for research reactors to the ultimate benefit of the international community. In many cases, however, the conversion to LEU has compounded the problems of spent fuel management because the facilities in question have been left with the spent HEU and in a few cases have had to deal with a greater throughput of LEU fuel after conversion.

The "Take-Back" Programme. When research reactors were first commissioned decades ago, it was assumed in most cases that the spent fuel would eventually be shipped back to the country where it was originally enriched, the country of origin. At many facilities, the return of spent fuel to the country of origin has not yet happened for various reasons. As a result, in some countries, ageing and corroding fuel is currently stored in facilities that were not designed for such long-term storage. The two main countries of origin are the United States and Russian Federation. In May 1996, the United States confirmed its intention to take back foreign research reactor fuel of US origin, thereby resuming an earlier policy. It is hoped that other supplier countries and partners in RERTR will follow suit and implement their own take-back programmes for foreign research reactor spent fuel they originally supplied.

Although the IAEA has fully supported RERTR since its inception, it was not until 1993 that the Division of Nuclear Fuel Cycle and Waste Technology extended its programme to focus specifically on spent fuels from research and test reactors. These activities now cover the collection, analysis and dissemination of information on storage, management and related experience with spent fuels, formulation

---

Mr. Ritchie is a staff member in the IAEA Division of Nuclear Fuel Cycle and Materials Section, Division of Nuclear Fuel Cycle and Waste Technology.

of norms, and provision of technical assistance to developing Member States.

A number of concerns were immediately apparent at the beginning of 1993. Many research reactors were in a crisis situation or rapidly approaching a crisis situation. In every case, this was due to spent fuel storage and management problems and the constraints of national laws. It was clear that the capacity for spent fuel storage had been reached or was close to the limit at many research reactors and there were concerns from a materials science point of view about ageing materials in ageing storage facilities.

The IAEA's activities in this area have been formulated to address these concerns. But the first step was to obtain an overall picture of spent fuel management and storage worldwide.

As of December 1997, the IAEA's Research Reactor Database (RRDB) contained information on 589 reactors regionally distributed around the world. Of these, 269 were operational and 303 were shutdown. Additionally, twelve were under construction, six planned, and one whose status was not completely verified.

The age distribution of operational research reactors in the RRDB peaks in the range of 30 to 40 years. In fact, 19% of the reactors are in the age range of 20 to 29 years and 51% in the range of 30 to 39 years. A large fraction, 46%, of operational research reactors operate at a thermal power of 100 kW or less. Almost all of these 122 reactors have fuel for life and will not have spent fuel problems until they permanently shut down.

SCOPE OF PROBLEMS

Based on responses to questionnaires sent to IAEA Member States, the Agency is developing a Research Reactor Spent Fuel Database (RRSFDB). Though its coverage to date is limited to about 210 research reactors, analysis of available information enables a clearer definition of the types of problems that countries are facing. In the months and years ahead, it will be important to keep building the database so that a clearer and more accurate picture can emerge and problems are adequately addressed. Analysis of the data so far paints the following picture.

A large variety of fuel types and fuel assembly geometries are in use in research and test reactors. Consequently, special storage conditions are often necessary, as well as different types of transport casks and different techniques for dealing with failed fuel.

Most research reactor fuels are shipped in assembly form. For this reason, in RRSFDB, spent fuel numbers are recorded in assemblies, where a fuel assembly is defined as "the smallest fuel unit that can be moved during normal reactor operation or storage". At any particular facility, several different spent fuel types or spent fuels of different enrichments are usually stored. For example, the store may contain one or more types of HEU from before core conversion and one or more types of LEU following conversion.

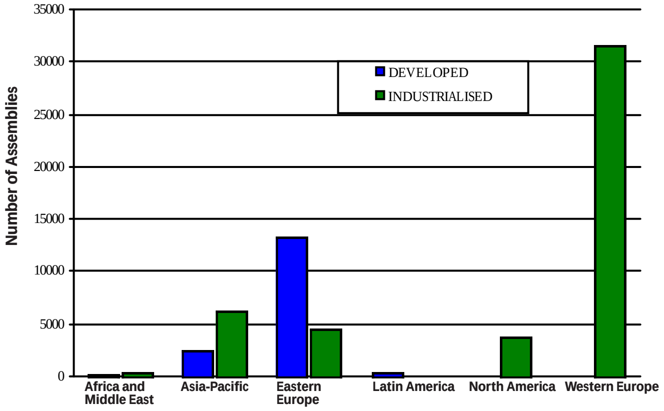
Overall, there are 62,870 spent fuel assemblies stored in the facilities that have responded to the RRSFDB questionnaires to date and another 32,932 assemblies in the standard cores. Of these 62,870 assemblies, 46,394 are in industrialized countries and 16,476 are in developing countries, while 22,686 are HEU and 40,184 are LEU.

The distribution of fuel types among the reactors in the RRSFDB shows that a significant percentage (28%) are classified as "other" types. This underlines the fact that many experimental and exotic fuels exist at research reactors around the world, posing problems for their continued storage, transportation, and ultimate disposal.

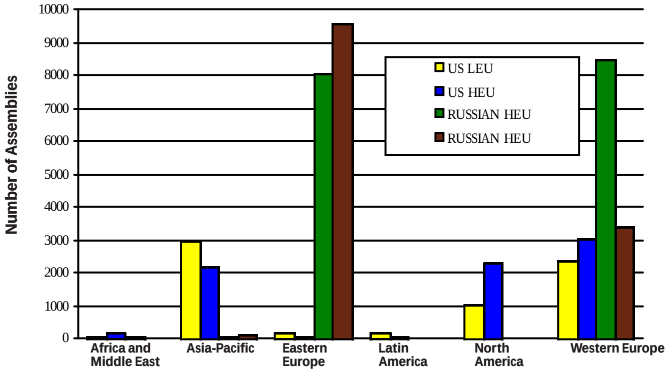
By region, the majority of spent fuel assemblies are stored in industrialized countries. *(See graph page 30.)* In examining the origins of the enrichment of spent fuel in the RRSFDB, the data shows, as expected, that the US supplied all of the enriched fuel in North America and most of that in Asia-Pacific, while Russia (or the former Soviet Union) supplied most of the enriched fuel in Eastern Europe.

Fuel of US and Russian origin fuel involves totals of 7756 HEU and 6775 LEU assemblies of US-origin and 13,035 HEU and 16,620 LEU assemblies of Russian-origin. Of interest is the fact that HEU outweighs LEU in North America, whereas the reverse is true in Western Europe. *(See graph page 30.)* To some extent this is because more research reactors in Western Europe have undergone core conversion than is the case in North America. It is worth noting that a significant fraction of Russian-origin HEU was originally enriched to only 36%, while most US-ori-

DISTRIBUTION OF RESEARCH REACTOR SPENT FUEL AMONG DEVELOPING AND INDUSTRIALIZED COUNTRIES



GEOGRAPHICAL DISTRIBUTION OF US- AND RUSSIAN-ORIGIN URANIUM FUEL BY ENRICHMENT



gin HEU was originally enriched to 90% or more.

The numbers of US-origin and Russian-origin HEU and LEU spent fuel assemblies at foreign research reactors which might be involved in take-back programmes also were compared. At present 15,531 spent fuel assemblies of US-origin are located at foreign research reactors, while the equivalent number of Russian-origin is 29,673.

As previously noted, the RRSFDB involves only a limited number of the known research reactors in the world; nevertheless these data give an idea of the scope of the problem represented by research reactor fuels. On the basis of these data and a rough knowledge of the numbers of assemblies used each year, projections indicate a rising trend over the next eight years.

Storage Methods. By far the most commonly used form of spent fuel storage is the at-reactor pool, pond or basin. Since the average age of these facilities in the RRSFDB is 25 years, the success of wet storage where the water chemistry has been well controlled is remarkable. In fact, many aluminium clad Material Test Reactor fuels and aluminium pool liners show few, if any, signs of either localized or general corrosion after more than 30 years of exposure to research reactor water. In contrast, when water quality was allowed to degrade aluminum clad, fuel is seriously corroded.

Data also show that many facilities also have an auxiliary away-from-reactor pool or dry well. At away-from-reactor facilities, the trend is to transfer fuel from wet storage to dry storage, which avoids some of the expense of water treatment facilities and their maintenance.

Clearly, dry storage requires less monitoring and maintenance than wet storage and at most dry storage facilities the operators monitor the activity continuously. Several, however, are recognizing the importance of assessing the moisture content of dry storage facilities.

The IAEA survey also addressed the concerns expressed by reactor operators about their spent fuel management programmes. Not surprisingly, the majority are concerned about the final disposal of their fuel. This is followed by concerns about limited storage capacity, and materials degradation. Surprisingly, finance is of lesser concern now than in previous responses to the IAEA questionnaire. Presumably, this is due, at least in part, to the US “take-back” programme, which is paying for the disposal of spent research reactor fuel from the lower income countries possessing fuel of US origin.

FINDING SOLUTIONS

The global picture that has emerged from the IAEA’s analysis of spent fuel management at research reactors underscores the need for greater international cooperation to resolve outstanding problems and issues. This includes broadening the aware-

SUPPORTING NEEDS

Through various avenues, the IAEA is supporting national and global efforts related to spent fuel management at research and test reactors. Besides compiling and maintaining databases on research reactors and their associated spent fuel management programmes, the Agency has actively supported the USA's programme called Reduced Enrichment at Research and Test Reactors (RERTR), which addresses nuclear non-proliferation goals.

It further has been involved, as an observer, in most meetings of the "ad hoc" group of research reactor operators, known as the Edlow Group, which successfully sought to return US-origin spent fuel from foreign research reactors. Towards this end, the IAEA Director General, in July 1993, wrote to the Secretary of the US Department of Energy and, in February 1995, to the Minister of Atomic Energy of the Russian Federation, suggesting that these major partners in RERTR could facilitate the non-proliferation goal of RERTR by taking back foreign research reactor fuel. To aid the US take-back programme, especially for developing Member States, the Agency has organized activities to help its Member States prepare their spent fuel for shipment back to its country of origin. Major activities have included a training course held at Argonne National Laboratory, USA, from 13-24 January 1997 and the preparation of draft technical guidance, *Guidelines Document on Technical and Administrative Preparations Required for Shipment of Research Reactor Spent Fuel to its Country of Origin.*

Other recent activities have involved national and international experts in the preparation of a Safety Guide, *Design, Operation and Safety Analysis Report for Spent Fuel Storage Facilities at Research Reactors*, which has been submitted for publication. During 1997 the IAEA further convened a Technical Committee Meeting to collect and evaluate information on procedures and techniques for the management of failed fuels from research reactors and an Advisory Group Meeting on the Management and Storage of Experimental and Exotic Spent Fuels from Research and Test Reactors. Also, the Agency offers advice through IFMAP, the Irradiated Fuel Management Advisory Programme, to operators of spent fuel storage facilities and more tangible assistance to developing Member States through the IAEA's Technical Assistance and Co-operation programmes.

Recognizing that the degradation of materials, equipment, and facilities through ageing is becoming of more concern to many operators, the Agency has organized several activities in the materials' science field. Prominent among these was the preparation of a document on the durability of nuclear fuels and components in wet storage, which is being published by the Agency. This document contains information on aluminium clad fuels used in research reactors developed as part of a Coordinated Research Project (CRP) on Irradiation Enhanced Degradation of Materials in Spent Fuel Storage Facilities. Another CRP is devoted specifically to research reactor fuel cladding and focuses on the monitoring and control of corrosion in wet storage. These programmes are supplemented by a series of regional workshops that have been organized to deal with all aspects of spent fuel handling, management, storage and preparation for shipment.

ness of the scope and urgency of concerns.

It is also clear that take-back programmes of foreign research reactor fuels, if and when they are implemented, will not continue indefinitely. At some stage in the not too distant future (in 2006 for foreign research reactors with US-origin fuel), research reactor operators will be faced with having to find their own solutions regarding the permanent disposal of their spent fuel. For countries with no nuclear power programme, the construction of geological repositories for the relatively small amounts of spent fuel from one or two research reactors is obviously not practicable. For such countries, access to a regional interim storage facility and eventually a regional or international repository for research reactor fuel would be an ideal solution. The time is ripe for serious discussion of regional or international solutions and to begin planning for the day when neither take-back programmes nor the reprocessing option might be available. ❐

TECHNOLOGY TRANSFER &
THE MANAGEMENT OF RADIOACTIVE WASTE

BY ARNOLD BONNE AND CANDACE CHAN-SANDS

One of the IAEA's fundamental roles is to act as a centre for the transfer of nuclear technologies, including those for managing radioactive wastes. In the area of waste management technology, the Agency is actively working to improve and develop new and efficient means to fulfill that responsibility. The work takes into consideration that:

- Almost eighty percent of the IAEA's 127 Member States do not have nuclear power programmes and use radionuclides principally for research, medical, industrial, and agricultural applications, for example, whereby the type of assistance they need varies.
- Radioactive wastes arise in different types and forms, and over the past decades, the technologies to effectively manage them have been developed and put into practice in many countries. The challenge is identifying the best ways and means to transfer demonstrated technologies, and associated experience, to all countries, especially developing IAEA Member States.
- Global technology trends and changing economic and political conditions are affecting nuclear energy's development. These include an expanding international framework for nuclear safety norms and standards; greater awareness of environmental implications; and the move towards deregulation and privatization of certain sectors, including energy and the management of radioactive waste. The developments require at the international level the establishment of more direct links with regional and local organizations, the use of modern information technologies for exchanging technical know-how and experience, and the transfer of practical tools and assistance for supporting management strategies and decisions.

Recognizing the above responsibilities and challenges, IAEA efforts related to radioactive waste management technologies into the next century are framed around three major areas: the development and implementation of mechanisms for better technology transfer and information exchange; the promotion of sustainable and safer processes and procedures; and the provision of peer reviews and direct technical assistance that help facilitate bilateral and multinational efforts.

To illustrate some specific elements of the overall programme, this article reviews selected technology-transfer activities that have been initiated in the field. Outside its scope are matters related to safety standards and conventions, aspects which are addressed through other Agency programmes.

TRANSFERRING EXPERIENCE & TOOLS

Over the coming decade, the IAEA will be working to further improve its support to developing countries that need to upgrade their technological capabilities for managing radioactive waste. Additional emphasis also is being placed on the efficient exchange of technical information and experience. To facilitate technology transfer, a number of waste management technology "packages" have been prepared. These components are specifically designed to also support the Agency's efforts under its Model Project called Sustainable Technologies for Managing Radioactive Waste. The packages include:

Spent Radiation Sources Registry. This computerized registry assists countries in keeping accurate records and tracking all their sealed radioactive sources *from the cradle to the grave*. It is one of the integral elements in the

---

Mr. Bonne is Acting Director of the IAEA Division of Nuclear Fuel Cycle and Waste Technology and Head of the Waste Technology Section. Ms. Chan-Sands is a staff member in the Section.

Agency's spent sources programme that aims to assist Member States to control and record all sealed radiation sources. This computerized tool is provided to Member States on request free of charge and includes training on its use and administration. To date, more than 50 requests have been received, more than 40 countries have the registry, and more than 35 administrators have been trained in the use of and administration of the system.

Reference Designs for the Spent Sealed Sources Facility and Waste Processing and Storage Facility. These reference packages feature model conceptual designs of the respective facilities with proven and verified technologies and processes that can be easily adapted to meet specific waste management needs of a country. They also provide the IAEA with an effective and economically feasible way to assist countries with similar waste management needs.

Conditioning of Spent Radium Sources. This project aims to help countries solve problems involving old radium sources. *(See box.)* It includes technical documents, expert advice, and, upon request, on-site expert support for conditioning the radium sources.

Demonstration of Pre-disposal Waste Management Methods and Procedures. This project focuses on practical hands-on training using actual radioactive waste in an environment similar to that existing in the trainees' home countries. In combination with other IAEA training approaches, the project helps ensure that countries have trained staff (scientists and technicians) who know how to collect, segregate, treat, condition, and store radioactive waste from nuclear applications, using methods and technologies existing in their countries. Even the most simple mechanical or chemical operations may become complicated and requier special attention when radioactive material is processed — and industrial, environmental, and radiation protection requirements must be met. The training demonstrations are organized in co-operation with Member States offering suitable waste processing facilities. Such facilities are being selected in all regions. To date, demonstrations have been held at the Çekmece Nuclear Research and Training Center in Istanbul, Turkey for participants from the European and West Asian region and at the Lo Aguirre Nuclear Research Center in Santiago, Chile for participants from Latin American countries. Agreement recently was reached with the Ministry of Atomic Energy of the Russian Federation for demonstrations in Moscow for Newly Independent States and other countries in Eastern Europe. In the East Asia and Pacific region, the IAEA is undertaking a review of the technical suitability of some waste management facilities there.

In support of these and other activities, the IAEA is developing modern information systems and tools for exchanging technical data and reference materials. These include the Waste Management Database, which provides technical information on waste management programmes and activities in IAEA Member States, and computerized summaries of research-in-progress abstracts, including activities related to the decommissioning of nuclear facilities and environmental restoration. These services, provided through the International Research Abstracts Information System, now are available in different computer media, including

Photo: IAEA regional training demonstrations for radioactive waste management have been held in Turkey for scientists and technicians from a number of countries.

INTERNATIONAL RESEARCH ABSTRACTS INFORMATION SYSTEM

Scientists and researchers worldwide now can access valuable reference materials on radioactive waste management over the Internet. The International Research Abstracts Information System (IRAIS) — the Agency's first Internet-based application — is a three-in-one system that allows researchers to search and retrieve published research abstracts, and the Agency to automate the validation and publication of waste management research abstracts. It is expected to reduce the cost, time, and manual effort involved in producing *Waste Management Research Abstracts,* a publication of the IAEA. The Internet address is http:www.iaea.org/programmes/irais.

over the Internet. *(See box.)* By the end of 1998, parts of the SRS Registry system also will be available on line.

TARGETING & COORDINATING ASSISTANCE

In many cases, countries are seeking assistance in specific areas of waste management, the advice of international experts in the field, or support for cooperative projects. One channel they have used is the Waste Management Assessment and Technical Review Programme (WATRP), which is designed for countries having developed nuclear programmes. Under the programme, the Agency coordinates peer reviews by international expert teams on proposed or ongoing radioactive waste management programmes; planning, operation or decommissioning of facilities; or organizational and regulatory matters, such as safety assessments. WATRP reviews – which have also assisted national efforts to improve public confidence of programmes – remains an important component of the IAEA's waste management programme.

Other types of technical support are being directed at emerging needs in Central and Eastern Europe, among other regions. In the Newly Independent States of the Former Soviet Union and in some East European Countries, for example, spent sealed radiation sources, of various types and characteristics, once used in industry and research were stored/disposed of mainly in boreholes in near-surface disposal facilities. With the political changes in these countries and the establishment of new regulatory authorities, national legislation and standards for nuclear, radiation and waste safety are being revised or developed. Continued IAEA technical support to these countries in a number of areas is expected over the near term.

At the request of Member States, the Agency also is facilitating bilateral and multinational efforts to address specific problems. In the Russian Federation, for example, one of most complicated ecological problems is the management of radioactive waste accumulated as a result of past activities in production of nuclear weapons, use of nuclear energy for peaceful purposes, and as a consequence of the reductions in the nuclear arsenals. Efforts have been undertaken by Member States to address these problems and the need was identified for setting up a contact group of experts to assist in coordinating their efforts. A Contact Expert Group (CEG) was established in September 1995 by interested countries with the aim to avoid redundancy and duplication, assure that priorities are properly assessed and made known to international community, and provide points of contacts to facilitate co-operation. The Agency was asked to perform the CEG Secretariat's duties. The CEG includes experts from twelve countries and organizations — Belgium, France, Finland, Germany, Norway, Russian Federation, Sweden, UK, USA, the European Union, the International Institute for Applied Systems Analysis, and the International Science and Technology Center — as well as two observers from Japan and the Nordic Environmental Finance Corporation.

MANAGING RADIUM

The Agency is providing on-site assistance to countries that have stopped using radium sources.

For much of this century, radium sources were widely used in medical and industrial applications all over the world. Because of radium's unfavorable characteristics, almost all countries now have stopped using the sources. About 30,000 spent radium sources now need to be safely stored and managed —many of them in the developing world. Radium's long half-life means that the sources eventually need to be disposed of in deep geological repositories, which are not available yet. For many years, the IAEA has been giving advice to countries on how radium sources can be conditioned for safe storage, pending their final disposal. But many countries do not have the technical infrastructure needed to ensure that the conditioning operation can be done properly and with the necessary quality assurance.

To address problems, the IAEA is providing hands-on assistance to developing countries that have stopped using radium sources. The approach involves the collection, treatment, and conditioning of all identified spent radium sources in a country by expert teams in a single campaign. The programme began in 1996 in the Latin American region, where four national campaigns now have been completed in Uruguay, Nicaragua, Guatemala, and Chile. One campaign in the Europe and East Asia region was successfully completed in Croatia in 1997. For the near future, the Agency will use a similar approach to establish expert teams in the African and Asian regions.

The Group recently targeted the country's North-West region as a top priority for global cooperative projects. The region has one of the highest concentrations in the world of nuclear reactors, spent fuel, and radioactive waste, and experts informed the IAEA in December 1997 of major problems being faced, including the availability of funds, in efforts to improve the situation. The Group has reported that radioactive waste accumulated in the Russian Federation by 1995 amounted to more than half a billion cubic meters with an activity of about two billion curies. In addition around 8500 tonnes of spent nuclear fuel with an activity of around four billion curies has been stored. Of 120 nuclear submarines taken out of operation, the spent nuclear fuel has been unloaded from only 42. In 1997, a total of about 150 nuclear submarines were listed as out of operation. In reaching its findings, the CEG reviewed reports by the Russian Federation ministries, institutes and organizations and the results of a number of specialized studies sponsored by CEG members.

Since its inception, the CEG has:

- established a database of cooperative projects containing detailed information on some 160 projects that have been suggested, negotiated or started under 19 major topics by countries and international organizations participating in the CEG;
- discussed in detail the waste management situation in the most pressing fields and regions and elaborated conclusions and recommendations;
- prioritized, with the Russian Federation ministries involved, the most important projects, to help concentrate efforts and financing.

Another initiative involves cooperation with the Paldiski International Expert Reference Group (PIERG). It was established in 1994 to support the negotiations between the Republic of Estonia and the Russian Federation on the transfer, to the Estonian Authorities, of the former Soviet Nuclear Training Center where two nuclear submarine reactors and all auxiliary operating facilities were located near the city of Paldiski. After the successful transfer of the site in September 1995, the PIERG work has concentrated on how to safely decommission the facility and, through its members, finance the implementation of individual tasks within the decommissioning process.

The IAEA presence in PIERG has ensured that the advice provided has been in line with IAEA recommendations and internationally accepted practice. During the past four years the safety situation has improved; the spent fuel has been returned to Russia; a strategic plan for decommissioning the facility has been established; the radiological characterization of the site has been completed; a new interim store for conditioned waste has been completed; and, most of the stored liquid and solid waste has been conditioned. Among the most important improvements overall have been the enhanced competence of the staff, both on the operator and regulatory side, involved in the decommissioning work and the initiation of steps to establish a new safety culture within the operating organization.

MOVING AHEAD

In addition to IAEA-supported activities outlined in this article, the Agency's programme in radioactive waste management technologies places considerable emphasis on the promotion of safer procedures and processes. This includes reenforcing the target of "minimum acceptable requirements" that the IAEA developed as a reference baseline for a set of conditions that must be satisfied to provide an acceptable minimum level of safety in dealing with radioactive waste. Also covered are aspects of quality control and management, which is becoming a more vital component particularly for disposal operations. In many countries, the confirmation of a quality management programme is required before waste management processes and facilities are licensed, as well as during operations.

Another initiative promotes the development and availability in IAEA Member States of "most appropriate technologies" that take into account economic, safety and environmental factors; the IAEA is preparing a report on this subject. Also drawing greater interest from Member States are the validation and qualification of waste management technologies.

Experience has shown that the use of the atom must be linked with the safe management of radioactive waste from all of its many uses. This imperative invariably involves taking steps to ensure that countries have the required knowledge and technological tools.

A key aspect of the IAEA programme is directed to creating an awareness among Member States of their responsibility to plan, develop, and implement effective national waste management programmes. The dynamic process entails a continuous evaluation of the needs of Member States to ensure that Agency resources are allocated and balanced to achieve the maximum benefits and results. As important, it involves ongoing assessments of new ways and means – from technology packages to technical support – that will be of practical assistance to countries, or that help them pool their resources and expertise for regional or global initiatives for effective waste management. ❑

Photo: One type of facility for low-level radioactive waste disposal in France. (Credit: ANDRA)

ACHIEVING MORE WITH LESS

TECHNICAL GUIDANCE FOR MINIMIZING RADIOACTIVE WASTES

BY RUDOLF BURCL, MICHELE LARAIA, AND ARNOLD BONNE

At a time when environmental and financial issues greatly affect industrial operations, the efficient operation of nuclear facilities and the management of associated wastes have taken on added importance. One key issue that has emerged in the decision-making process focuses on ways to minimize radioactive wastes, in the interests of holding costs down. Yet focusing on cost considerations alone can oversimplify the issue, and could entail other drawbacks, especially in the field of radioactive waste management where many factors are involved and the timing of decisions is important.

In its technical documents, the IAEA defines waste minimization as "a concept which embodies the reduction of waste with regard to its quantity and activity to a level as low as reasonably achievable". However, this definition does not describe the complexity of waste minimization, which is an integral part of a wider and comprehensive waste management and safety culture that aims at efficiently reducing radiological and environmental impacts of generated wastes.

An improper waste minimization strategy could be "a coin with two faces" – it may offer financial savings, but it also can introduce new hazards or modify those already associated with the facility. In each approach to waste minimization, the cost gain must always be compared with other factors, especially those related to the safety of operators and the general public.

This article presents an overview of major technical aspects involved in efforts to minimize wastes, and it points out considerations that should be taken into account in the decision-making process. The main focus is on the operation and decommissioning of nuclear power plants, since these activities are major sources of radioactive waste and are expected to have the greatest potential to achieve success in waste minimization policy and techniques. The relevant waste minimization approaches could also be applied by other waste producers.

ASSESSING THE PICTURE

Waste minimization encompasses organizational, technological, and economical aspects. Each project should therefore be carefully assessed considering individual conditions and circumstances. The type of assessment that needs to be made, the level of detail to which the assessment is taken, and the thoroughness of reviews by internal bodies and/or regulatory authorities should be related to the significance of the changes involved. Of course, some types of waste are clearly more problematical than others and their generation should be avoided at any cost. One typical example is radioactive wastes which are simultaneously chemically toxic, often identified as mixed waste.

The real benefit from waste minimization projects is proportional to their complexity and scope. The highest effectiveness can be expected from national or company projects covering one or more nuclear facilities and/or from the systematic implementation of improvements in radionuclide applications.

The following components are usually considered in the planning and implementation of complex, more significant waste minimization projects: waste minimization strategy; reduction of waste sources; and minimization of waste volumes for storage or disposal.

Mr. Burcl and Mr. Laraia are staff members in the IAEA Department of Nuclear Energy's Division of Nuclear Fuel Cycle and Waste Technology. Mr. Bonne is the Acting Director of the Division and Head of the Waste Technology Section.

Waste minimization strategy. A strong requirement for waste minimization arises from the generally accepted principal objective of radioactive waste management: "...to deal with radioactive waste in a manner that protects human health and the environment now and in the future without imposing undue burdens on future generations" (*The Principles of Radioactive Waste Management,* IAEA Safety Series No.111/F, 1995). This rule is properly reflected in most of the relevant IAEA documents and also in basic regulatory and legislative documents in IAEA Member States.

A waste minimization strategy should be established to serve as a conceptual basis for co-ordinated planning and implementation of desired measures. The following topics, among others, may be covered:

Administrative considerations. These include the legislative basis for waste management and waste minimization, including proper and sound waste clearance and discharge policies; identification of responsibilities and commercial arrangements between utilities and waste managers; economic assumptions (economic support, tax rates, discount rates); the quality assurance system; and qualification and training of staff.

Technical and safety considerations. These include the power plant capacity and performance, reactor type, location; design principles of the nuclear facility and individual components; the expected operational lifetime of facilities; the waste conditioning strategy (national and also facility-specific); and the waste disposal strategy, scale, type and location of storage and disposal facilities.

Reduction of waste sources. The most straightforward method for lowering waste processing and disposal costs is to reduce the generation of wastes in terms of volume and activity at the source. The most proactive way is to consider the means of waste minimization during the definition of design and construction specifications of new facilities. Reviewing and changing existing practices at operating facilities also can significantly reduce the waste generation. A significant reduction of waste can be gained by considering potential decommissioning procedures as early as during the design stage as part of steps to properly plan the decommissioning operation.

Considering waste minimization requirements in the design and construction phase of nuclear facilities may have a direct impact on future waste production during both operational and decommissioning periods. The main design-related technical options are:

- the proper choice of materials (resistance to corrosion, high-quality surface treatments, low tendency to activate and/or produce radionuclides that may cause problems);
- application of the most effective, reliable and up-to-date technology to assure that equipment will remain operable as long as possible without replacement and/or maintenance;
- high performance of components and prevention of unintended accumulation of waste, and minimization of leakage/drainage to avoid repairing active components and producing additional waste; and
- strong separation of active and non-active media and segregation of active media according to their nature and activity.

Decommissioning of nuclear facilities is a source of extremely large volumes of radioactive waste, most of them classified as low- or intermediate-level waste. Moreover, a large part of them belong to the category called "very low-level waste". The volume contribution of intermediate- and high-level waste is comparatively small, roughly below 5%. The generation of decommissioning wastes can be significantly reduced through the application of proper decontamination techniques; the rigorous segregation and separation of the waste flow streams; the recycle and reuse of selected metals and construction materials; and the establishment and implementation of proper clearance and discharge policies.

At nuclear power plants, the coordinated efforts of operators over the last 10 years have enabled large reductions – by a factor of four to five when measured by volume and by a factor of ten when measured by total activity – in the production of operational wastes. The largest potential benefit from waste reduction efforts can be expected in the decommissioning phase. The main reason is that about 75% of waste from dismantling could be categorized as very low-level waste, which would have a high potential for clearance from regulatory control.

Typical practical steps that can contribute to the reduction

of operational radioactive waste generation are to:

- limit the number and size of the controlled areas and identify all points in the working areas and all stages in the process where it is possible to prevent material from becoming radioactive waste;
- establish waste accounting and tracking systems to quantify sources, types, amounts, activities and characteristics of waste;
- apply recent technological processes (good operational practice) and modify maintenance and refurbishment procedures leading to waste reduction;
- reuse recovered materials (e.g. boric acid, special metals, fission material) to reduce waste generation and decrease operational costs;
- recycle and reuse liquids within the process (such as decontamination solutions and laundry water) to reduce the volume and potential environmental impact of discharged liquids;
- establish a system of sorting waste and separating waste streams to prevent improper mixing and to assure more efficient characterization and subsequent processing;
- establish a rigorous system for segregation of non-active and active contaminated waste in the controlled area; and
- increase the flow of information among staff regarding waste reduction philosophies, techniques and improved methods, and emphasize the training of staff in waste reduction practices.

These procedures are oriented mostly to the reduction of waste generation by operators of large nuclear facilities. Nevertheless they are fully applicable as well to small users of radionuclides.

Minimization of waste volumes for storage or disposal. Storage and disposal costs are often the main, though not the single reason, for operators to reduce the volume of generated wastes. In the face of public and political opposition to construction of facilities, for environmental or other reasons, the effort to maximize the use of space in existing storage and disposal facilities has taken on added importance for waste management organizations.

Various treatment and conditioning techniques enable substantial reduction in the final volume of conditioned waste.

One technique is to store waste materials for sufficient time periods over which their radioactivity levels decay. It is commonly used for reduction

---

Photo: The reactor vessel head of a prototype reactor in Germany was cut during dismantling operations. Proper planning of reactor decommissioning can lead to a large reduction in wastes.

of waste from short-lived radioisotope applications, and to a certain extent for waste from nuclear facilities in operation or being decommissioned. This approach could simplify and increase the effectiveness of subsequent waste treatment and/or conditioning processes, or lead to the waste's clearance from regulatory control. Reduction of radioactive waste volumes by natural decay is one important factor leading to the selection of a deferred dismantling strategy for decommissioned nuclear facilities.

Another technique is to recycle and reuse metals, as well as some types of civil construction materials (concrete), arising from the refurbishment and decommissioning of nuclear facilities. The main economic benefit arises from savings achieved in avoided disposal costs, rather than through the material's reuse or recycling directly. The same reasoning applies to the melting of metal scrap, through which significant reductions in waste volumes are achieved.

For certain types of wastes, advanced methods of processing can be applied to reduce waste volume and to meet regulatory requirements for its storage and/or disposal.

For large volumes of highly diluted aqueous waste containing radiochemical and chemical contaminants, advanced membrane and micro-filtering processes are being developed. At the Los Alamos National Laboratory in the United States, for example, a new integrated membrane filtration system was developed to treat about six to ten million litres of liquid radioactive waste. The titanium-dioxide microfiltration system yields a higher concentration factor over the previous treatment method, reduces chemical usage, and provides high-quality effluent water for discharge.

Membrane methods also can be applied for the treatment of complex waste containing various proportions of organic components. They can serve as an efficient alternative method to more complicated high-temperature, catalytic and biodegradation methods used for the decomposition of organic compounds.

Other methods build upon the use of incineration and supercompaction, which are most widely applied to reduce the volume of solid radioactive wastes, offering reduction factors of more than ten. Through the combined incineration of solid waste and many types of low-level organic wastes, some specific problems can be resolved. For example, used oil and ion exchange resins can be transformed into stable, homogenous mineral forms suitable for final conditioning and disposal.

TIMELY GUIDANCE

Throughout nuclear energy's development, technologies and methods have been developed for the effective management of radioactive wastes, including their minimization. Recent years have seen further advances in processing techniques and practices designed to save costs and meet regulatory requirements that are becoming stricter for environmental and other reasons.

As part of its work in the field, the IAEA has issued a number of technical reports on various aspects of radioactive waste management, including minimization strategies and practices.* To achieve real benefits from strategies to minimize radioactive wastes, a full evaluation of all available options is needed from environmental, economic, and technical perspectives.

Over the coming years, the cooperative exchange of technical experience will have to remain an important element of radioactive waste management programmes, as more nuclear facilities become candidates for decommissioning and new technologies are developed for processing different types of waste streams. ❒

---

*These reports include *Factors Relevant to the Recycling or Reuse of Components Arising from the Decommissioning and Refurbishment of Nuclear Facilities* (TRS-293); *Planning and Management for the Decommissioning of Research Reactors and other Small Nuclear Facilities* (TRS-351); *Status and Technology for Volume Reduction and Treatment of Low- and Intermediate-Level Solid Radioactive Waste* (TRS-360); *Assessment and Comparison of Waste Management System Costs for Nuclear and Other Energy Sources* (TRS-366); *Minimization of Radioactive Waste from Nuclear Power Plants and the Back End of the Nuclear Fuel Cycle* (TRS-377); and *Characterization of Radioactive Waste Forms and Packages* (TRS-383).