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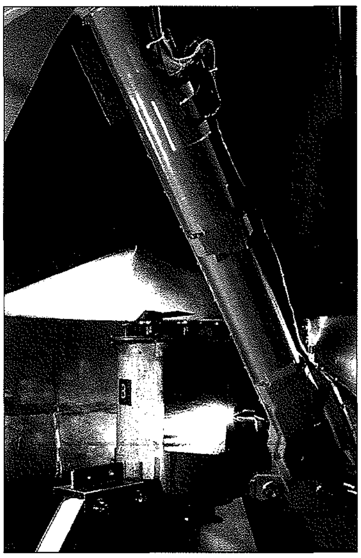
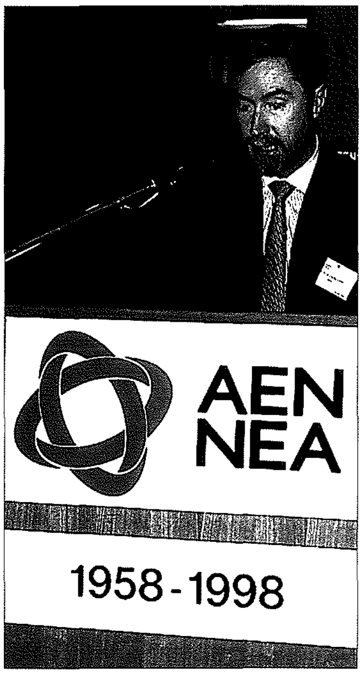
The OECD Nuclear Energy Agency (NEA) was established in 1958 as the OEEC European Nuclear Energy Agency and took its present designation in 1972 when its membership was extended to non-European countries. Its purpose is to further international co-operation related to the safety, environmental, economic, legal and scientific aspects of nuclear energy. It currently consists of 27 Member countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States. The European Commission takes part in the NEA's work and a co-operation agreement is in force with the International Atomic Energy Agency.

For more information about the NEA, see:

http://www.nea.fr

Facts and opinions





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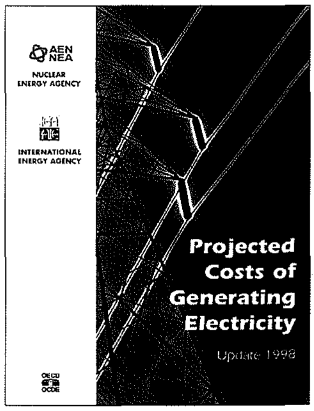

Cover photo: Control rods at the Chooz nuclear power plant, France. Credit: J-P. Salomon, Framatome, France.

The contribution of nuclear energy co-operation to a new global age

At the NEA's 40th anniversary special session in September, the Agency looked back at its genesis and growth, and ahead to its role in the third millennium. Now it seems right to intensify that gaze into the future, and to further map out the landscape on which the NEA's strategy will unfold in the years ahead, as its work will constantly interact with changing global trends that go beyond the issue of nuclear power itself.

Nuclear energy in today's world

Globalisation is one crucial trend which needs to be considered. Greater global economic integration via trade, capital and technology flows is a fact of life. People are increasingly interdependent: they trade, they invest, and they are on-line internationally, and frontiers are becoming less visible as reality is being overtaken by a virtual world.

In the sphere of energy, a vital aspect of globalisation is the impact of environmental behaviour in one part of the globe on all the other parts. Ecological interdependency has become the clarion call, and is becoming louder.

Burning carbon fuel, whether in the form of natural gas, wood, oil or coal, means more than a fall of dust onto a neighbouring garden. It means that our communal ecosphere catches the sulphur and carbon emissions from the global bonfire. We all share the consequences. Conversely, we all share the responsibility of working towards non-carbon paths which will help ease the prime environmental anxiety of the international community, global warming. This, indeed, is the environmental area in which nuclear power has a role to play.

For this, a scientifically responsible approach must be taken. A full understanding of the interdependencies of complex ecosystems is still some distance off. The difficulty is that much of the knowledge required will only be gained as the natural environment continues to be transformed. So wisdom lies in adopting the "precautionary approach". This is neatly expressed in Principle 15 of the Rio Declaration on Environment and Development: "Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation".

A key step towards the reduction of greenhouse impact will be the internalisation of pollution costs, whether through carbon taxes, systems based on tradeable permits, or other methods. These are effectively charges for protection of the human and natural environment. Nuclear *power in many cases already makes financial and practical provision for the containment of its limited waste products. This will be a growing strength as clean-up pressures, with their associated costs, mount across all the energy industries. Prices and market mechanisms will need to be increasingly adjusted to reflect environmental costs, becoming an integral part of business calculations. Society must establish adequate prices for the use of goods held in common, and often thought in the past to be "free": water, atmosphere, air, land.*

There is a further powerful reason for the application of nuclear power as one of the contributors to dealing with the global warming problem. Emerging economies will produce more carbon pollution in the future than they do today, as they industrialise and use more energy, and may well find the cost burden of equipment to reduce pollutants from coal too great. The enormous potential for reducing pollution and improving global environmental protection lies at present mainly with the industrialised countries. A reduction of carbon emissions there would both be in their own enlightened self-interest and set an example for poorer countries, which ultimately must follow suit if global emissions are to be meaningfully controlled.

The global community must likewise be prepared for a surge in energy demand, and nuclear power along with other appropriate energy forms will have its part to play. One cause of the surge will be population growth. World population has doubled since 1950 from 2.5 billion to 5 billion. Experts estimate that this figure could increase up to 8.5 billion by 2025, and stabilise at between 10 and 12 billion by mid-century. Over the past 50 years world economic activity has more than quadrupled, not least in the two mega-nations of the east, India and China. By 2025 India may possess the world's largest population – even bigger than China's.

Sustainable energy is sometimes taken to mean only renewables such as solar, wind, hydro, biomass and wave energy, and the so-called fifth fuel, energy efficiency. In this incomplete definition, nuclear energy is discounted. However, nuclear fuel also meets a good number of the criteria of sustainability, since it consumes very little raw material that essentially serves no other purpose, and offers the potential for recycling and for utility over the very long term. Chauvinism about the different forms of sustainable energy is largely misplaced. The point is not to try to compare the different forms of sustainable energy as if this is a race with only one winner, for every form of sustainable energy has, alongside its strengths, certain drawbacks.

The OECD Nuclear Energy Agency

The role of the NEA will increasingly be to facilitate further international co-operation on bringing about strategies for the proper use of nuclear energy in a sustainable manner, notably in the framework sketched by the parties to the UN Convention on Climate Change at their recent meetings in Kyoto and Buenos Aires.

As a central repository of data, the NEA will have a key role in supporting its members' adjustment to the changing energy market place. It will be well placed to provide information *resources and act as a forum for benchmarking and the exchange of scientific, technical, regulatory, economic and legal experience, helping nuclear energy programmes of its members to come to grips with deregulated markets and to maintain their potential for the future. In particular, it will be available to support Member countries in working towards consolidating the competitiveness of nuclear energy vis-à-vis other sources of fuel. Nuclear energy is a typical long-term investment, as against the typically short-term economics of, for example, gas. Nevertheless, nuclear must deliver cost-effective energy as well as the added value of environmental benefit.*

The NEA's role will also have a research and development angle. In a time when funds flow less freely from the public purse, the NEA can facilitate the pooling of national resources to maintain the necessary nuclear R&D effort, by, for example, identifying national research centres capable of becoming the focus for international projects. Furthermore, the NEA will sharpen its focus as a unique clearing house where the research work of its members is brought together and shared and where consensus views on key technical and policy issues are reached. For example, the well-established Halden Reactor Project and the newer Rasplav Project will continue to carry out experiments and furnish data of prime importance to safety improvement.

A large number of nuclear power plants and associated nuclear fuel cycle facilities will continue to operate in NEA Member countries. Maintaining high standards of nuclear safety and enhancing the quality and effectiveness of nuclear regulation are two interrelated goals that the Nuclear Energy Agency will pursue as essential requirements for ensuring that nuclear energy can remain a sound option for inclusion in the energy supply mixes of OECD countries. Past NEA efforts in safety research and regulation have resulted in improved knowledge and understanding of plant behaviour, new procedures, better training, and changes in hardware and software, which have increased confidence in the safety of plant operation. Additional efforts will concentrate on maintaining performance and further improving it where possible, and addressing existing and future safety and regulatory issues.

As a focal point of expertise, the NEA will also be called to step up international co-operation on other emerging issues for the nuclear community, such as the extension of the lives of existing reactors and the safe decommissioning of nuclear plants at the end of their useful lives.

The radioactive waste issue, chiefly for high-level and long-lived wastes, remains primarily a problem of political and public acceptance, although further technical progress still needs to be pursued and demonstration of repositories is essential. The NEA's work on safety assessments for the long-term geological disposal of waste will be central to this effort. The objective will be to gain public and political confidence in the safety and feasibility of the disposal of high-level waste in deep geological repositories, and to win agreement beyond national borders on the technical aspects of key future policy decisions in this field. Here, as in all the other aspects of its work, the NEA will act as a conduit for accessible and digestible information to its members' many stakeholders, especially at the senior decision-taker level.

The task of achieving a better public and political understanding of nuclear energy may in the future be made easier by the onset of objective factors such as growing awareness of the contribution that nuclear power can make in dealing with global warming. At the same time, that task will surely be made more complex by the growth in communications channels and the number of voices wanting to be heard. The NEA will need to ensure that its message is heard. This will pose a challenge to the NEA's skills as a communicator in an era of revolution in communications, for which the Agency must have adequate resources.

In conclusion, as the third millennium unfolds, the NEA will direct its efforts towards certain very specific goals. It will strengthen its position as an international centre of excellence, within which its members can pool, preserve and develop the expertise necessary for their nuclear programmes. It will endeavour to keep alive the infrastructure - whether human, technical, scientific or know-how-based - that will be necessary for the nuclear energy option to play a full role in the decades to come, when there is higher pressure on energy demand. And on the question of safety, which is most fundamental to nuclear acceptability, the NEA will play a key role in conveying the true dimensions of nuclear risk to the public by highlighting agreement among international experts in this field. It will aim to be a trusted source of data, analyses and recommendations directed to the political community and others, enabling them to optimise the contribution of nuclear power to the realisation of the objectives set by the OECD for sustainable development. It will develop, within the international community, its role as a front-line player in co-operation on nuclear energy.

Luis Echávarri
Director-General

T. Lazo*

Radiation health sciences and radiation protection

Radiation protection is the science and practice of protecting the public, workers and the environment from the harmful effects of ionising radiation. One of the foundations of this science is the understanding and appropriate assessment of the biological risks associated with ionising radiation. Over the past years, biological sciences have advanced very rapidly, particularly in the studies of DNA, genetics and cancer.

Some five years ago, the NEA had pointed out in a Collective Opinion that scientific and technological developments in the near future could have a profound influence on the concepts and the practice of radiation protection. In particular, a number of lines of research in radiation health sciences, notably in molecular biology and epidemiology, had been identified which might result in modifications to the scientific basis of the System of Radiation Protection and to its practical application.

In 1996, the NEA Committee on Radiation Protection and Public Health (CRPPH) undertook a study to examine the potential impacts of these changes. Following 18 months of research it has published a report on the relationship between scientific knowledge on radiation health effects, including its uncertainties, and the application of the "precautionary principle" in regulatory radiation protection.[1] This article presents the most important points raised in this publication. In particular, in reviewing the field of radiation biology, the report has highlighted four areas of importance: dose-effect relationships, causality, genetic susceptibility, and combined effects.

Dose-effect relationships. For many years, but particularly over the past two, there has been much international discussion and debate regarding the shape of the dose-effect curve; that is, what is the risk of an adverse effect on health (a fatal cancer for example) from a given dose of ionising radiation. In particular, the question of whether there is a dose threshold below which there are no measurable effects has been hotly debated. The current doctrine is that there is no threshold, and that any dose carries a risk.

Causality. Although there are many causes of cancer, none leaves an identifiable "fingerprint". If such a fingerprint could be identified, the risks associated with exposure to various carcinogens, including ionising radiation, could be accurately calculated. This would greatly improve the epidemiologically based risk estimates which are currently used, and would have a great impact on questions such as the shape of the dose-effect relationship mentioned above.

Genetic susceptibility. It is known that, genetically, certain populations are more sensitive than others to various carcinogens. If this is the case for ionising radiation, how much more sensitive

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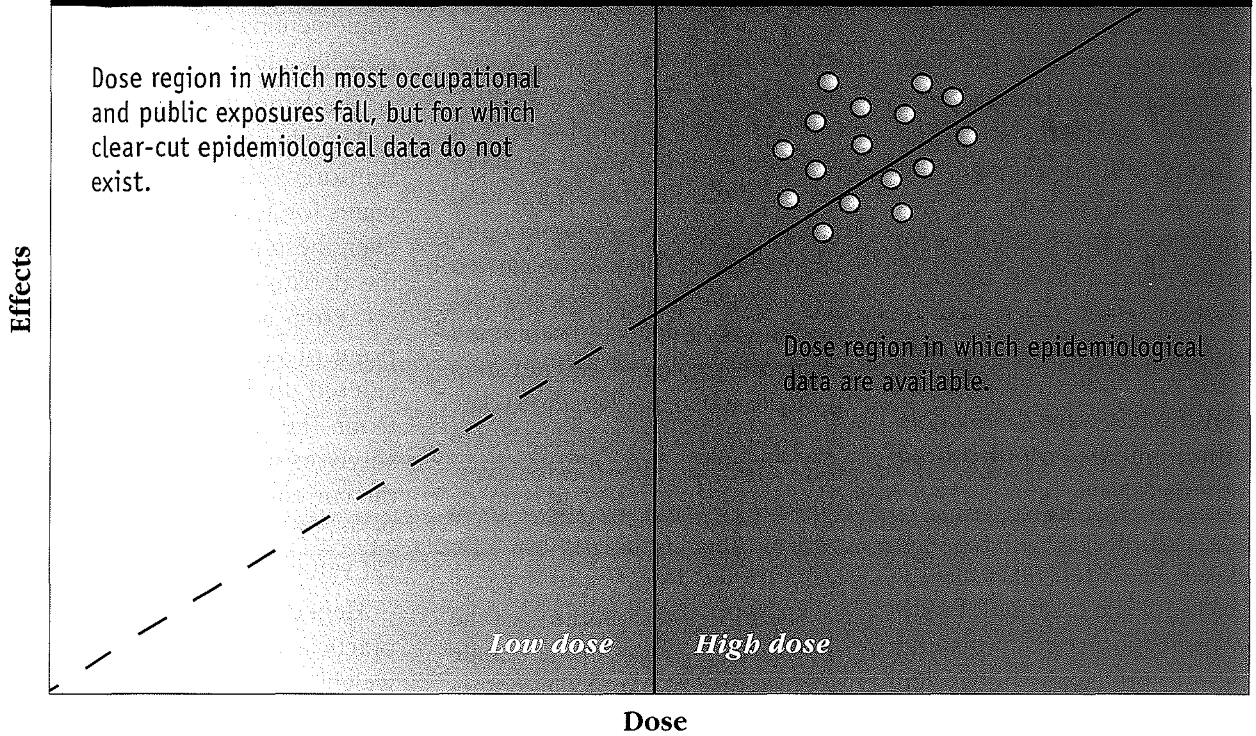
Figure 1: The linear no-threshold hypothesis



are such populations, how large are such populations, and what implications does this have in terms of protection if a genetic test for such sensitivity were to become easy, cheap and reliable?

Combined effects. Although the exact nature of interactions is not yet understood, it is known that when multiple carcinogenic agents act upon the same individual, the risks are more than simply additive, and can in some cases result in significantly enhanced risk (exposure to high levels of radon in a mine, and smoking for example).

Dose-effect relationships

The relationship between exposure to a specific dose of ionising radiation and the resulting risk of some deleterious effect, such as contracting a fatal cancer, is at the heart of radiation protection regulation and application. For this reason, discussions as to the nature of this relationship are very important.

Our current knowledge of the shape of the dose-effect relationship is mostly based on large populations of highly exposed individuals, but is also somewhat based on experience from animal and cellular experiments. For populations with very high exposures, such as those who survived the atomic bomb explosions at Hiroshima and Nagasaki, it is possible statistically to establish that excess cancers and leukaemias have occurred, and to correlate these with the doses received. This gives an estimate of the dose-effect relationship at these high doses.

However, cancer and leukaemia are very common diseases in modern society, and from one population to another there will be natural variation in the number of cancers and leukaemias found. Although many populations which have been exposed to low doses of ionising radiation have been studied, because ionising radiation is a relatively weak cause of these diseases, excesses have not been statistically identified. From animal and cellular experiments, however, it has been demonstrated that radiation does cause cellular damage, and that it can cause cancer in organisms.

The result of these various studies is that we know the shape of the dose-effect relationship at high doses, and, although the mechanisms are not understood, we know that radiation can cause cancer and leukaemia. Based on this knowledge, from the very early days of radiation protection it has been assumed, for protection purposes, that *any* exposure to radiation carries a risk. This is a conservative approach intended to err on the side of caution in the face of uncertainties. As such, the dose-effect relationship known for high doses has been extrapolated from these high doses to zero. Figure 1 shows this relationship.

A contentious point has always been the question of where exactly "zero" risk is. As mentioned above, it has been shown that any dose might cause cellular damage. Since the exact mechanism which transforms cellular damage into cancer is unknown, it has traditionally been assumed, again for protection purposes, that any dose could result in a cancer or leukaemia. Thus, "zero" risk only exists at "zero" dose. This assumed relationship has come to be know as the linear no-threshold hypothesis (LNT).

This simplified, theoretical approach has been quite useful as a basis for the creation of radiation protection regulations and practices to protect the public and workers from the harmful effects of radiation. However, there are several practical problems with this approach. First, natural background radiation exists, has always existed, and varies significantly depending upon location in the world. Epidemiological studies of a wide range of populations have not shown significantly different rates of cancer or leukaemia even when average exposures to natural background radiation have been significant. Various studies have been carried out to prove or disprove the LNT hypothesis, and it is not supported by all radiobiologists and radiation protection experts. Results to date are not conclusive in either direction. The LNT hypothesis nevertheless remains the underlying philosophical foundation of radiation protection.

Scientific questions are not the only driving factors in the debate over the use of the LNT hypothesis. There are also significant questions being raised from social, political and economic standpoints, for example public fear of radiation because there is risk associated with any dose no matter how small, the cost of implementing radiation protection policies, etc.

The latest data from the study of Hiroshima/Nagasaki survivors reinforces the present risk estimates for acute irradiation. However, these new data do not solve the debate on the LNT hypothesis. From a radiation protection point of view it should be considered unlikely that future data from the Hiroshima/Nagasaki survivors will significantly change the current basis of the Radiation Protection System or the numerical values of dose limits.

Hence, from a regulatory and practical viewpoint, based on the weight of current scientific knowledge and practical experience, and assuming that a cautious approach is appropriate in this context, the use of the LNT assumption and of the current

Monitoring for the presence of radioactive iodine in the thyroid gland. The instrument measures the gamma radiation given off by the iodine.

Radiation Protection System are justified where a unified approach must be applied.

However, this approach to limiting radiation risk need not be automatically applied by experts to estimate risk in specific circumstances, where a specified population or a particular individual can be identified, and where the nature of radiation exposure and the associated cancer risks are known and can be specifically assessed. In all cases, experts should use the best scientific information available concerning a given exposure situation. They may choose not to use the LNT assumption or other dosimetric concepts in their assessment, but rather to derive this assessment from a realistic use of the specific, scientifically well-founded information available for that particular situation. Examples of the use of such an approach are a) the application of a dose convention for occupational and non-occupational exposures to radon; b) the development of practices (criteria) for the release from regulatory control of contaminated sites for unrestricted use; and c) dose estimation for exposures related to the disposal of long-lived radioactive waste.

Causality

There are many different causes of cancer and leukaemia. Because of this, for some time there has been interest in being able to identify "the cause" of an individual case of a solid tumour cancer or leukaemia. Research is ongoing in many areas affecting this issue, however no such "biomarker" which will identify the cause of a particular cancer currently exists.

There are several reasons to be interested in such a biomarker. In the longer term, such a finger-print, particularly at low exposures, would be instrumental in establishing actual risks from such low dose exposures. If such biomarkers could be complemented by biological dosimeters, which would allow the measurement of individual, lifetime doses, such risks could be even more accurately calculated. The results of such studies could potentially have a great affect on the system of radiation protection, including public perception of radiation risks.

Even without such biological dosimeters, however, biomarkers would be useful to establish causality in individual cases of cancer. Such cases are currently resolved, in terms of liability and insurance questions, worker employability, and worker compensation, based on assessments of attributable risks (such as estimates of the probability of causation inferred from epidemiological data). Should the establishment of causality become possible, this would also have implications for national programmes in the areas of employment/employability, health insurance and worker compensation. The "perfect" biomarker, however, will most likely remain unattainable. The uncertainty of the origin of the radiation, from natural, occupational or medical sources, will probably always remain.

Genetic susceptibility

Research has shown that certain populations are genetically predisposed to be at higher risk of environmentally induced cancer than the average individual. As mentioned earlier, ionising radiation is a common environmental carcinogen, and individuals who have certain genetic diseases, such as ataxia telangectasia (AT), are in this category.

Radiosensitivity would appear to be a minor host factor in carcinogenesis if compared with diet and cigarette smoking, which account for approximately two-thirds of cancers. Age is also a major determinant of risk for almost all cancers. Although this varies considerably with cancer type, age is particularly important for lung, prostate and colon cancer; older individuals being more at risk than younger persons.

Currently, exposure limits for the general population and for workers are based on the "average" radiosensitivity of individuals in the exposed population. An exception to this is the use of supplementary equivalent-dose limits for pregnant workers because of the greater radiosensitivity of the developing embryo and foetus. However, if the radiosensitivity of certain populations is felt to be significant, these limits should perhaps be reviewed, and this will require careful consideration.

For the public, the significance of enhanced radiosensitivity within the general population is not clear. The alternative between reducing exposure limits for radiosensitive individuals or reducing exposure limits for the entire population to account for the most radiosensitive subgroups is a critical aspect of this issue. However, doubts may be raised about the net public health benefit of such changes. Current radiogenic cancer risk estimates may already reflect the responses of the most sensitive component of the population if it is correct, as is assumed, that the prevalence of genetic susceptibility in the major radio-epidemiological studies is similar to that in the general population.

For workers, it could be attractive to develop pre-employment genetic sensitivity tests. However, should such tests be based on voluntary acceptance or on employer sorting? It seems reasonable that information concerning individual worker radiosensitivity should be personal and confidential. Employees who have declared high radiosensitivities should be provided with additional information regarding job-specific strategies to reduce dose. Where possible, employers should provide optional job responsibilities entailing smaller radiation exposure possibilities. Such recommendations appear difficult to implement, particularly in companies where alternative job opportunities may not be available.

Given the great uncertainty which currently exists in genetic testing, such screening may not be advisable except for individuals with a pronounced familial history of cancer. In addition to uncertainty, there is a lack of clear association of mutations detected in a screening test with an increased risk of cancer. Either positive or negative test results may create a false sense of security. These types of questions raise significant ethical and social problems and, therefore, they should be treated out of the field of radiation protection by philosophers, sociologists, employers, trade unions and politicians who will have the final responsibility to decide and to control. Radiation protection scientists should, however, contribute as experts to the dialogue in this area.

In conclusion, genetic predisposition is likely to become an important issue in radiation protection, particularly in the case of workers, as it might impact national policy in the areas of employability, insurability and compensation. However, if science is able to give useful information in the future, the discussion of the use of such data should not be made only within the radiation protection field, but should be a broader responsibility of other segments of society.

Combined effects

Combined exposures are a basic consequence of living. A multitude of natural and man-made agents have the potential to interact with biological materials in ways leading to irreversible changes. In addition, it is well known from epidemiological and toxicological studies that interactions exist between different toxic agents at moderate to high dose levels. Some of these interactions lead to effects which are greater or lesser than what simple addition of the effects from exposure to single agents would predict.

As discussed, the radiation dose-effect relationship is at this point uncertain at low doses and low dose rates. The assessment of health effects from single chemical agents at low levels found in environmental and occupational settings is also prone to large uncertainties. For the combined effects, there is a scarcity of experimental and epidemiological data and, even more, of appropriate models to explain and predict combined effects of different noxious agents (radiation, chemicals, etc.).

With the exception of ultraviolet rays, asbestos and maybe radon daughters, the projected excess relative risk from environmental exposures for a specific endpoint, and even for the lifetime risk, are generally too low to be directly accessible by epidemiological studies. However, examples of more than additive interactions have been established with cigarette smoking. It has been shown that smokers exposed to either asbestos or radon daughters exhibit an increase in lung cancer mortality well beyond the level expected from the sum of the independent actions of either agents.

Theoretically, the most critical interactions are multi-step mechanisms. Changes in sensitivity, due to the influence of one agent, might thus allow a more pronounced effect due to a second agent, resulting in highly synergistic effects. However, other than the combination of exposure to radon and smoking, little experimental or human evidence exists of such dangerous combinations at the work place or in the environment. Epidemiology indicates, however, that indoor radon exposure and cigarette smoking warrant special consideration due to the large proportion of the world population exposed to high levels of both toxic agents. Sound results in this field could have significant implications in regulation and risk mitigation strategies.

Radiogenic risks should not be considered in isolation, particularly at exposures of interest to radiation protection. Risk profiles can be complicated, and individuals are exposed to many different types of detriments. Inferences of population-based risk estimates from epidemiological studies may not always be validly transferred across ethnic and cultural boundaries, and such transfers should be carefully considered.

Follow-up

The four areas above are important, in both the medium and long term, for the regulation and application of radiation protection. They will continue to be examined by the Committee on Radiation and Public Health, with a new report planned for the year 2000.

Note

1. Developments in Radiation Health Science and their Impact on Radiation Protection. *Available free of charge from the OECD Nuclear Energy Agency.*

E. Bertel, L. Van Den Durpel*

Innovative alternatives for the back-end of the nuclear fuel cycle

Extensive R&D activities are ongoing world-wide to investigate alternative back-end nuclear fuel cycle strategies with a view to helping nuclear power meet the objectives of sustainable development. These activities involve improvements to current fuel cycle options as well as new fuel cycle strategies using dedicated, optimised systems. Improvements in the fuel cycle include optimisation of reactor performance aimed at reducing fuel cycle costs while enhancing the safety and operating margins of such reactors.

Nuclear power is one of the carbon-free electricity generation options that can help to alleviate the risk of climate change, and contributes already to the lowering of carbon intensity in the energy sector. In this context, it is important to assess the technological and economic feasibility of alternative nuclear development paths as well as their sustainability. Optimisation of the nuclear fuel cycle is a key factor in this regard. A recent NEA workshop on "The Back-End of the Fuel Cycle in a 1 000 GWe Nuclear Scenario"[1] investigated alternative options for the back-end of the fuel cycle and assessed their capability to enhance the sustainability of nuclear power in the long term, to 2050 and beyond. It is the basis for this article.

Background

The emissions of greenhouse gases in the nuclear fuel cycle are amongst the lowest that have been identified for any means of producing electricity. Studies of the complete fuel cycle, including the indirect emissions of carbon dioxide and other relevant gases resulting from the construction and dismantling of nuclear facilities, show that when operated in accordance with appropriate national regulations that are consistent with international norms, the nuclear fuel cycle as a whole is relatively benign in its effect on the environment.

For example, nuclear power contributed to more than 1.5 billion metric tons of avoided carbon emissions in the USA during the period 1973-1994. If 75 per cent of US nuclear plants have their licences renewed, an additional 2.8 billion metric tons of carbon emissions would be avoided by 2035.

At the beginning of 1998, there were nearly 440 nuclear reactors in operation in 32 countries world-wide, with a total capacity of around 350 GWe.[2] In 1997, nuclear power plants accounted for 17 per cent of the electricity produced world-wide.

Nuclear power development over the next five to six decades will be affected by a number of factors specific to nuclear technology, as well as other factors that relate to the overall energy and electricity markets at the international, regional and national levels.

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Nuclear scenarios to 2050 and beyond have been developed by the Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA) in the context of a joint project on the potential role of nuclear power in sustainable energy strategies. One of them, the nuclear scenario leading to a 1 000 GWe nuclear park in 2050 assumes continued nuclear power growth in the context of energy strategies aiming at sustainable development. More specifically, it is consistent with the "ecologically driven" case described in the 1995 International Institute for Applied Systems Analysis/World Energy Council (IIASA/WEC) study on long-term demand and supply.[3] It assumes that energy policies would integrate explicitly environmental objectives. According to this scenario, in 2050, the world primary energy use would reach some 14 Gtoe involving some 23 000 TWh of electricity supply. Within this primary energy demand case, the continued growth nuclear scenario assumes that nuclear power programmes would grow in countries where nuclear units are already in operation including replacement of retired nuclear plants by new nuclear units, and would be launched in countries which currently are planning to implement nuclear units by 2010-2015.[4] Nuclear electricity generation in the world would reach 7 850 TWh in 2050 as compared with 2 276 TWh in 1997. In this case in 2050 nuclear would supply some 35 per cent of total electricity consumed corresponding to about 12 per cent of total primary energy demand, as compared with some 17 per cent and 6 per cent respectively in 1997. Natural uranium requirements would depend on the reactor and fuel cycle options adopted.

Evolution of current technologies: Issues and challenges

The performance of nuclear reactors and fuel cycle facilities available on the market will be an important factor in the development of nuclear power. Key issues affecting the future of nuclear power include competitiveness, safety, radioactive waste management and disposal, and non-proliferation. These areas are the focus of R&D programmes worldwide that deal with improvements in fuel cycle or reactor operation.

Issues

The economics of nuclear power production have steadily improved, but nuclear power currently faces increased competition from gas-fired power plants. Projected generation cost reductions vary widely from country to country and from technology to technology. However, cost reductions appear to be generally higher for gas-fired power plants (16 to 54 per cent) and coal-fired power plants (3 to 34 per cent) than for nuclear power plants (2 to 27 per cent).

Fuel costs (front-end and back-end) account for around a quarter of the cost of producing a unit of nuclear-generated electricity. Therefore, fuel cost reductions can have a significant impact on nuclear power competitiveness. However, the pursuit of such cost reductions must take into account the overall reactor and fuel cycle constraints.

Any improvement of the fuel itself, therefore, has to be considered in the context of the fuel cycle strategy optimisation, taking into account back-end fuel cycle management in particular.

In addition, the strategy for the development of fuel products and their utilisation in reactors should be responsive to the following objectives: to improve the reliability of the fuel in the reactor, to reduce the radiation exposure to staff, and to reduce electricity generation costs.

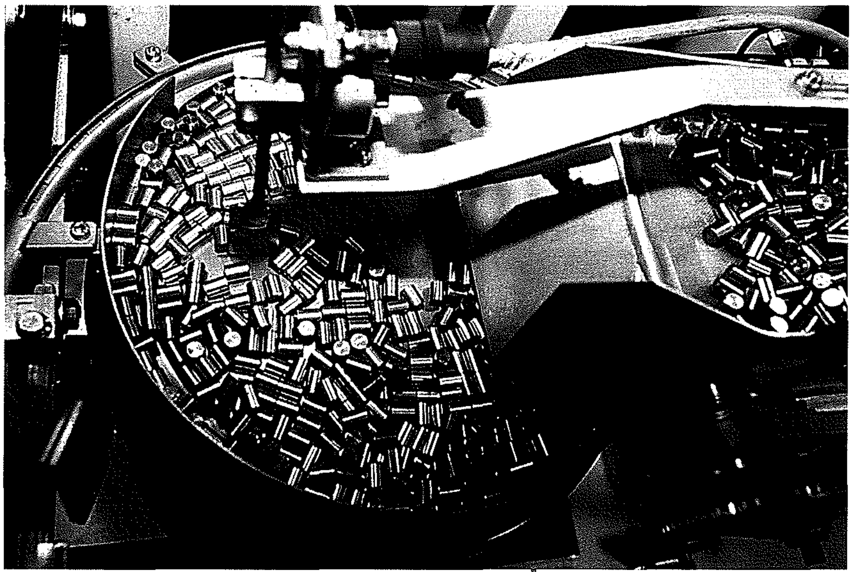
In this connection, utilities have generally given top priority to *extended cycles*, an objective dictated by the search for a reduction in the number of annual outages at each site, lower overall radiation exposure, higher availability of plants, and lower operation costs. For example, 18-month cycles are currently common in EdF's 1 300 MWe pressurised water reactors (PWR).

Principal fuel development objectives for the coming decade are generally evolutionary and include:

- maintaining high fuel reliability while reducing the incidence of assembly deformation in the short term;
- obtaining a product for existing reactors which performs better from the standpoint of pellet-clad interaction, and results in fewer operational constraints;
- raising the performance of fuels fabricated with recycled uranium and/or plutonium (mixed oxide fuel – MOX – and enriched recycled uranium fuel – ERU) so that they are capable of the same energy output and burn-up as enriched natural uranium fuel;
- developing within the next ten years a fuel capable of achieving a burn-up of 60 Gigawatt-day per tonne (GWd/t), with a view to obtaining better economic optimisation of core management without hampering reactor operation or compromising safety or fuel reliability (e.g. the European pressurised water reactor, EPR).

In short, increasing the uranium and plutonium fuel burn-up is the main focus of the fuel development programme as that would lead to a more cost-effective management of reactor operation. The trend towards higher burn-up, however, has led safety authorities to raise questions about verifying safety and the prospect of expensive experimental programmes to do so.

Non-proliferation discussions focus on plutonium in the fuel cycle. They also address the once-through versus the closed fuel cycle option. While it is recognised that adequate safeguard systems can be implemented for any fuel cycle option and facility, R&D programmes are exploring more proliferation-resistant fuel cycles in order to facilitate safeguards and reduce its cost.



Leenhardt, MELOX, France

Fabrication of MOX fuel pellets at the MELOX facility in France.

The decline of infrastructure*, including the potential shortage of qualified manpower to carry out R&D programmes*, is one of the issues which deserves attention in the coming years. A reasonably balanced supply of and demand for qualified manpower currently exists in most countries.[5] However, it is anticipated that, even assuming zero growth in total nuclear generation, it will become increasingly difficult to maintain this balance in the future. Developing and implementing advanced technologies in the fuel cycle will require suitable educational programmes but could contribute to attracting students in the field.

Challenges

The recycling of irradiated fuel and the link to fuel performance, as well as to front-end and back-end issues of the fuel cycle, are current challenges. Only reprocessing using Purex technology has gained maturity today. However, after some four decades of intensive nuclear development and major achievements, an integrated view of the nuclear fuel cycle is required through an assessment of the different interactions in fuel cycle options with the ultimate aim to improve cost-effectiveness. Such an integrated view could point towards major changes through the adoption of new reactor systems or fuel cycle facilities.

By 2020-2030 oxide fuel will be standard and will constitute the bulk of irradiated fuel arising from light water reactors due to the long life spans of capital-intensive nuclear facilities. Although the trend has favoured higher enrichment to achieve higher performance, average burn-ups are now approaching an optimum economic band for reactors in the 50-60 GWd/t region. Of course, much higher burn-ups mean that the proportion of fission products and minor actinides in the fuel will increase, and this may cause some operating challenges to existing plants.

Current specifications for reprocessed uranium require extremely high decontamination factors so that it can be re-enriched and re-fabricated alongside virgin uranium. Alternative re-enrichment processes under development, such as the use of lasers, may reduce the chemical purity requirements and so reduce processing and associated secondary effluents. Thermal MOX specifications, and hence process feeds and products separated by reprocessing, have been kept high to keep MOX fuel very similar to uranium fuel and thereby minimise re-licensing issues. As experience with the use of thermal MOX fuels accumulates, it may be possible to relax these specifications for new plants and doing so could ease up-stream processing requirements and reduce direct or indirect costs.

As the residence time of nuclear fuel in reactors and cooling ponds is spread over many years, the challenges of multiple recycling on a large scale is decades away and needs not be faced by current facilities. Large-scale recycling, however, will eventually lead to large volumes of irradiated MOX, which can justify dedicated facilities for recycling fuel in fast and thermal reactors. Alternative enrichment technologies under development may further simplify multiple recycling.

Reprocessing 10 000 t/yr of irradiated fuel would reduce high-level waste volumes (which contain 99 per cent of the activity) to around 3 000 m³ using current technology. Final repositories for high-level waste (i.e. spent fuel or smaller quantities of conditioned reprocessing waste) still need to be established. If a closed fuel cycle is considered, siting reprocessing capacities close to repositories would minimise transport requirements.

Reducing environmental impacts even further is a challenge that the nuclear industry has to face in order to ensure the long-term viability of the nuclear option. Moreover, if the number of nuclear facilities is to rise, then the constraints on individual facilities can be expected to become more stringent in order to limit the cumulative environmental impacts. Reprocessing, conditioning, and recycling allow the conversion of waste residues to meet specific requirements of society for disposal in permanent repositories. Vitrification processes in current facilities meet the challenge of providing a safe mechanism for the immobilisation and indefinite storage of high-level waste. Current developments include investigating matrices and supporting processes to increase the incorporation factor and heat loading of the waste form in order to reduce the volume arising, as well as the environmental impact for generations in the distant future.

MOX assembly at the FBFC fuel fabrication facility in Dessel, Belgium.

COGEMA, France

As installed nuclear capacity increases and pushes up the consumption rate of uranium, it is likely to result in increases in the price of uranium and hence favour recycling not only uranium, but also plutonium. Recycling the fissile uranium and plutonium from this fuel in similar thermal reactors could amount to the provision of around a quarter of the volume of fresh fuel, thus obviating the need for mining more than 50 000 tonnes of virgin uranium per annum under this scenario. This is equivalent to about 300 million tonnes of oil, i.e. about half of Europe's present oil consumption.

At some point in time before 2050, changing economics may require a review of the current recycling strategy, i.e. the balance between breeding and burning plutonium and the role of fast reactors. Fast reactors are currently being considered, not for their ability to be self-sustaining by breeding plutonium, but for their ability to burn minor actinides and even plutonium and uranium isotopes. These long-lived actinide species have a major potential environmental impact when consigned to a repository. A balanced use of fast reactors would allow prolonged thermal recycling as well as minimisation of the environmental impact from final repositories. Integrating plutonium in a cycle involving fast reactors would require lower product purification and afford maximum safeguardability. Since any breeding blanket produces fresh, "clean" plutonium, this is ideal for furnishing thermal MOX fuel to reduce the need for virgin uranium further.

The current Purex technology used for reprocessing irradiated fuel does not present technical obstacles in terms of sustaining projected nuclear capacity, but it must be improved and extended to cope with minor actinide reprocessing and recycling.

Several programmes related to minor actinide transmutation are conducted world-wide. The fast reactor programmes in countries such as Japan, France and Russia have resulted in the gaining of considerable knowledge. Current research focuses mainly on the improved characterisation of these reactors and especially the assessment of minor actinide and long-lived fission product transmutation.

In brief, transmutation in fast reactors is a feasible option within the current fuel cycle and fast reactors could be an integral part of future fuel cycles if one wished to decrease further the impact of these minor actinides and long-lived fission products on waste management. Fast reactor technology is, however, not yet mature and further R&D in this domain is mandatory prior to its deployment.

Innovative alternatives

The limits of evolutionary systems are leading to the investigation of alternative technologies and schemes, such as pyrochemistry, accelerator-driven systems, innovative reactor concepts or new fuel cycle strategies involving thorium fuels, aimed at the optimisation of the fuel cycle from the viewpoints of resource management, economics, emission and waste minimisation and proliferation resistance.

The desirability of developing innovative alternatives to current fuel cycles justifies undertaking more R&D. These innovative alternatives aim at addressing some of the major issues raised above. Most of them focus on an integrated fuel cycle in which recycling is considered within an on-line reprocessing scheme using mainly fast reactors. Other innovations involve new fuels or major improvements to current fuels. These alternatives will not be available on the market before well into the 21st century but could enhance the long-term sustainability of the nuclear option.

Innovative fuel forms

As mentioned above, future research on the optimisation of the fuel cycle will have to address the integration of front-end and back-end issues together with the operational performance of nuclear power plants. In that respect, innovative fuel forms have been proposed and studied from the point of view of better waste management and resource conservation. These fuel forms, which satisfy these newer requirements without penalising the economy of the fuel cycle, have yet to be established but current investigations and experiments have already led to the selection of some promising developments.

Depending on each country's nuclear policy, there are two main options for nuclear fuel technology innovation: fuel for improved spent-fuel management and fuels for improved actinide burning or actinide recycling. The fuels for improved spent-fuel management will have to focus on ultra-high burn-up to reduce the quantity of spent fuels and to provide a better immobilisation of radioactivity. If recycling is selected, the fuels should permit more efficient actinide burning and/or breeding and improved economy and proliferation resistance of the fuel cycle.

Although the aims and the technological targets of these fuel options appear to be diverse, the technical issues involved are interconnected. Ultra-high burn-up (above 70 GWd/t) and actinide burning both demand reduced fission-gas release and swelling. Use of inert matrices for fuels, or "integrated" fuel types by application of IFR-type of fuel or fuels mimicking natural minerals, are developments useful in both fuel options.

The demand for plutonium burning in thermal and fast reactors will necessitate new fuel forms, i.e. inert matrix fuel to maximise the burning rate. This inert matrix fuel can be of different types, one of which involves composite fuel such as CERCER and CERMET. In this case, the plutonium oxide fuel is a ceramic (CER), which is dispersed with an adequate volumetric ratio in an inert matrix which is either a ceramic (CER) or metal (MET). These fuel types are currently studied mostly in France. Based on these fuel matrices, different concepts of fuel assemblies have been suggested aiming at maximum plutonium loading or maximum burning rates by minimal modifications in the core and in the control system of a standard PWR. One of the first aims concerns the stabilisation of the plutonium inventory in the French nuclear power plants using these kinds of fuels.

Further improvement in spent-fuel management is expected by using a fuel matrix in which fission products and actinides are chemically fixed. The concept of using rock-like oxide fuel (ROX) in light water reactors was brought forward by the Japan Atomic Energy Research Institute (JAERI).

Comparable developments hold for fast reactor fuels. Plutonium and minor actinide burning is particularly suited to fast reactors by application of homogeneous or heterogeneous recycling. Minor actinides can be burnt by homogeneous recycling where high-plutonium content oxide fuel is enriched with minor actinides up to 10 per cent. Currently, most attention is focused on heterogeneous recycling.

A last option involves the use of very innovative fuels and core management. For example, nitride fuels are very promising due to their high heavy metal density, large thermal conductivity and high melting point.

Bringing about innovation in long-term actinide management might not be an urgent issue, and might even be considered to hinder the solution of more urgent issues. At the same time, it is not yet clear if there is a real way out of the actinide problem without introducing innovative measures. While the fuel and fuel-treatment technologies are pivotal in developing the future nuclear systems, R&D on them are costly and time-consuming.

Innovative reactors and fuel cycles

The above considerations show that most innovative alternatives for fuel will have an impact on the operational aspects of reactors. New reactor concepts can alleviate some of the constraints related to current light water reactor technology or fast breeder reactors.

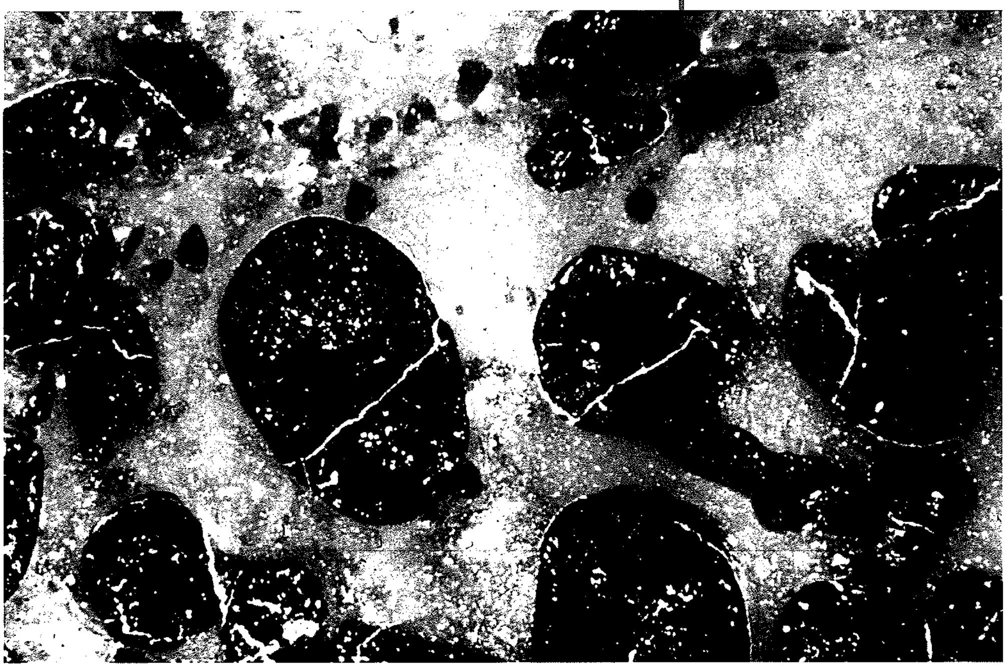
Such reactor concepts have been proposed during the past decades and, today, some of them have been redesigned according to current practices and a better definition of nuclear needs. This is the case with the BREST-300, a typical liquid metal fast reactor and the high temperature gas cooled reactors.

A BREST-300, lead-cooled fast reactor with uranium plutonium nitride fuel was developed by a number of Russian design and research institutions aiming at enhanced safety and economic efficiency. Reconciling these two objectives was solved by the use of natural safety principles with introduction of new design decisions. It is assumed that this kind of reactor can be used as a heat source for generation of water vapour, as a consumer of plutonium obtained from the reprocessing of spent fuel from thermal and fast reactors or weapons-grade plutonium released in disarmament programmes, and as a fuel breeder for the final burning of actinides.

The modular helium reactor (MHR) is the result of the direct coupling of a small reactor with a helium-driven gas turbine. This package has been made possible by taking advantage of the latest developments in two domains: high temperature reactors and large industrial gas turbines; and magnetic bearings and high capacity heat exchangers. It encompasses high levels of passive safety while promising reduction in power generation costs by increasing plant net efficiency to 47 per cent. The fuel consists of microspheres of uranium oxycarbide cladded with layers of carbon and silicon carbide, and can withstand very high burn-up (almost ten times more than current reactors). Several fissile materials may be considered such as ^{235}U, a combination of ^{235}U and ^{232}Th, but also plutonium from weapons-grade material or from reprocessed commercial reactor fuel.

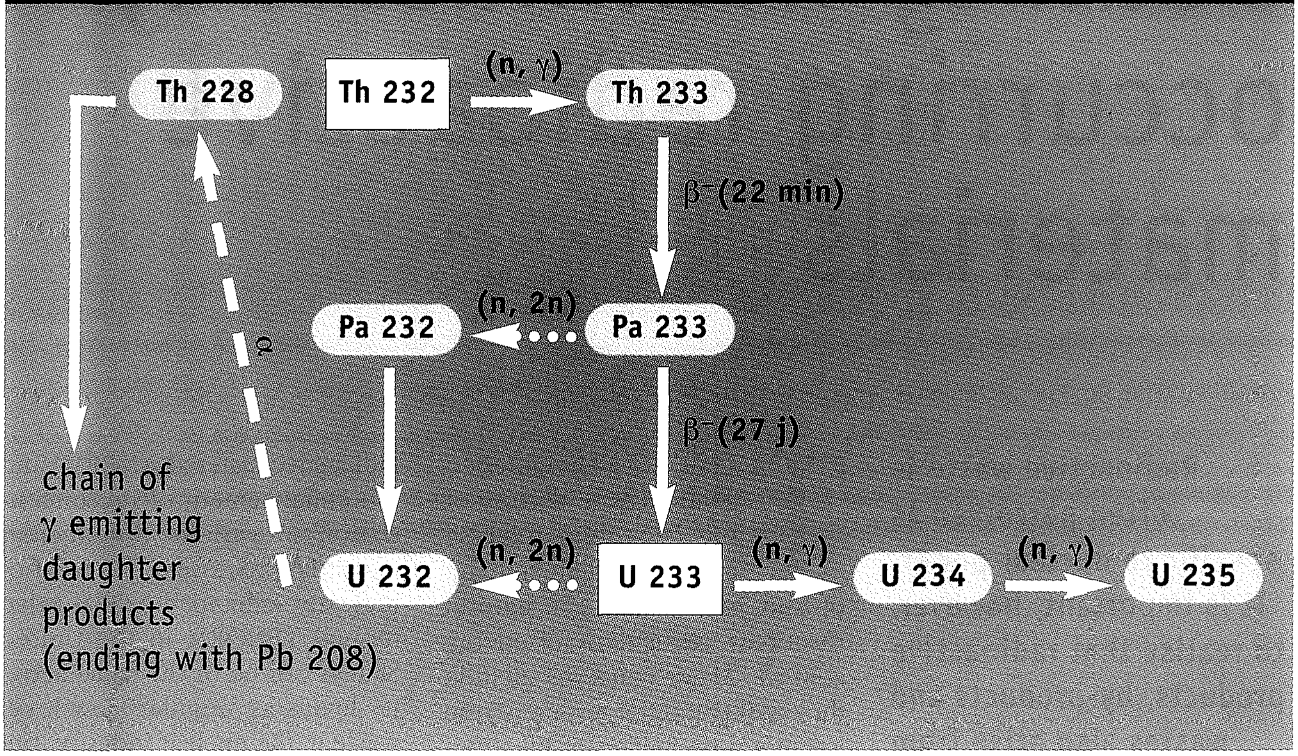
An even more innovative option involves the future use of thorium fuel. Despite the studies performed in the 1950s on using

Micrography of an inert matrix fuel, particularly useful for plutonium and/or actinide burning.



CEA, France

A schematic view of the physics of the thorium fuel cycle.
^{232}Th is not fissile in itself, but does allow to produce ^{233}U which is.



thorium as nuclear fuel, this fuel cycle was never industrially exploited. Today, in the quest to improve and optimise nuclear fuel cycles, this thorium potential is again being explored in the context of thermal and fast reactors or even accelerator-driven systems. One of these projects, the Radkowsky Thorium Fuel concept, involves a Th-U fuel in the blanket of a reactor.

Conclusion

Today, nuclear power is a significant component of energy supply mixes and one of the few commercially available carbon-free options. Nuclear technology has a very good track record leading to state-of-the-art reactors and fuel cycle facilities supporting reliable production of base-load electricity on a large scale. In order to enhance economic performance and sustainability of nuclear power, a number of issues have to be faced. These issues are known and are being addressed within the nuclear fuel cycle by technological and managerial means. However, the present challenge is to optimise the solutions in an integrated way. The nuclear industry is aware of this and has initiated R&D programmes in relevant fields.

For the future, an even higher emphasis will be placed on the integration of current practices and new developments will be assessed based on a life-cycle design. This life-cycle design is aiming at close integration of the fuel cycle; reduction of costs; minimisation of the potential health and environmental impacts; enhancement of public acceptance; and reduction of proliferation risks.

Nuclear fission has the potential to play a key role in the 21st century as a carbon-free, safe and economic energy source, provided it is demonstrated to be a sustainable option. R&D programmes and industrial initiatives world-wide demonstrate that it holds this potential and that it can cope with the current issues being presented as bottlenecks for its future. New incremental and innovative solutions are being pursued that are responsive to existing challenges. ■

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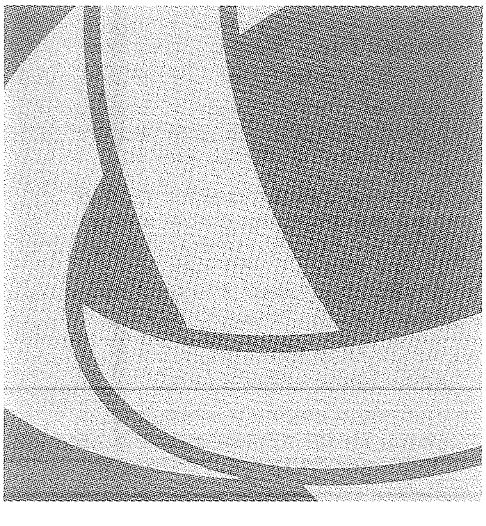
Dealing with naturally occurring radioactive materials

Radioactive waste is often perceived as specific to nuclear power. It is important, however, to realise that radioactive products, by-products and wastes also arise from practices other than nuclear power generation. This article briefly reviews the current management of materials that are radioactive, but often not recognised as such, with a view to placing the management of radioactive materials from the nuclear industry in perspective.



There is a heightened awareness in society of the possible adverse environmental impact of the exploitation of natural resources, particularly of energy sources. Major concerns include the conservation of resources, the long-term protection of the environment and sustainable development. There is also increasing awareness of the scale of the remediation problems to be faced as a result of some former, unsafe practices regarding the management of various forms of waste that may lead to the need for intervention. This applies to both non-radioactive, chemically hazardous waste *and* radioactive waste.

What is NORM?

Radiation protection and the management of radioactive material have hitherto been concerned mainly with artificial nuclides arising within the nuclear fuel cycle. However, in the last few years, there has been an increasing awareness of naturally occurring radioactive materials (NORM) and the enhancement of its concentration in various non-nuclear industrial processes. This technologically enhanced NORM (also termed TENORM in the United States) can be of the same activity levels as "regular" low-level waste in the nuclear industry, but occurs in quantities that are huge in comparison. Table I illustrates some of the technologically enhanced NORM arising annually in the United States. ^{226}Radium, with a half-life of 1 600 years, is by far the most abundant radionuclide in this category. These data are shown only to give an idea of the quantities and activity levels involved. Other industries with significant radioactive waste streams are coal ash, petroleum processing, geothermal plants and paper mills. More or less comparable quantities of NORM arise in Europe, with similar concentrations of radioactivity.

Radiological impact of NORM

A characteristic of NORM is that, because of their wide distribution from many sources, they give rise to relatively large collective radiological doses to the public in comparison to those caused by the nuclear industry. This is vividly illustrated in a study[1], carried out in 1990 by the radiation protection authorities of

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the five Nordic countries, on the annual collective dose to their populations from natural radioactive sources, including some NORM-related ones. A pie chart (Figure 1) was prepared in connection with the report, showing the respective contributions of the various sources and comparing them with the collective dose from the Chernobyl accident received by the Nordic populations during the first year after it occurred, as well as with the annual collective dose from the operation of the 16 nuclear reactors in Sweden and Finland. On closer examination, the comparative impact of some of the NORM-related industries is, in fact, even more significant than shown. Examples are provided in the paragraphs hereafter.

Table I: Some NORM quantities

Waste stream	Production rate t/a	U + Th + Ra Bq/g
Phosphates	5×10^7	up to 3 700
Petroleum production	2.6×10^5	up to 3 700
Water treatment	3×10^5	up to 1 500
Mineral processing	10^9	up to 1 100

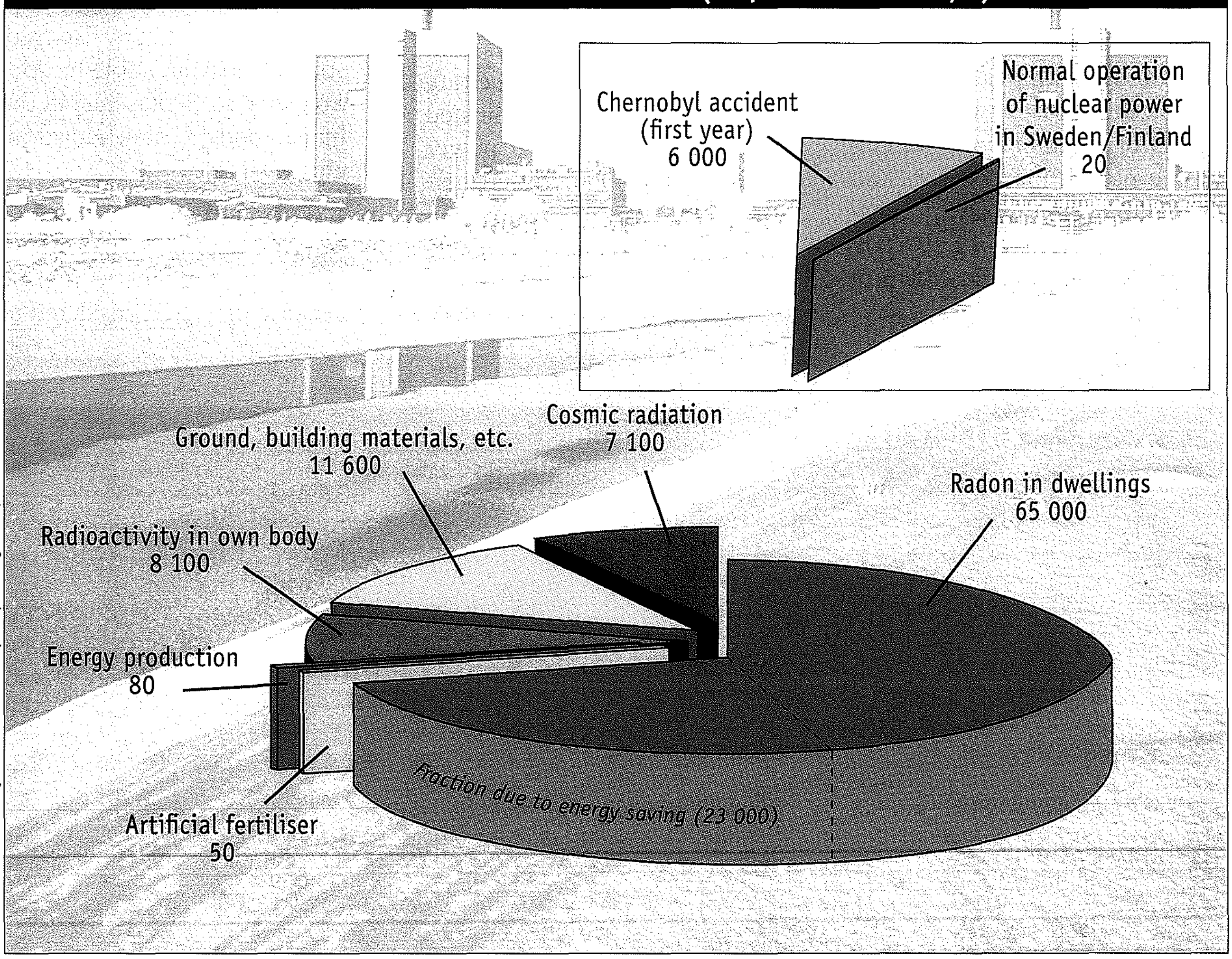
Diffused NORM Waste – Waste Characterisation and Preliminary Risk Assessment, April 1993, Draft RAE-9232/1, 1993.

US Environment Protection Agency, United States

The 20 person-Sv/year from the operation of the nuclear reactors are mostly occupational doses to the operating personnel. The total collective dose to the general public from plant emissions is less than 1 person-Sv/year.

The annual 50 person-Sv dose coming from artificial fertiliser covers only the internal doses taken by the Nordic public, through ingestion of food produced in the fertilised soil. The external doses have not been

Figure 1: Average annual collective dose to population in Nordic countries from natural radioactive sources (in person-Sievert/a)



NKS Nordic Nuclear Safety Research RAS 430 (1990). Background photo: Olkiluoto, Finland included. Similarly, the figure does not cover the use of the fertiliser by-product, gypsum, as a building material. Even a modest use of gypsum in homes could lead to an annual collective dose of about 100 person-Sv.

The figure of 80 person-Sv/year due to energy production from coal (mainly in Denmark) and from peat (mainly in Finland) refers only to radioactive emissions from the power plants. Not shown are the effects of the use of some of the fly ash in concrete, which increases the external gamma radiation in buildings and is likely to dominate the total dose from the use of coal and peat. The report mentions that most of the bottom ash ends up in municipal landfills but does not attempt to estimate the radiological impact.

The Nordic study thus shows that the collective dose from the operation of the 16 nuclear plants is 1 person-Sv/year, while the use of artificial fertiliser and the operation of coal and peat for energy production causes two to three orders of magnitude higher collective population doses. It also shows that energy saving measures have resulted in a substantial increase of the dose due to radon in dwellings.

Another interesting study illustrating the comparative impact of nuclear facilities and NORM was recently published in Sweden.[2] The doses to individuals in a critical group from radioactive emissions from three sources were compared:

- The Barsebäck nuclear power plant with 2 x 500 MWe boiling water reactors (BWR) (each 1 800 MW-th, 7 000 h/year).
- The 50 MW-th Materials Testing Reactor, R2, at Studsvik.
- The 8 MW-th wood chip briquette burning plant, used for heating office buildings at the Studsvik site. Even such a source as wood chips has NORM, which is released during combustion.

The results are shown in Table II.

At the same site as the R2 reactor and the wood chip plant, Studsvik RadWaste has an incinerator for burning dry active waste from both nuclear plants and hospitals, as well as a melting facility for recycling contaminated metal scrap from nuclear power plants. During 1996, the incinerator gave rise to a dose of 11 nanosieverts (nSv) to members of the critical group (mostly due to tritium in waste from hospitals and pharmaceutical manufacturers) and the melting facility, which treated 500 t of metal during the year, caused a dose of 0.9 nSv.

In summary, per GWh of heat generated, the wood chip burning plant at Studsvik releases seven times as much radioactivity to the atmosphere and dose to the public than the two BWRs at the Barsebäck Nuclear Power Plant. The radioactive emissions from the wood chip plant are also almost three times those from the neighbouring facility, which melts contaminated scrap from nuclear power plants.

Regulation of NORM and the need for consistency amongst NORM-producing industries

In connection with the regulation of radioactivity, the following terms are conventionally used to denote specific conditions:

- **Exclusion** covers activity sources not amenable to control, such as ^{40}Potassium in the human body, cosmic radiation, etc.
- **Exemption** denotes radioactive materials which never enter the regulatory regime because they are considered to

Table II: Radioactive emissions from various sources (calculated annual doses)

	Individual dose to critical group nSv (1995)	C-14 (calculated) nSv	Generated power GWh-th	nSv/GWh-th
Barsebäck	37	570	25 200	0.024
R2 (mostly Argon)	6	–	–	–
Wood chip plant	2.4	–	14	0.17

give rise to low risks, and control would be a waste of societal resources.

- **Clearance** refers to material that was regulated earlier, but has been released from regulatory control.

It is to be noted that, in principle, "exempted", "cleared" and "regulated" materials have, at the same activity levels, the same radiological impact on human beings.

To a large extent, the radiation protection regulators have been focusing on the nuclear fuel cycle with little attention being given to the technological concentration of radioactivity in the NORM industries. Consequently, the current regulatory management of NORM is very inconsistent with that of similar material arising in the nuclear industry. For example:

- The current level for clearance of material from the nuclear industry in Sweden is 0.5 Bq/g, while the current exemption level for non-nuclear industries* is 100 Bq/g (or 500 Bq/g for "solid natural material").
- Exemption levels for oil and gas industry NORM wastes[3] are 100 Bq/g in the Netherlands and 500 Bq/g in Germany.
- For subsurface road stabilisation in Germany the clearance level for concrete from a nuclear plant is 0.5 Bq/g, while the exemption level for slag from the melting of scrap from the oil and gas industry is 65 Bq/g (to be diluted by a factor of four).

The EC issued a new Directive in May 1996 with revised basic safety standards (BSS) for the radation protection of both workers and the general public.[4] The Directive covers radioactivity in both nuclear and non-nuclear industries and will have to be ratified by member states within four years, i.e. by May 2000. In the BSS, industries are divided into "practices" (where radionuclides are, or have been processed in view of their fissile or fertile properties) and "work activities" (where the presence of radioactivity is incidental). Broadly speaking, "practices" refer to the nuclear industries, while "work activities" to the non-nuclear ones, e.g. oil, gas or phosphate industries. The table of exemption values in the new EC-BSS only covers practices. The exemption values for work activities are not explicitly given. It is not clear from the text (and from other technical reports published by the EC) whether the same or different criteria would be considered for exemption/clearance in the nuclear and non-nuclear industries.

In the United States, a draft set of regulations for technologically enhanced NORM (TENORM) was released in February 1997 by the Conference of Radiation Control Program Directors (CRCPD). The CRCPD is an organisation primarily consisting of directors and technical staff from state and local radiation control programs and functions as the common forum for state, local and federal regulatory agencies to address NORM-related health and safety issues. Several states already have regulations in place to meet their specific individual needs. There is, however, no uniformity in these regulations. One of the main aims of the CRCPD is to promote uniformity in regulations governing radiation.[5]

The current international recommendations for the *exemption* of radioactive material from being regulated and the *clearance* (release) of such material already regulated are both based on criteria laid down by the IAEA Safety Series 89** regarding individual doses (10 μSv/year) and collective doses (1 person-Sv/year). Typically, exemption levels are a factor of ten higher than clearance values, the explanation being that exemption is intended to be applied to moderate quantities of material (say 1-10 t), while clearance concerns large quantities (10 000 t/year used in European studies).

If radioactivity is to be regulated in a consistent manner, it will not be practically feasible to relate release levels to quantities when the huge inventories of NORM (100 000 to 1 000 000 t) will be brought under regulation. So the resolution of the NORM issue is of the highest interest to nuclear decommissioners, whose projects are characterised by potentially large volumes of very low-level radioactive materials arising, with very similar activity concentrations as in NORM.

One of the main problems regarding NORM in non-nuclear industries is that plants handling such materials are typically not aware that radioactivity is being concentrated in various technological processes. Very often, the first indication is received when waste is taken to a melting plant or a landfill with portal monitors for radioactivity, which are usually set to alarm at a level only slightly above background.[6]

Steel melters recycling scrap have become increasingly aware of the risks of radioactivity contaminating their products. Even though the most serious incidents have involved ^{60}Cobalt and ^{137}Caesium sources, the largest single contribution to radioactivity in

* *By European Commission Directive 84/467/Euratom of 1984.*
** *Presently under revision.*

scrap in the United States has been NORM.[3] In any event, just like human beings, monitoring devices at melting plants cannot discriminate between natural and artificial radionuclides. For this and many other reasons, all radioactivity, whether from the nuclear or the non-nuclear NORM-related industries, needs to be regulated in a consistent manner.

Significance of NORM to waste management in the nuclear industry

One of the main problems for the nuclear industry has been its artificial separation from other industries also resulting in risk to the public. As part of the NORM regulatory discussions, direct, exposure-to-radioactivity comparisons can be made between nuclear and other industries and the relative impacts can be brought into perspective.

Considering the large number of industries involved, the relevant activity levels, the collective radiological dose actually being received by the population, as well as the vast quantities of technologically enhanced NORM, the main message from the NORM issue is that radioactivity is not only part of the human environment but needs to be viewed globally.

This message could hopefully be useful to promote a constructive dialogue – and bridge the gap – between "environmental" and "nuclear" agencies and interest groups. This would be useful not only in regulatory decision making but also in various ongoing discussions, e.g. with the steel industry on the recycling of materials from decommissioning NPPs, or with the public regarding the location of deep geological repositories (which are built to isolate radioactive waste over many thousands of years and to prevent any harmful radiological dose from reaching the public).

In a broader sense, the nuclear industry has been, for decades, regarded by the general public, some environmentalists and other industries as being uniquely hazardous, due to the central role played by radioactive material. With the emergence of the NORM issue, it can be seen that, in the area of waste management and disposal, the nuclear industry represents just one of many global radioactive waste generators. A full, open-minded discussion of the NORM issue may not only help resolve current national waste management problems but may also help preserve nuclear power generation as an option for the sustainable development of society at large. ■

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Wolfgang Wiese, Germany

View of a steel factory in Germany.

E. Sartori, P. Vaz*

Computer programs for nuclear energy and technology applications

The NEA Data Bank is recognised by Member countries as a repository of knowledge, computational modelling and methodologies, and data libraries in the different fields related to nuclear energy and technology applications. The Computer Programs Service (CPS) of the NEA Data Bank, in operation since 1964, operates as a software centre which collects, packages and disseminates computer codes and data libraries. The number of programs distributed to establishments in NEA and IAEA Member countries has progressively increased over the years, as shown on the bar chart, to a level of about 2 000 program packages distributed per year to some 1 200 establishments spread over four continents, including industry, universities, national laboratories, international organisations, engineering companies, consulting companies, hospitals and clinics, and regulatory bodies. The service is provided in close co-operation with similar centres in the US, namely the Engineering Science and Technology Software Center (ESTSC) and the Radiation Safety Information Computational Center (RSICC).

The composition of its "community of users" has evolved quite dynamically, in time with the evolution of nuclear science and technology. Indeed, over the last ten to fifteen years, the number of technological applications of the energy and radiation released in the nuclear processes has extended significantly beyond the traditional activities related to the production of electricity by nuclear reactors, to reach such areas as material science and medical physics. These new applications have been developed thanks to a better knowledge and understanding of the interactions of the different particles involved in the nuclear reactions, and to the possibility developed gradually to control the different mechanisms and particles produced at different energy ranges.

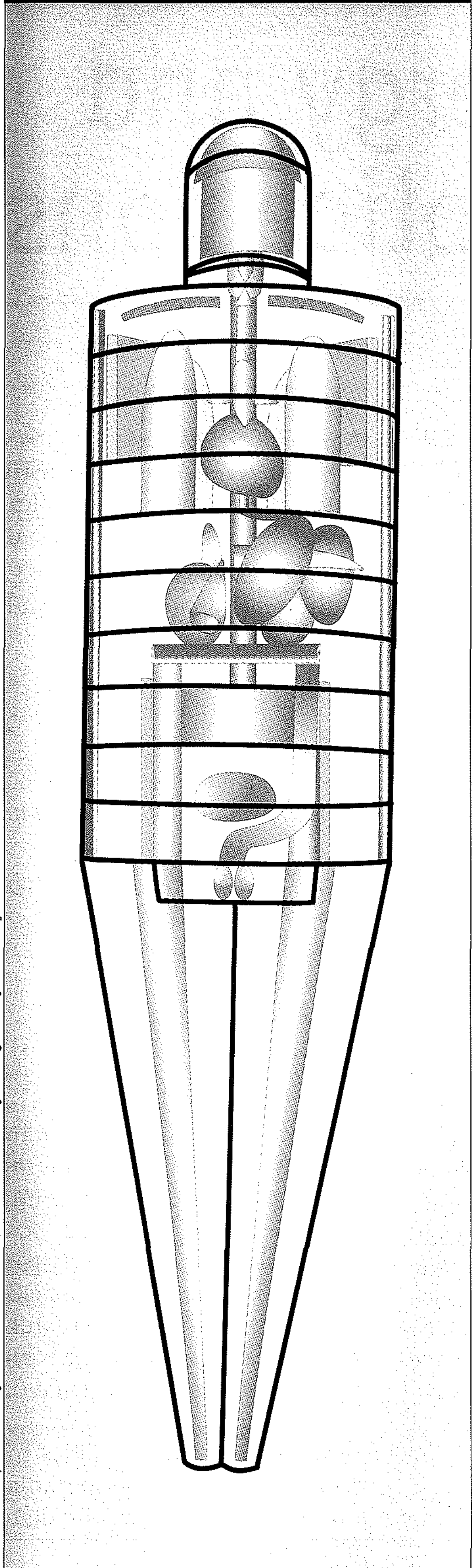
The computer programs and packages contributed by Member countries and distributed by the NEA Data Bank are unique tools for the modelling, simulation and design of systems, utilities and facilities. The complexity of such programs has gradually increased and over the years they have become powerful tools for solving problems in different areas of science and technology. They implement modelling techniques and computational methods which are useful for solving the different scientific and technological problems and for predicting the behaviour of systems in, among others:

- the nuclear industry;
- the aeronautics industry (e.g. detection of mechanical problems in the turbines of airplanes);
- the oil industry (oil-well logging);
- analysing the mechanical properties of components (e.g. corrosion);
- studying the atomic and molecular structure of crystals and other substances;
- radiation therapy (treatment planning and computation of irradiation doses to patients in hospitals);
- biomedical engineering;
- agriculture;
- the detection of explosives.

Another particularly important domain, which is of emerging importance, concerns recently developed applications made possible by the use of elementary particle accelerators in different fields of basic and applied research. Examples of such applications are accelerator-driven transmutation of nuclear waste; spallation sources; irradiation facilities for radiation oncology; and irradiation of materials for solid state physics applications.

** Dr. Enrico Sartori and Dr. Pedro Vaz are members of the NEA Data Bank.*

Figure 1: Computational model of ADAM



View of the splitting planes of the trunk. Some internal organs are shown.

EC, ERPET, EURADOS, ENEA, OECD/NEA, *"Use of MCNP in Radiation Protection and Dosimetry", Bologna, Italy, 13-16 May 1996*

These applications led to the design and construction of several multidisciplinary facilities world-wide, the construction and operating costs of which are estimated in the dozens to hundreds of million of US dollars, and which are currently in the design, commissioning or operation phase. The behaviour of the subsystems involved in the operation of these facilities can also be studied and optimised using the same code packages.

Computation and modelling techniques

There are essentially two major categories of computer codes using methods that are complementary to each other: deterministic codes and stochastic (or Monte Carlo) codes. Both types of methods exhibit advantages and disadvantages. In order to take advantage of the complementarity of these methods, some codes implement a combination of the two, thus allowing the codes to solve problems and predict behaviour of complex systems.

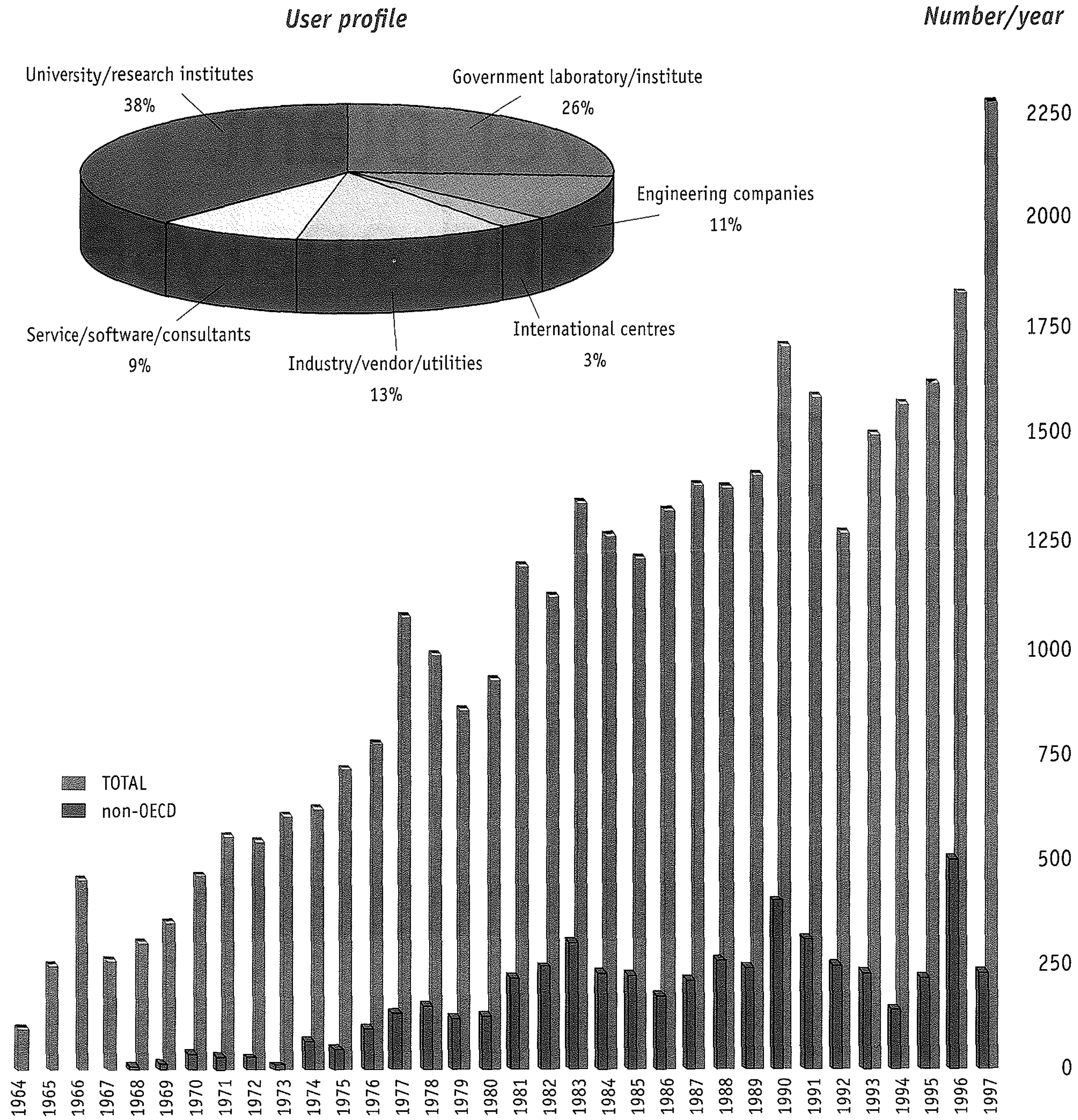
However, all models used in computer codes contain approximations. This is the case, for example, of the simplified geometric description (see Figure 1) of the human body based on simple volume elements such as cones, cylinders, spheres, etc. This description is used with satisfactory results for dosimetry purposes when simulating absorbed doses of radiation in human body tissues and organs.

The validity of such approximations are checked against real scale experiments and by using sensitivity and uncertainty analysis. This allows one to establish the level of confidence that can be placed in the models and serves as a guide as to the ways in which models can be improved. In most cases the task of computer codes is to use the knowledge of many basic, elementary phenomena and to predict the macroscopic result of their interplay, symbiosis and synergy in large numbers.

The sophistication of the models used depends on the objective and the application. In a scoping study, relatively simplified models are used many times. This procedure leads to the identification of interesting possibilities in a design, meeting predefined target criteria. This subset is then studied in detail with full-scale simulation models to determine optimal design.

The tremendous increase of calculational power reached by today's computers, be it the ones available on the office desk or specialised supercomputers, has led to the solving of complex scientific and technical problems for which no solution could be found a decade ago. However, no computer today is powerful enough to be able to predict macroscopic behaviour from microscopic events in complete detail. The scientific and technical community therefore needs to work with several different computational tools (codes) best suited for the study being undertaken.

Figure 2: Dispatched computer programs



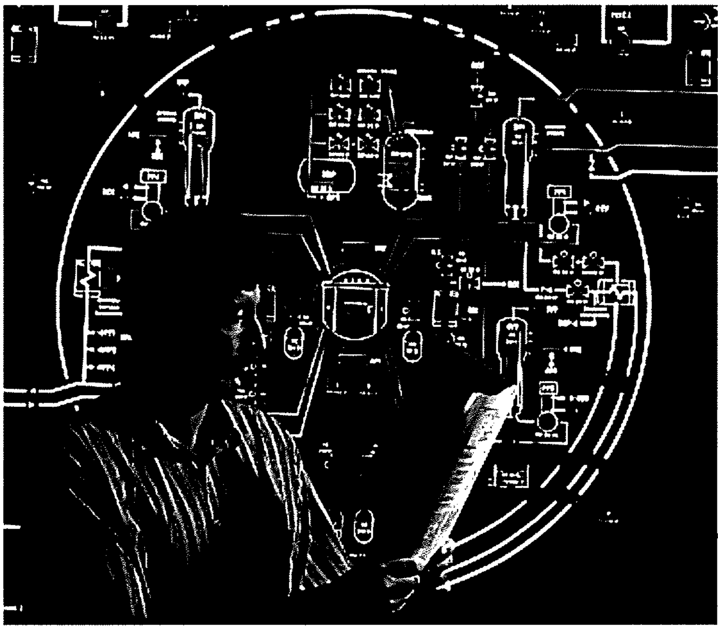
The CPS of the NEA Data Bank provides a large number of such tools, including data from experiments for their validation, and training courses for the most important codes. The set of computer codes is continuously revised, obsolete methodologies removed and state-of-the-art codes added. This ensures that the quality of the codes follows current technology.

Electronic memory of nuclear science and technology developments

Computer codes incorporate the knowledge acquired during multiple generations of scientists, engineers and technicians, both at the theoretical and experimental levels. This is certainly the case with the most popular programs available and distributed by the CPS of the NEA Data Bank. They also implement state-of-the-art computational methods and models. The set of computer programs and databases stored and available at the NEA Data Bank thus constitutes an electronic memory of the evolution and developments in nuclear science and technology over the last decades. ■

A. Drozd*

Current experience with nuclear power plant simulators and analysers



EDF, France

Simulator at Le Bugey NPP, France.

Simulation of physical processes is, in general, one of the most challenging issues of modern engineering. It requires a combination of thorough understanding of many complex phenomena, adequate mathematical representations or "models", along with a very efficient numerical programming compatible with available computer technology. The crucial part of any simulation is having an analytical model. In the case of nuclear plant simulation it is a thermal-hydraulic code coupled with a neutronic (reactor physics) model. Simulation of physical processes also requires development of "user-friendly" features that allow efficient definition of a problem and "easy-to-read" presentation of the results. The nuclear industry has been dealing with these challenges ever since nuclear reactors started to produce electricity commercially.

Results of a specialist meeting

Last fall, the NEA Committee on the Safety of Nuclear Installations (CSNI) held a Specialist Meeting on Simulators and Plant Analysers: Current Issues in Nuclear Power Plant Simulation, in Espoo, Finland. The meeting attracted some 90 participants from 17 countries. A total of 49 invited papers were presented in addition to 7 simulator system demonstrations.

The major topics addressed during discussions dealt with the need for maintaining expertise, training and education; control rooms and operator support tools; and simulators as tools for plant safety analysis. The question was also raised whether future activities should include development of current technology or focus on new approaches. Some more specific conclusions included:

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The role of simulators is changing and the applications are becoming more diverse.

The simulators are used in a wider variety of operator training; more safety analyses are being performed; and there are more simulators being used as support for regulators. In addition, the simulators are changing faster and faster, leading to possible applications in the areas of man-machine interaction and human factors. Interesting work is carried out in this field through the OECD Halden Reactor Project. There are, however, some doubts about the actual usefulness of the real-time simulators in the control room during accident conditions (but not in normal operations), as the operators may not be able, or would not have the time to take advantage of the simulator results.

The differences between training simulator and plant analyser software are disappearing.

This conclusion is currently somewhat controversial. Some experts point out that it is based solely on dramatic improvements in the speed and computational power of today's computers. However, it is also true that progress in analytical methods leading to a "real-time" simulation is significant.

As regards advanced computer modelling, there is a need for a two-phase, two and three-dimensional hydrodynamics code based on existing computational fluid dynamics (CFD) techniques. Such an advanced code needs to be coupled with the three-dimensional neutronics consistent with the level of detail of thermal hydraulic models. Within the NEA there is an ongoing exercise of analysing a specific accident scenario (Main Steam Line Break in a PWR Plant) based on specific plant data (TMI-1).

There is a related problem worth mentioning regarding uncertainties that exist in code calculations. The awareness of these uncertainties should be increased because, too often, the simulator results are taken as "true" plant response, which may not be the case.

It would be useful to establish a basis, or a set of rules for comparing simulators.

This idea, although very interesting, would be very difficult to implement as an actual simulator comparison exercise. It is well known that simulators are very plant specific, and the existing differences among current plants would make it very difficult to define an "objective" comparison. However, an example was given of an artificial intelligence benchmark that was successfully established about two years ago. An overall sentiment was that such a comparison exercise would be potentially very useful.

Finally, in the process of developing new and "better" computer codes, there is a simultaneous effort to validate and verify the models. In a process of merging various codes and/or subroutines that were validated separately, it is also necessary to validate the "combined" codes, since putting together various modules requires some changes that may affect the validation of the final product. The engineering "culture" and practices continue to differ between the thermal-hydraulic and neutronic code developers. More contact and joint meetings are needed to bridge this gap. ■

A control room simulator used for training plant operators at REPSI-INSTN, France.

CEA, France

I. Vera*

Environmental issues in uranium mining and milling

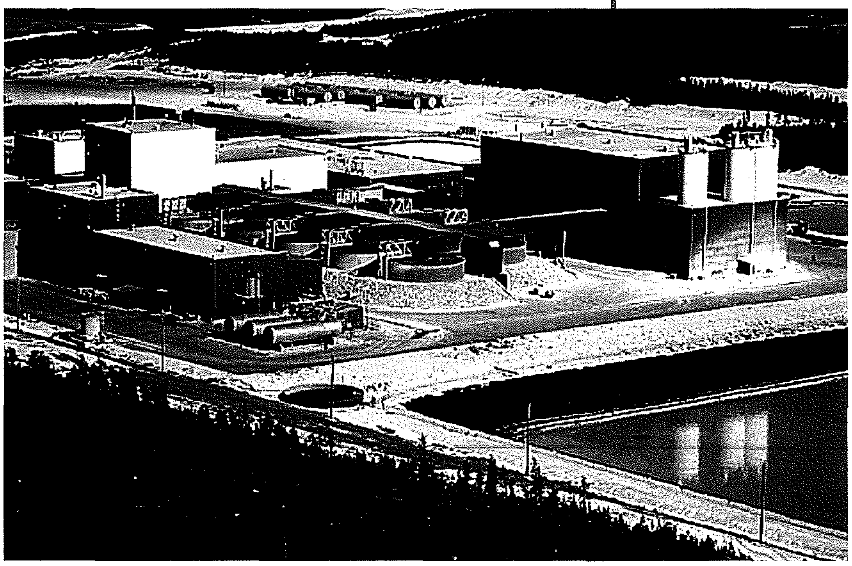
There are increasing environmental concerns related to the mining and milling of raw materials used in the production of energy. These arise in part from a renewed effort to use integrated assessments in the evaluation of technological processes that could potentially contribute to sustainable development.

The only large-scale civilian use of uranium is for nuclear fuel. There are sufficient known uranium resources to sustain nuclear power for many years without compromising the needs of future generations. The sustainability of this industry will only be possible, however, as long as managers and owners of uranium production facilities implement responsible planning, operational and closure programmes, to minimise environmental and health impacts.

In the case of uranium mining and milling, environmental issues have become increasingly important in the last few decades due to several developments affecting the uranium industry. These developments include: the large number of uranium production facilities which have been taken out of operation over the last 15 years; the increasingly stringent requirements for new facilities being imposed by many countries in the form of environmental clearance approvals; and, the restoration and reclamation measures that are being considered for many old sites which were abandoned at a time when provisions for decommissioning and rehabilitation were not sufficient.

Mine and mill closure activities have been or are being conducted in most of the 27 countries with a history of uranium production. The technology for closing mines and mills has improved considerably. Advanced methods have been developed for long-term isolation of mine and mill wastes. The new "Joint Convention on the Safety of Spent Fuel and on the Safety of Radioactive Waste Management" approved in 1997 by 20 countries will be applied in the future to wastes from uranium mining and milling.

Each major step in the uranium milling process at Key Lake, Canada, is contained in a separate building linked to the others. Material is transferred from plant to plant in pipes as solution or slurry.



CAMECO, Canada

** Dr. Ivan Vera is a member of the NEA Nuclear Development Division.*

For new projects, managers in most countries must prepare and submit an environmental impact assessment to regulatory authorities. This normally includes detailed planning for the life of the project, including relevant safety and environmental aspects. These plans and assessments are scrutinised by the responsible authorities before decisions are taken to allow – or not – the new project to proceed. The environmental assessment process may involve public hearings that provide for discussion of socio-economic impacts and the concerns of stakeholders in the communities affected by the project. For example, major new projects are being developed in Australia and Canada that must successfully complete the environmental assessment process.

Related research activities concentrate on the potential impact of radiation safety and environmental programmes on existing uranium production facilities, the expansion of some of these facilities and the schedule and design of new production facilities. Radiation safety procedures include the monitoring and control of direct radiation exposure, airborne radiation resulting from decay of radon gas and contamination by ore dust or concentrate. Major environmental programmes consider the management of waste (including mine wastes, milling wastes or tailings, and water waste), environmental impact assessments, decommissioning and restoration.

Measures taken to limit emissions to air and water, and new rules for radiation protection of both project personnel and the general public are being implemented in many countries. These measures, implemented as "Basic Safety Standards", are becoming increasingly stringent to provide increased radiation protection. New technology such as "non-entry mining" has been developed to make possible the mining of deep, high-grade ores like the ones found in Canada. In this system, mine personnel carry out routine ore extraction without entering the ore zone. Radiation exposure of personnel is therefore kept within acceptable limits, even for high-grade ores with elevated levels of radiation.

A comprehensive report on "Environmental Issues in Uranium Mining and Milling" is to be published by the OECD Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA) in 1999. The report will provide an overview of environmental activities related to uranium production. The profile of activities and concerns is based on survey responses from 29 countries, and a review of relevant activities at the NEA and the IAEA. The report also discusses environmental and safety activities related to: closure and remediation of formerly utilised sites; the operation, monitoring and control of producing sites; and the planning, licensing and authorisation of new facilities. It provides an overview of the reported interests of specialists working in the field including sensitivity of ecosystems; environmental impact assessment; emissions to air and water; work environment; radiation safety; waste handling and disposal; mine and mill decommissioning and site restoration; and the regulation of these activities. Discussions of one or more of these key topics are included in several of the country reports. ■

Comisión Nacional de Seguridad

The mining and milling plant of radioactive mineral at Villa Aldama and the tailings impoundment (Spain).

News briefs

Nuclear power and regulatory reform in the electricity sector

Regulatory reform in the electricity sector is likely to have significant impacts on the future of nuclear power programmes since, traditionally, the nuclear power sector has been a monopoly and under state control in a number of Member countries. In a deregulated market, power generators may be reluctant to invest in capital-intensive nuclear power plants and may prefer options having a more rapid rate of return. The maintenance of a high level of safety in an economically deregulated framework is one of the issues that has raised some concerns, as has the management of liability funds set aside for radioactive waste disposal and decommissioning.

Recognising the importance of the potential impacts of regulatory reform in the electricity sector on nuclear power, the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC) has launched a study to review the effects of this reform on nuclear power generation.

An expert group was established in February 1998 to carry out the study. It includes representatives from eleven Member countries and three international organisations, including the International Energy Agency (IEA). At the first meeting of the group, held in March 1998, the particpants agreed on the objectives and scope of the study as well as on the working mode and schedule for completion of the report.

The overall objectives of the study are to collect information on the experience already acquired in some Member countries; to assess the significance of concerns expressed about the impact of economic deregulation on the nuclear sector; and to provide findings and recommendations for consideration by Member countries. The scope of the study includes impacts of economic deregulation on nuclear power plants currently in operation and on future nuclear units that might be commissioned.

Other OECD studies, already carried out or ongoing, provide relevant background material for the present NDC activity. In particular, the OECD has recently initiated studies on the regulatory reform of such economically important sectors as electricity, telecommunications, road transport, airlines and distribution. The International Energy Agency (IEA) has been responsible for the electricity study and its report has pointed to one or two broad questions arising in the nuclear sector. Also, the study on *Future Nuclear Regulatory Challenges*, which was carried out by the NEA Committee on Nuclear Regulatory Activities (CNRA), looked into the potential effects of economic deregulation on safety regulation.

There is a trend in both OECD countries and throughout the world to liberalise electricity markets. Electricity market liberalisation aims to improve the economic efficiency of electricity supply industries by introducing elements of competition and moving towards market-based pricing, thereby reducing the prices paid by electricity consumers. Recently, some Member countries have introduced a competitive market in the electricity sector and some others have begun reviewing the methods, timing and effects of doing so.

The effects of electricity sector liberalisation on nuclear power should be reviewed in the context of the three major goals of energy policy: maintaining the security of energy supply; lowering energy costs; and minimising damage to the environment. There are a number of issues which require careful consideration during the process in order to avoid adverse effects on the sustainability of nuclear power and/or the energy policy goals. The internalisation of external costs and benefits is a key issue in a deregulated electricity market. It is important to investigate whether and how the external benefits of nuclear power in terms of, for example, the reduction of carbon dioxide emissions, might be internalised within the process of deregulating the power sector.

It may be argued that nuclear safety might improve in a competitive market, because competitiveness of nuclear plants will be linked to the reliability of their performance and the safety of plant operation. It is generally understood that nuclear operators run good operations not only because of regulatory requirements, but also in order to be competitive. A number of safety regulators believe that economic competition and safety can be compatible. The competitive market in the United Kingdom has improved efficiency and business performance of British nuclear power plants. On the other hand, there are concerns about a number of additional costs which may be caused by enhanced competition. The riskier environment for electricity utilities could incite safety regulators to adopt different practices in order to preserve their confidence that their requirements are being fulfilled.

The main points to be addressed in the study being prepared by the NEA will be the following:

For current nuclear plants:

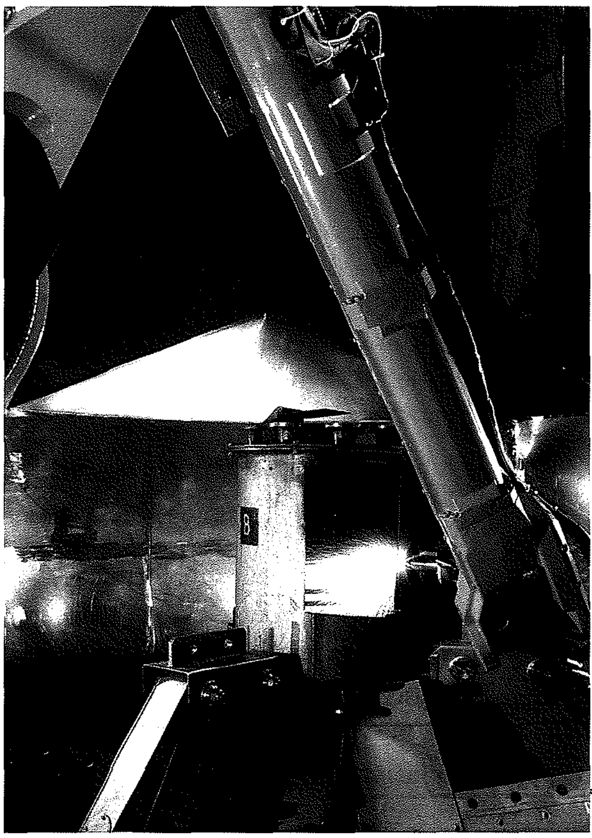
- the impacts of different models of electricity market liberalisation on the nuclear power sector;
- data on operation parameters that have changed as a consequence of competition or in preparation for competition (e.g. staffing, productivity, availability, safety, radiation exposure);
- the competitiveness of existing nuclear units in the new power market;
- effects of deregulation on nuclear liabilities and insurances;
- effects of deregulation on the restructuring of nuclear generators.

For new nuclear power plants:

- competitiveness of nuclear power in the short and long term;
- effect of regulatory risks on future nuclear power programmes;
- internalisation of external effects (climate change, political risks, etc.);
- prospects for the restructuring of nuclear generators and the emergence of independent nuclear power producers.

The expert group in charge of the study is expected to complete its work within two years. A report will be published soon thereafter. ■

The regulatory aspects of nuclear installations decommissioning



British Nuclear Fuels plc, United Kingdom

Robotic techniques used in decommissioning.

In the coming years, as more and more installations reach the end of their useful lives, for technical or economic reasons, the regulatory policy areas of decommissioning will come increasingly into focus.

With the ageing of a number of nuclear installations, decommissioning projects have been undertaken and the technical aspects of the decommissioning process have become better understood. The decommissioning process has moved from "case-by-case" R&D programmes to more standardised industrial processes, taking specific site characteristics into account as necessary. In parallel, interest has risen in more generically applicable regulations, guides and standards, both nationally and internationally.

In order to facilitate progress towards better mutual understanding of the rationale behind – and the practical implications of – decommissioning regulations, dialogue between regulators and implementers is seen as being particularly valuable, notably in the following areas.

- The regulatory process of site "declassification" is of great interest to regulators and implementers alike. The phases of declassification of an operational facility will most likely involve some or all of the following: passage from operation to a cold-shutdown configuration, cold-shutdown phase, passage from cold-shutdown to a safe storage phase, safe storage phase, dismantling phase, restricted and/or unrestricted site release. The regulatory process necessary for this declassification will most likely be stepwise, but will have larger or smaller steps depending upon the national regulatory context. The definition of this process will be of interest to all stakeholders, and should be discussed in an international and national context to help ensure that consensus is obtained and that national differences are understood.
- As part of the declassification process, it is essential to have the appropriate regulatory criteria in place and to be able to demonstrate compliance with them. There has been much discussion of this subject both at the national and international levels. In 1996, the NEA published the results of a questionnaire to its Member countries on the management of very low-level wastes which, *inter alia*, addressed the question of criteria being used for release from regulatory control. In 1997, the IAEA organised a specialist meeting on the application of the concepts of exclusion, exemption and clearance. The meeting concluded that, in the future, it would be necessary to clarify terminology in the subject area and to address the whole range of regulatory mechanisms by which materials can be released from control. The NEA Liaison Committee Task Group on Recycling and Reuse has made proposals for a tiered system to be applied to the release of materials from regulatory control.
- Other aspects of the demonstration of compliance with national and international regulations are also of interest, for example, the technical aspects of release measurements. The regulatory aspects of compliance with clearance levels, and of regulatory certification for release, will be influenced by the technical aspects of the process, but, as with these other issues, will need to be discussed in a forum between regulators and implementers.
- Once the decision has been made to decommission a reactor, there still exist safety concerns until the spent fuel is completely removed from the reactor and fuel storage pool, particularly in terms of human factors. The significance of these issues, and of how they should be taken into account in the regulation of reactors during this early phase of decommissioning, should be discussed.
- For those materials which cannot, because of their contamination levels, be released for uncontrolled use, a national low-level waste disposal infrastructure must exist. This includes such things as a regulatory basis for waste disposal, the availability of licensed repositories, waste transportation issues, etc. Without such an infrastructure, decommissioning will not be possible.
- Problems are occurring with the transboundary movement of very low activity materials, in particular metal scrap. Detection systems at borders are not an answer in themselves and often cause undue concerns because of false alarms. With more of such materials becoming available through decommissioning, an agreed international system of control needs to be established.
- Public acceptance of recycled materials from nuclear power plants is an issue of concern in some countries, and the problem of how to explain and provide a proper perspective to members of the public for the release of these materials needs to be addressed.

To further dialogue in these areas, a workshop will be organised by the NEA in the late spring of 1999 to bring together regulators and implementers to identify those regulatory issues which are of the most concern. The IAEA will co-sponsor the workshop, which is to include the following objectives:

- to hold a focused dialogue among the organisations responsible for regulation of decommissioning activities, for operational decommissioning of nuclear installations, and for receiving and disposing of waste arising from the decommissioning process, in order to share viewpoints concerning the most significant regulatory aspects in this area;
- to identify the points of international consensus regarding the regulation of decommissioning activities;
- to identify those issues where further discussion and work is needed in order to reach consensus among the various stakeholders; and
- to suggest processes by which consensus can be reached on the above issues.

A report should be published following the workshop. ■