

# NUCLEAR TECHNOLOGY REVIEW

2008



**IAEA**

International Atomic Energy Agency

# NUCLEAR TECHNOLOGY REVIEW 2008

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INTERNATIONAL ATOMIC ENERGY AGENCY  
VIENNA, 2008

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## EXECUTIVE SUMMARY

The year 2007 saw signs of recent rising expectations for nuclear power starting to translate into increased construction. There were seven construction starts, plus the resumption of active construction at Watts Bar 2 in the USA, and a total of 33 reactors under construction at the end of the year. Watts Bar 2 is the first active construction in the USA since 1996. The US Nuclear Regulatory Commission (NRC) received four applications for combined licences (COLs), the first applications for new nuclear reactors in the USA in nearly 30 years. Construction also began at Flamanville 3, the first construction start in France since 1991.

Current expansion, as well as near term and long term growth prospects, however, remain centred in Asia. Of the 33 reactors under construction, 19 were in Asia. By the end of the year, 28 of the last 39 new reactors to have been connected to the grid were in Asia.

The IAEA revised its medium term projections for global growth in nuclear power upwards in 2007, to 447 GW(e) and 691 GW(e), respectively in its low and high projections for 2030. Others, for instance the OECD International Energy Agency, also revised their projections upwards.

Reported uranium resources increased significantly relative to those in the last edition of the 'Red Book', Uranium 2005: Resources, Production and Demand, due mainly to resource increases reported by Australia, the Russian Federation, South Africa and Ukraine. The spot market uranium price reached almost \$360/kg in June before falling back to \$240/kg in December.

Construction began on USEC's new American Centrifuge Plant, and Japan Nuclear Fuel Limited started cascade tests at its advanced centrifuge uranium enrichment plant at Rokkasho. Kazakhstan and the Russian Federation established the International Uranium Enrichment Centre in East Siberia as one step in President Vladimir Putin's 2006 proposal to create a system of international centres providing nuclear fuel cycle services, including enrichment, on a non-discriminatory basis and under the control of the IAEA.

Nineteen countries signed a statement of principles of the Global Nuclear Energy Partnership, which aims at accelerating development and deployment of advanced fuel cycle technologies to foster development, improve the environment, and reduce the risk of nuclear proliferation.

The NRC approved the release of most of the Big Rock Point nuclear power plant site and most of the Yankee Rowe nuclear power plant site for unrestricted public use. Thus, ten power plants around the world have been completely decommissioned with their sites released for unconditional use. Seventeen plants have been partially dismantled and safely enclosed.

Thirty-two are being dismantled prior to eventual site release, and thirty-four reactors are undergoing minimum dismantling prior to long term enclosure. In September, the IAEA launched a new Network of Centres of Excellence for Decommissioning to improve the flow of knowledge and experience among those engaged in decommissioning and to encourage organizations in developed Member States to contribute to the activities of Member States requiring decommissioning assistance.

Nuclear and isotopic techniques continue to make substantive contributions in agriculture, human health, the marine and terrestrial environments as well as in water resource management. In food and agriculture, plant mutation breeding is supporting the development of new varieties of crops that bring enhanced yields while also providing significant environmental benefits through reduced requirements for fertilizers and increased resistance to biotic and abiotic stresses. The genetic enhancement of biomass crops is useful in responding to increasing demands for biofuels. In addition to the continuing use of irradiation for sanitary purposes, the use of irradiation for phytosanitary applications, especially those applications related to quarantine measures, is increasing.

In the health field, advances in the use of positron emission tomography are redefining many aspects of cancer treatment and providing the basis for more individualized and more successful treatments. The recent development of high dose rate (HDR) cobalt-60 sources may allow modern HDR brachytherapy to be performed with replacement of the sources needed less frequently than with other sources and enable more cost effective radiotherapy. Stable isotope techniques are being used to develop and evaluate strategies to combat micronutrient deficiencies as part of efforts to improve nutrition.

Nuclear analytical techniques are being used for estimating the quality and suitability of traded goods. The quality of measurement results needs to be assured with the required infrastructure in place and with the availability of tools such as appropriate reference materials.

Climate studies increasingly focus on the interlinkages between climate and the marine and terrestrial environments. Marine isotopes enable us to understand key climate induced changes, such as increasing ocean acidification as well as potential impacts on marine biodiversity and fisheries. The looming impacts of climate change on rainfall patterns and freshwater availability make groundwater an even more critical resource. Isotope data are of growing importance for providing a time and space integrated set of information to support groundwater assessment and management without significant investments of time and resources.

Radiation processing of natural polymers is a promising area as unique characteristics of polymeric materials can be exploited for practical

applications in medicine, cosmetics, agriculture, biotechnology and environmental protection. In another important development, recent research results have shown the utility of ionizing radiation for addressing such threats as the deliberate spread of biological toxins.

## **A. POWER APPLICATIONS**

### **A.1. Nuclear Power Today**

Worldwide, there were 439 nuclear power reactors in operation at the end of 2007, totalling 372 GW(e) of generating capacity (see Table A-1). In 2007, nuclear power supplied about 14% of the world's electricity.

Three new reactors were connected to the grid in 2007, one each in China, India and Romania, and one laid-up unit was reconnected in the USA. This compares with two new connections in 2006 and four new connections in 2005 (plus one reconnection). There were no reactor retirements in 2007, compared to eight in 2006 and two in 2005. Taking uprates of existing reactors into account, the effect was a small increase in global nuclear generating capacity during 2007 of 2526 MW(e).

There were seven construction starts in 2007: Qinshan II-4 (610 MW(e)) and Hongyanhe 1 (1000 MW(e)) in China, Flamanville 3 in France (1600 MW(e)), Severodvinsk–Akademik Lomonosov 1 and 2 (2 × 30 MW(e)) in the Russian Federation, and Shin Kori 2 (960 MW(e)) and Shin-Wolsong 1 (960 MW(e)) in the Republic of Korea. In addition, active construction resumed at Watts Bar 2 in the USA. This compares with three construction starts plus resumed construction at one reactor in 2006, and three construction starts plus resumed construction at two reactors in 2005.

Current expansion, as well as near term and long term growth prospects, remain centred in Asia. As shown in Table A-1, of the 33 reactors under construction, 19 were in Asia. By the end of the year, 28 of the last 39 new reactors to have been connected to the grid were in Asia.

In the USA, the Nuclear Regulatory Commission (NRC) approved one additional licence renewal of 20 years (for a total licensed life of 60 years), bringing the total number of approved licence renewals to 48. The operating licence for Canada's Gentilly 2 was renewed for a further four years to 2010. The licences for Loviisa 1 and 2 in Finland were renewed through 2027 and 2030, respectively.

In Bulgaria, the Belene site was approved for the construction of a new nuclear power plant. The three Baltic States, together with Poland, agreed in principle to construct a nuclear power plant in Lithuania by 2015, and Lithuania passed the necessary legislation to make construction possible. Turkey also passed new legislation to enable nuclear power plant construction.

In Finland, Fortum submitted an environmental impact assessment (EIA) programme for the possible construction of a new reactor at the Loviisa nuclear power plant, and Teollisuuden Voima Oy (TVO) submitted an EIA

TABLE A-1. Nuclear Power Reactors in Operation and Under Construction in the World (as of 31 December 2007)<sup>a</sup>

| Country                   | Reactors in Operation |             | Reactors under Construction |             | Nuclear Electricity Supplied in 2007 |            | Total Operating Experience through 2007 |        |
|---------------------------|-----------------------|-------------|-----------------------------|-------------|--------------------------------------|------------|---|--------|
|                           | No. of Units          | Total MW(e) | No. of Units                | Total MW(e) | TW·h                                 | % of Total | Years                                   | Months |
| Argentina                 | 2                     | 935         | 1                           | 692         | 6.7                                  | 6.2        | 58                                      | 7      |
| Armenia                   | 1                     | 376         |                             |             | 2.4                                  | 43.5       | 33                                      | 8      |
| Belgium                   | 7                     | 5 824       |                             |             | 45.9                                 | 54.1       | 219                                     | 7      |
| Brazil                    | 2                     | 1 795       |                             |             | 11.7                                 | 2.8        | 33                                      | 3      |
| Bulgaria                  | 2                     | 1 906       | 2                           | 1 906       | 13.7                                 | 32.1       | 143                                     | 3      |
| Canada                    | 18                    | 12 610      |                             |             | 88.2                                 | 14.7       | 546                                     | 1      |
| China                     | 11                    | 8 572       | 5                           | 4 220       | 59.3                                 | 1.9        | 77                                      | 3      |
| Czech Republic            | 6                     | 3 619       |                             |             | 24.6                                 | 30.3       | 98                                      | 10     |
| Finland                   | 4                     | 2 696       | 1                           | 1 600       | 22.5                                 | 28.9       | 115                                     | 4      |
| France                    | 59                    | 63 260      | 1                           | 1 600       | 420.1                                | 76.9       | 1 582                                   | 2      |
| Germany                   | 17                    | 20 430      |                             |             | 133.21                               | 25.9       | 717                                     | 5      |
| Hungary                   | 4                     | 1 829       |                             |             | 13.9                                 | 36.8       | 90                                      | 2      |
| India                     | 17                    | 3 782       | 6                           | 2 910       | 15.9                                 | 2.5        | 284                                     | 4      |
| Iran, Islamic Republic of |                       |             | 1                           | 915         |                                      |            |   |        |
| Japan                     | 55                    | 47 587      | 1                           | 866         | 267.3                                | 27.5       | 1 331                                   | 8      |
| Korea, Republic of        | 20                    | 17 451      | 3                           | 2 880       | 136.6                                | 35.3       | 299                                     | 8      |
| Lithuania                 | 1                     | 1 185       |                             |             | 9.1                                  | 64.4       | 41                                      | 6      |
| Mexico                    | 2                     | 1 360       |                             |             | 10.0                                 | 4.6        | 31                                      | 11     |
| Netherlands               | 1                     | 482         |                             |             | 4.0                                  | 4.1        | 63                                      | 0      |

9 TABLE A-1. Nuclear Power Reactors in Operation and Under Construction in the World (as of 31 December 2007)<sup>a</sup> (cont.)

| Country                  | Reactors in Operation |             | Reactors under Construction |             | Nuclear Electricity Supplied in 2007 |            | Total Operating Experience through 2007 |        |
|--------------------------|-----------------------|-------------|-----------------------------|-------------|--------------------------------------|------------|---|--------|
|                          | No. of Units          | Total MW(e) | No. of Units                | Total MW(e) | TW·h                                 | % of Total | Years                                   | Months |
| Pakistan                 | 2                     | 425         | 1                           | 300         | 2.3                                  | 2.3        | 43                                      | 10     |
| Romania                  | 2                     | 1 305       |                             |             | 7.1                                  | 13.0       | 11                                      | 11     |
| Russian Federation       | 31                    | 21 743      | 6                           | 3 639       | 148.0                                | 16.0       | 932                                     | 4      |
| Slovakia                 | 5                     | 2 034       |                             |             | 14.2                                 | 54.3       | 123                                     | 7      |
| Slovenia                 | 1                     | 666         |                             |             | 5.4                                  | 41.6       | 26                                      | 3      |
| South Africa             | 2                     | 1 800       |                             |             | 12.6                                 | 5.5        | 46                                      | 3      |
| Spain                    | 8                     | 7 450       |                             |             | 52.7                                 | 17.4       | 253                                     | 6      |
| Sweden                   | 10                    | 9 034       |                             |             | 64.3                                 | 46.1       | 352                                     | 6      |
| Switzerland              | 5                     | 3 220       |                             |             | 26.5                                 | 40.0       | 163                                     | 10     |
| Ukraine                  | 15                    | 13 107      | 2                           | 1 900       | 87.2                                 | 48.1       | 338                                     | 6      |
| United Kingdom           | 19                    | 10 222      |                             |             | 57.5                                 | 15.1       | 1 419                                   | 8      |
| United States of America | 104                   | 100 582     | 1                           | 1 165       | 806.6                                | 19.4       | 3 291                                   | 9      |
| Total <sup>b,c</sup>     | 439                   | 372 208     | 33                          | 27 193      | 2 608.1                              | 14         | 13 036                                  | 5      |

<sup>a</sup> Data are from the IAEA's Power Reactor Information System. (<http://www.iaea.org/programmes/a2/index.html>)

<sup>b</sup> Note: The total includes the following data in Taiwan, China:

- 6 units, 4921 MW(e) in operation; 2 units, 2600 MW(e) under construction;
- 39.0 TW·h of nuclear electricity generation, representing 19.3% of the total electricity generated in 2007;
- 158 years, 1 month of total operating experience at the end of 2007.

<sup>c</sup> The total operating experience includes also shut down plants in Italy (81 years) and Kazakhstan (25 years, 10 months).

programme for a possible new reactor at the Olkiluoto nuclear power plant. In Canada, Energy Alberta applied for a site licence for a new nuclear power plant in northwest Alberta. Most of its power would be used for extraction of oil from local tar sands.

In the USA, the NRC issued its first three early site permits (ESPs), certifying the Clinton site in Illinois, the Grand Gulf site in Mississippi and the North Anna site in Virginia as suitable for new construction. It is currently processing two additional ESP applications. Also in 2007, the NRC received four applications for combined licences (COLs), the first applications for new nuclear reactors in the USA in nearly 30 years. The NRC expects a total of 21 such applications, for a total of 32 reactors, by the end of 2009.

In the United Kingdom, in 2007, the government completed a public consultation on nuclear energy and potential new construction. In January 2008, it published a White Paper entitled *Meeting the Energy Challenge*, which stressed that it was in the public interest for nuclear energy to continue to form part of the United Kingdom's low carbon energy mix in order to help meet carbon reduction targets and ensure secure energy supplies. In the opening phase of the generic design assessment (GDA) of new nuclear reactors, UK regulators determined that all four submitted designs, from Atomic Energy of Canada Limited, AREVA, GE–Hitachi and Toshiba–Westinghouse, met the eligibility criteria for the first stage of the pre-licensing process.

## **A.2. Projected Growth for Nuclear Power**

Each year the IAEA updates its low and high projections for global growth in nuclear power. In 2007, both the low and high projections were revised upwards. In the updated low projection, global nuclear power capacity and generation reach 447 GW(e) and 3325 TW·h, respectively, in 2030, compared to 370 GW(e) and 2660 TW·h at the end of 2006. In the updated high projection they reach 691 GW(e) and 5141 TW·h.

In the low projection, 145 of today's reactors will have been retired by 2030, and 178 new reactors will have been built. Eighty-five per cent of the retirements will be in Eastern and Western Europe. While there will be new reactors built in all regions, most will be in the Far East and Eastern Europe, with substantial but less new construction also in the Middle East and South Asia.

In the high projection, there are only 82 retirements, and there is more than twice as much new construction, 357 new reactors by 2030. Most of the retirements would still be in Europe. New construction would be spread more broadly, although the Far East, Eastern Europe, and the Middle East and South Asia would have the most.

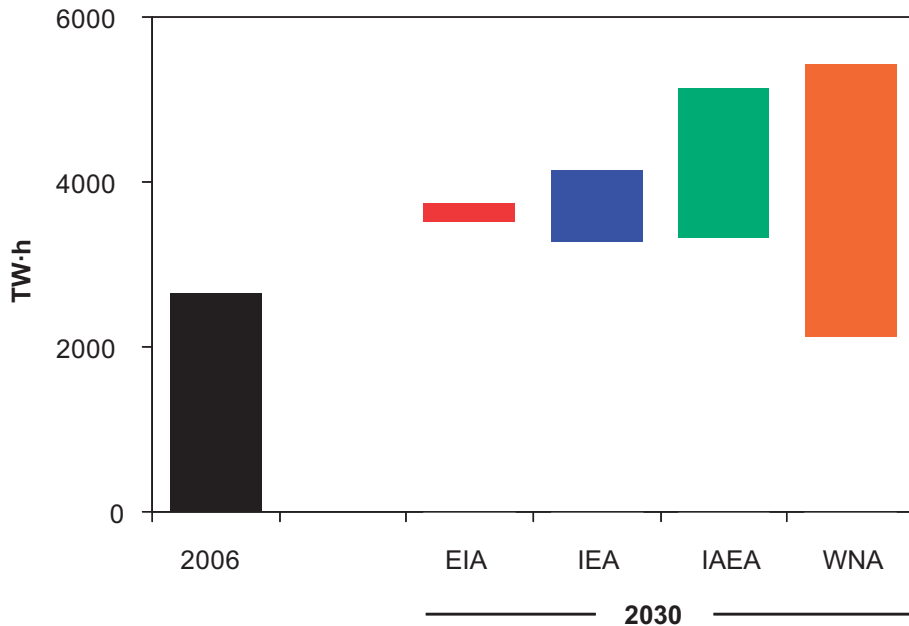


FIG. A-1. Comparison of nuclear power projections by the EIA, IEA, IAEA and WNA.

The IAEA's were not the only nuclear projections to have been revised upwards in 2007. Updated projections were also published in 2007 by the US Energy Information Administration (EIA), the OECD International Energy Agency (IEA) and the World Nuclear Association (WNA). Each organization raised its nuclear projections with one exception. The WNA reduced the high end of its range slightly. Figure A-1 compares the ranges of the 2007 nuclear projections of the EIA, IEA, IAEA and WNA.

### A.3. Internationalization of the Nuclear Reactor Industry

The nuclear reactor industry has been continually restructuring in recent decades as shown in Fig. A-2. However, rising expectations for the future expansion of nuclear power have contributed to several major developments over the past 18 months. Towards the end of 2006, Toshiba acquired a majority share of Westinghouse. In 2007, it then sold 10% of this share to Kazatomprom, the Kazakh State owned uranium producer. Also, towards the end of 2006, AREVA and Mitsubishi Heavy Industries (MHI) announced a new alliance to begin development of a new 1000 MW(e) nuclear power plant. General Electric (GE) and Hitachi also formed an alliance in 2007 to provide services for operating BWRs and to compete for new reactor projects around the world.



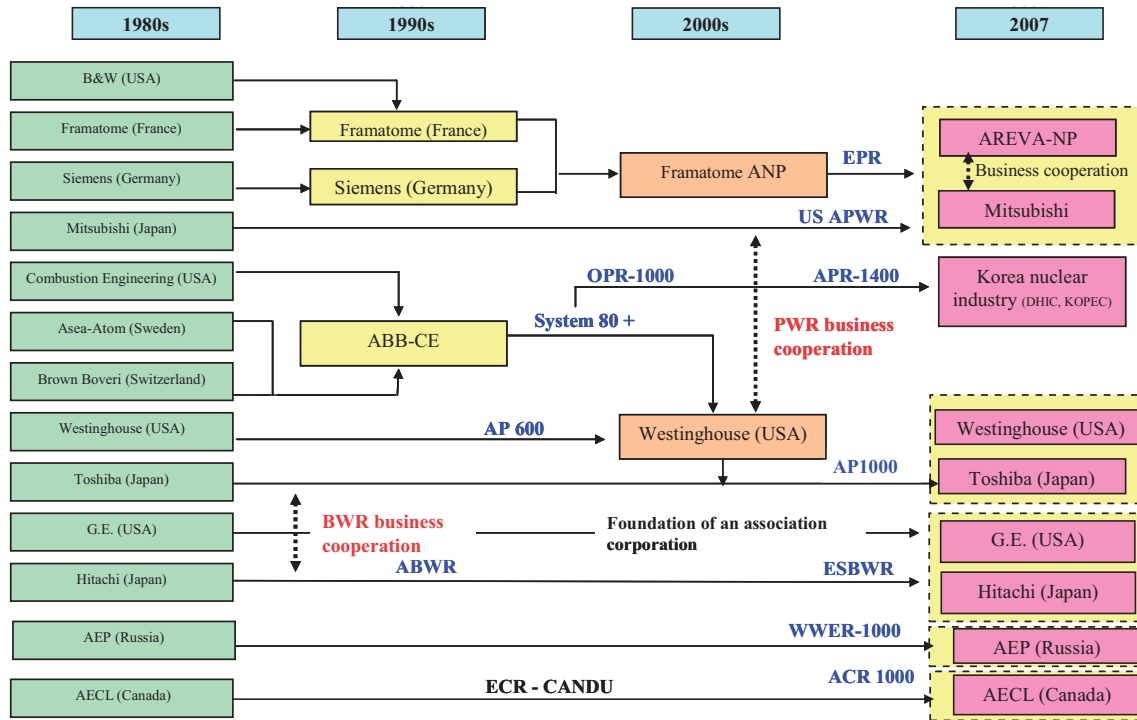


FIG. A-2. Evolution of the nuclear reactor industry (AP600/AP1000: Advanced Passive PWR (600/1000MW(e)); EPR: European Pressurized Water Reactor; ABWR: Advanced Boiling Water Reactor; ESBWR: Economic Simplified Boiling Water Reactor; APR 1400: Advanced Power Reactor 1400; OPR 1000: Optimized Power Reactor 1000; ACR: Advanced CANDU Reactor; ECR: Enhanced CANDU Reactor; WWER: Vodo-Vodyanoi Energetichesky Reactor; US APWR: US Advanced Pressurized Water Reactor; DHIC: Doosan Heavy Industry Company; AEP: Atomernergoprojekt).

#### A.4. The Front End of the Fuel Cycle<sup>1</sup>

*Identified conventional uranium resources*, recoverable at a cost of less than \$130/kg U, are currently estimated at 5.5 million tonnes uranium (Mt U). This is a significant increase of about 800 000 t U relative to 2005, due mainly to increases reported by Australia, the Russian Federation, South Africa and Ukraine. For reference, the spot market uranium price reached almost \$360/kg in June before dropping back to \$240/kg in December.

*Undiscovered conventional resources* are estimated at 7.3 Mt U at a cost of less than \$130/kg U. This includes both resources that are expected to occur either in or near known deposits, and more speculative resources that are thought to exist in geologically favourable, yet unexplored areas. There are also an estimated further 3.0 Mt U of speculative resources for which production costs have not been specified.

*Unconventional uranium resources and thorium* further expand the resource base. Unconventional resources are those from which uranium is only recoverable as a minor by-product. Very few countries currently report unconventional resources. Past estimates of potentially recoverable uranium associated with phosphates, non-ferrous ores, carbonatite, black schist and lignite are of the order of 10 Mt U. Thorium, which can also be used as a nuclear fuel resource, is abundant, widely distributed in nature, and an easily exploitable resource in many countries. Worldwide resources have been estimated to be about 6 Mt thorium. Although thorium has been used as fuel on a demonstration basis, significant further work is needed before it can be considered on an equal basis with uranium.

Seawater contains an estimated 4000 Mt U, but at a very low concentration of 3–4 parts per billion (ppb). Thus, 350 000 t of water would have to be processed to produce one kg of uranium. Currently, such production is too expensive. Research was carried out in Germany, Italy, Japan, the United Kingdom and the USA in the 1970s and 1980s. Research continues in Japan with estimated production costs in a test operation of \$750/kg U.

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<sup>1</sup> This section is based on the forthcoming 'Red Book' (OECD NUCLEAR ENERGY AGENCY-INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium 2007: Resources, Production and Demand, OECD, Paris (2008)), more detailed information on IAEA activities concerning the front end of the fuel cycle is available in relevant sections of the IAEA Annual Report 2006 (<http://www.iaea.org/Publications/Reports/Anrep2006/>) and at <http://www.iaea.org/OurWork/ST/NE/NEFW/index.html>.

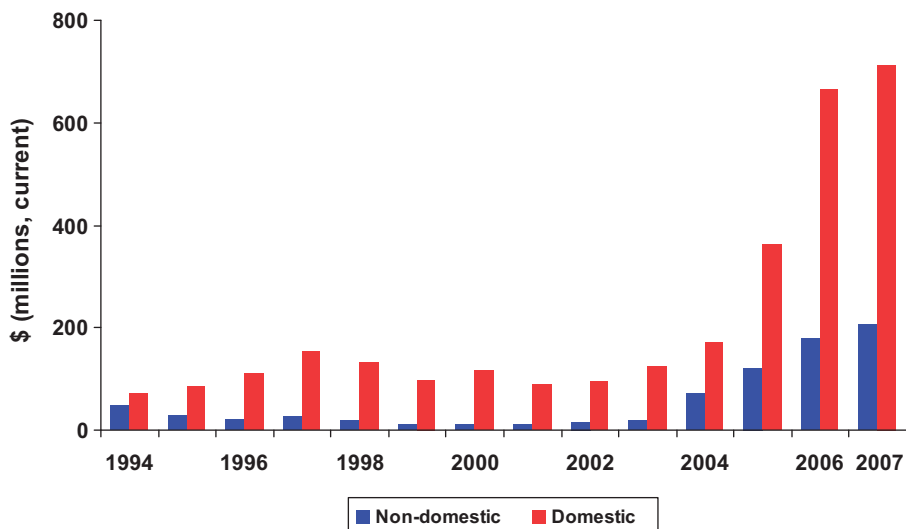


FIG. A-3. Trends in reported uranium exploration and development expenditures. Values for 2007 are estimates.

Driven by increases in the uranium spot price, uranium exploration and development increased significantly in 2005 and 2006 and are expected to increase further in 2007 (see Fig. A-3). This increase has occurred both in countries that have explored and developed uranium deposits in the past and in many countries new to uranium exploration.

In 2006, uranium production worldwide was 39 695 t U, down almost 6% from 42 114 t U in 2005. It is estimated that production will increase in 2007 to 43 600 t U. Australia and Canada alone accounted for 44% of world production in 2006. Together with another six countries (Kazakhstan, Namibia, Niger, the Russian Federation, the USA and Uzbekistan) they accounted for 92% of production.

Uranium production in 2006 covered only about 60% of the world's reactor requirements of 66 500 t U. The remainder was covered by five secondary sources: stockpiles of natural uranium, stockpiles of enriched uranium, reprocessed uranium from spent fuel, mixed oxide (MOX) fuel with uranium-235 partially replaced by plutonium-239 from reprocessed spent fuel and re-enrichment of depleted uranium tails (depleted uranium contains less than 0.7% uranium-235).

The next step in the fuel cycle is conversion. Currently, supply and demand are balanced in the conversion market, and supply capacity is expanding as needed to meet expected growth. The US NRC renewed the licence of the Metropolis uranium hexafluoride (UF<sub>6</sub>) conversion plant for a

further ten years to May 2017. At the same time the plant's capacity was increased by 20%. AREVA announced the launch of the Comurhex II project, a new uranium conversion facility in southern France with first industrial production planned for 2012.

In the area of enrichment, there is some overcapacity. However, the older diffusion plants are expected to close in the near future, and they will be replaced by centrifuge plants that require less input energy. In 2007, the NRC issued a construction licence for USEC's new American Centrifuge Plant. Construction began in April, and testing of the lead cascade began in September. Japan Nuclear Fuel Limited (JNFL) started cascade tests at its advanced centrifuge uranium enrichment plant at Rokkasho with a new, more effective type of centrifuge. Several companies signed non-binding letters of intent to contract for uranium enrichment services from GE-Hitachi Nuclear Energy, which is working to commercialize the next generation SILEX laser enrichment technology, now known as Global Laser Enrichment (GLE) technology.

In May, Kazakhstan and the Russian Federation established the International Uranium Enrichment Centre (IUEC) in East Siberia. In December the Armenian Government announced it would also join the Centre, which it did in February 2008. The IUEC is one step in President Vladimir Putin's 2006 proposal to create "a system of international centres providing nuclear fuel cycle services, including enrichment, on a non-discriminatory basis and under the control of the IAEA". Discussions are also in progress for a joint venture between Kazakhstan and the Russian Federation to build another enrichment plant at Angarsk.

### **A.5. Spent Fuel and Reprocessing<sup>2</sup>**

Annual discharges of spent fuel from the world's reactors total about 10 500 tonnes of heavy metal (t HM) per year. Two different management strategies are being implemented for spent nuclear fuel. In the first strategy, spent fuel is reprocessed (or stored for future reprocessing) to extract usable material (uranium and plutonium) for new MOX fuel. Approximately one third of the world's discharged spent fuel has been reprocessed. In the second strategy, spent fuel is considered as waste and is stored pending disposal. Based on more than 50 years of experience with storing spent fuel safely and

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<sup>2</sup> More detailed information on IAEA activities concerning spent fuel and reprocessing is available in relevant sections of the IAEA Annual Report 2006 (<http://www.iaea.org/Publications/Reports/Anrep2006/>).

effectively, there is a high level of technical confidence in both wet and dry storage technologies and in the ability to cope with rising volumes pending implementation of final repositories for all high level waste.

As of today, China, France, India, Japan and the Russian Federation reprocess most of their spent fuel or store it for future reprocessing. Reprocessing plants are in operation in France, India, the Russian Federation and the UK, although in 2007 the UK plant at Sellafield was out of operation due to an internal leak. In Japan, active testing began at the new Rokkasho vitrification plant, with separated high level wastes being combined with borosilicate glass. However, because of limited fabrication of MOX fuel, less than 50% of the world's existing reprocessing capacity is currently used. Canada, Finland, Sweden and the USA have currently opted for direct disposal, although in 2006 the USA announced a Global Nuclear Energy Partnership (GNEP), which includes the development of advanced recycling technologies for use in the USA. Most countries have not yet decided which strategy to adopt. They are currently storing spent fuel and keeping abreast of developments associated with both alternatives.

#### **A.6. Waste and Decommissioning**

The Finnish, French, Swedish and US repository programmes continue to be the most developed, but none is likely to have a repository in operation much before 2020. The construction of the ONKALO underground characterization facility, which could be part of the repository at Olkiluoto in Finland, is progressing according to plan. By the end of 2007, the tunnel had reached 2.5 km in length and 240 m in depth. Following new legislation in 2006 the French repository programme has moved into a detailed siting phase with the goal of applying for a licence in 2015. In Sweden, extensive site investigations have been finalized at two sites, and a licence application for the selected site is planned for 2009. In the USA, preparation of the licence application for a repository at Yucca Mountain is well advanced, and the application is planned for mid-2008. In 2007, the Canadian Government accepted the proposal of its Nuclear Waste Management Organization (NWMO) for an 'adaptive phased management' approach to the long-term management of spent nuclear fuel with the goal of finding and preparing a repository site with continued monitoring for the possibility of retrieval.

Concerning decommissioning, the release for unrestricted public use of most of the site of the Big Rock Point nuclear power plant, which was decommissioned in 2006, was approved by the NRC, as was the similar release of most of the Yankee Rowe nuclear power plant site. Big Rock Point's and Yankee Rowe's licences will still apply to the sites' dry cask storage facilities. Thus, as

of 2007, ten power plants around the world had been completely decommissioned with their sites released for unconditional use. Seventeen plants have been partially dismantled and safely enclosed. Thirty-two are being dismantled prior to eventual site release. Thirty-four reactors are undergoing minimum dismantling prior to long term enclosure, including four Magnox reactors in the UK, Sizewell A-1 and -2 and Dungeness A-1 and -2, which were shut down on 31 December 2006.

Following a series of consultations with experts from Member States representing both potential donors and recipients, the IAEA launched a new Network of Centres of Excellence for Decommissioning at the General Conference in September 2007. The network's purpose is to improve the flow of knowledge and experience among those engaged in decommissioning and to encourage organizations in developed Member States to contribute to the activities of Member States requiring decommissioning assistance.

## **A.7. Additional Factors Affecting the Future of Nuclear Power**

### *A.7.1. Sustainable Development and Climate Change<sup>3</sup>*

The UN Commission on Sustainable Development (CSD) first discussed energy at its ninth session (CSD-9) in 2001, and all parties agreed that “the choice of nuclear energy rests with countries”. The 2002 World Summit on Sustainable Development (WSSD) reaffirmed this conclusion and the CSD placed the topic of energy on its agenda for its 14th and 15th sessions. CSD-14 in 2006 was a ‘review session’ to analyse the impact of energy policy changes and technological advances on progress towards sustainable development. At the corresponding ‘policy session’, CSD-15 in May 2007, no agreement was reached on a new text on energy issues, leaving the decisions reached at CSD-9 and at the WSSD as the operative CSD agreements on energy.

The Kyoto Protocol, which entered into force in February 2005, requires most developed countries to limit their greenhouse gas (GHG) emissions in the ‘first commitment period’, which started on 1 January 2008 and runs through 2012. Different countries have adopted different policies in response. Not all benefit nuclear power despite its low GHG emissions, but in the longer run the limits on GHG emissions should make nuclear power increasingly attractive.

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<sup>3</sup> More detailed information about IAEA activities on energy related aspects of sustainable development and climate change is available in relevant sections of the IAEA Annual Report 2006 (<http://www.iaea.org/Publications/Reports/Anrep2006/>) and at <http://www.iaea.org/OurWork/ST/NE/Pess/climate.shtml>.

In November 2007, the Intergovernmental Panel on Climate Change (IPCC)<sup>4</sup> published its Fourth Assessment Report, which confirmed that the effects of climate change have already been observed and that scientific findings indicate that near-term action is needed to reduce GHG emissions. In December, the Thirteenth Conference of the Parties to the UN Framework Convention on Climate Change (COP-13) and Third Meeting of the Parties to the Kyoto Protocol (COP/MOP-3) were held in Bali. The meetings produced the Bali Action Plan<sup>5</sup>, which includes the decision “to launch a comprehensive process to enable the full, effective and sustained implementation of the Convention through long-term cooperative action...” in order to adopt a decision at COP-15 regarding a long-term global goal for emission reductions. This includes verifiable mitigation commitments or actions by all developed country Parties, verifiable mitigation actions by developing country Parties in the context of sustainable development, and reduced emissions from deforestation and forest degradation in developing countries. The Action Plan does not include specific quantified emission reduction targets. Nuclear power was not a principal topic of discussion.

#### A.7.2. *Economics*

Nuclear power plants have a ‘front-loaded’ cost structure, i.e. they are relatively expensive to build but relatively inexpensive to operate. Thus, existing well-run operating nuclear power plants continue to be a competitive and profitable source of electricity. For new construction, however, the economic competitiveness of nuclear power depends on the alternatives available, on the overall electricity demand in a country and how fast it is growing, on the market structure and investment environment, on environmental constraints, and on investment risks due to possible political and regulatory delays or changes. Thus, economic competitiveness is different in different countries and situations.

Noteworthy trends in 2007 include rising prices of all inputs for new construction, from concrete to labour, due to rapid economic growth and high demand. This trend may continue and more than offset any anticipated decrease in construction costs due to learning effects. This trend affects all

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<sup>4</sup> The previous month, the IPCC and former US Vice President Al Gore were awarded the Nobel Peace Prize “for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change”.

<sup>5</sup> See [http://unfccc.int/files/meetings/cop\\_13/application/pdf/cp\\_bali\\_action.pdf](http://unfccc.int/files/meetings/cop_13/application/pdf/cp_bali_action.pdf).

energy sources, from coal to wind, but the more front-loaded the cost structure, the greater the impact. Perhaps the largest uncertainty for today’s potential investors in nuclear power is the future price of carbon emissions in different countries.

### A.7.3. Safety<sup>6</sup>

Safety indicators, such as those published by the World Association of Nuclear Operators and reproduced in Figs A-4 and A-5, improved dramatically in the 1990s. In recent years, in some areas the situation has stabilized. However, the gap between the best and worst performers is still large, providing substantial room for continuing improvement.

More detailed safety information and recent developments related to all nuclear applications are presented in the IAEA’s annual Nuclear Safety Review (GC(52)/INF/2).

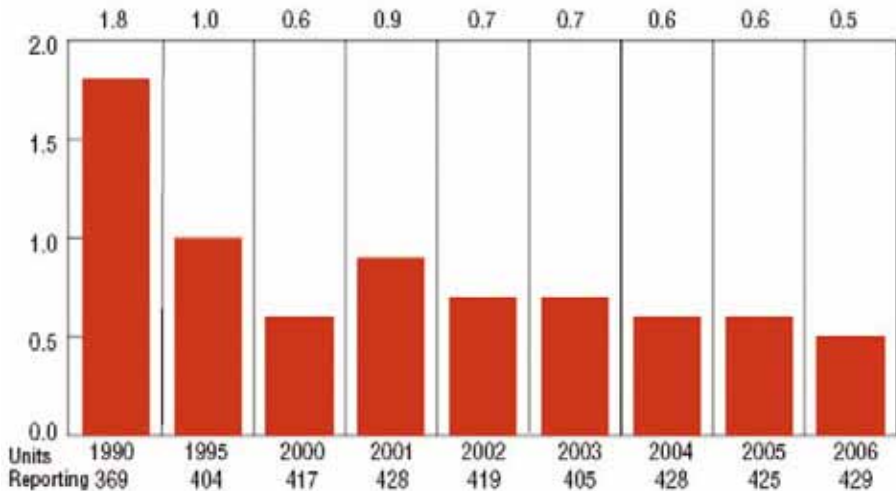


FIG. A-4. Unplanned scrams per 7000 hours critical. Source: WANO 2006 Performance Indicators.

<sup>6</sup> More detailed information on IAEA activities concerning nuclear safety is available in relevant sections of the IAEA Annual Report 2006 (<http://www.iaea.org/Publications/Reports/Anrep2006/>) and at <http://www-ns.iaea.org/>.



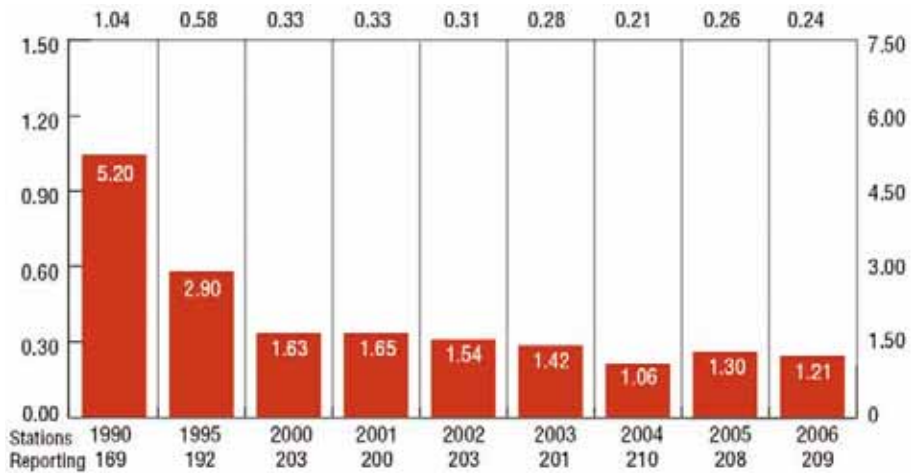


FIG. A-5. Industrial accidents at nuclear power plants per 200 000 person-hours worked (left scale and at the top of the chart) and per 1 000 000 person-hours worked (right scale and on the bars). Source: WANO 2006 Performance Indicators.

#### A.7.4. Human Resource Development

Rising expectations for nuclear power have focused attention on the human resources that would be required for these expectations to be realized, encompassing both skilled workers and graduates from nuclear degree programmes.

In 2007, the OECD/NEA's Steering Committee for Nuclear Energy released a statement regarding the government role in ensuring qualified human resources in the nuclear field. The OECD/NEA noted that recent studies had shown that nuclear education and training had suffered declines of various degrees in OECD/NEA countries, and if no action were taken, the nuclear sector would risk facing a shortage of qualified personnel to ensure the appropriate regulation and operation of existing nuclear facilities as well as the construction of new ones. For Europe, this conclusion was reinforced in a 2007 European Commission report, *The Sustainable Nuclear Energy Technology Platform: A Vision Report*, which recommended that "...education and training in nuclear science and engineering must be strengthened."

Following a period of decline, the current trend for university enrolment is one of modest growth, affected by:

- The continuing underlying need for human resources in non-power applications, e.g. medical applications and agriculture;

- The still existing need in mature nuclear programmes and established nuclear organizations to replace retiring staff;
- Expectations of future growth leading to an increased intake of new staff in the nuclear industry, including utilities, regulators and research organizations.

Prospective future growth, recent initiatives in technology innovation (see Section B), increased government funding, accelerating nuclear programmes in countries like China and India and renewed nuclear programmes in other countries are also attracting new students, e.g. dedicated government funding in the USA has led to a quadrupling, from 2000 to 2007, in undergraduate enrolment in nuclear fields (from 500 to 2000).

Human resource issues are also being addressed by expanding nuclear knowledge management programmes through international organizations and nuclear industry organizations. In addition to the IAEA and the training it provides in areas ranging from reactor simulators to nuclear law,<sup>7</sup> examples include regulators like the NRC, utilities like Germany's Energie Baden-Württemberg (EnBW) and designers like Canada's AECL. In addition, academic networking and cooperation have become more widespread. The Asian Network for Education in Nuclear Technology has grown to 28 member institutions from 12 countries. The European Nuclear Education Network now has 28 members, plus 16 associate members, from 17 countries. The Third Summer Institute of the World Nuclear University was held in Seoul, the Republic of Korea in 2007, attracting 102 fellows from 35 countries.

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<sup>7</sup> In 2007 the IAEA's technical cooperation programme supported projects involving 2287 participants in training courses and 1661 fellows and scientific visitors.

## B. ADVANCED FISSION AND FUSION

### B.1. Advanced Fission<sup>8</sup>

#### B.1.1. INPRO and GIF

The IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) provides an open international forum for studying nuclear power options and associated requirements. It helps to build up competence for developing and deploying innovative nuclear energy systems (INSS) and assists Member States in coordinating related collaborative projects.

INPRO has developed a methodology for the assessment of INSS. It is currently being used in assessment studies by Argentina, Armenia, Brazil, China, France, India, Ukraine and the European Commission, and in a joint assessment of a closed fuel cycle with fast reactors by Canada, China, France, India, Japan, the Republic of Korea, the Russian Federation and Ukraine.

INPRO is also developing common user criteria for the development and deployment of nuclear power plants in developing countries. The objective is to facilitate understanding between technology users and holders about users' needs.

Finally, work is progressing on 12 collaborative project proposals that were endorsed in July 2007 by the INPRO Steering Committee.

Through a system of contracts and agreements, the Generation IV International Forum (GIF) coordinates research activities on the six next generation nuclear energy systems selected in 2002 and described in A Technology

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<sup>8</sup> More detailed information on IAEA activities concerning advanced fission reactors is available in relevant sections of the IAEA Annual Report 2006 (<http://www.iaea.org/Publications/Reports/Anrep2006/>). See also INTERNATIONAL ATOMIC ENERGY AGENCY, Terms for Describing New, Advanced Nuclear Power Plants, IAEA-TECDOC-936 (1997); Status of Liquid Metal Cooled Fast Reactor Technology, IAEA-TECDOC-1083 (1999); Current Status and Future Development of Modular High Temperature Gas Cooled Reactor Technology, IAEA-TECDOC-1198 (2001); HWRs: Status and Projected Developments, Technical Reports Series No. 407 (2002); Review of National Accelerator Driven System Programmes for Partitioning and Transmutation, IAEA-TECDOC-1365 (2003); Status of Advanced Light Water Reactor Designs: 2004, IAEA-TECDOC-1391 (2004); Status of Innovative Small and Medium Sized Reactor Designs, IAEA-TECDOC-1485 (2005); Status of Small Reactor Designs without On-site Refuelling, IAEA-TECDOC-1536 (2007).

Roadmap for Generation IV Nuclear Energy Systems: gas cooled fast reactors (GFRs), lead cooled fast reactors, molten salt reactors, sodium cooled fast reactors (SFRs), supercritical water cooled reactors (SCWRs) and very high temperature reactors (VHTRs).

In 2007, the sodium cooled fast reactor project arrangements were signed for research and development of advanced fuel, component design and balance of plant, and the Global Actinide Cycle International Demonstration, which aims to demonstrate that fast neutron reactors can manage the whole actinide inventory. The SCWR and GFR system research plans were finalized, and, for VHTRs, project arrangements were in the final stages of negotiation to study the development and validation of VHTR materials, fuels and fuel cycle issues, and hydrogen production. INPRO and GIF cooperate to avoid duplication and create synergy, and in February 2008 they agreed on a 14-point joint action plan. It includes the use of GIF's economic evaluation model ECONS by the IAEA to estimate the costs of gas cooled reactors and the use by GIF of the IAEA's economic evaluation model for nuclear generated hydrogen, HEEP.

### *B.1.2. GNEP*

The Global Nuclear Energy Partnership (GNEP) is a cooperative effort by 19 countries<sup>9</sup> who agree on the necessity of expanding nuclear energy around the world. The aim is to accelerate development and deployment of advanced fuel cycle technologies to encourage development, protect the environment, and reduce the risk of nuclear proliferation. In 2007, GNEP established a ministerial level Executive Committee and a Steering Committee, both of which held initial meetings during the year, as well as working groups on reliable nuclear fuel services and infrastructure development.

### *B.1.3. Additional Development of Advanced Fission*

In addition to INPRO, GIF and GNEP, a number of countries, companies and partnerships are researching, developing and deploying advanced fission reactors. These programmes were summarized in the Nuclear Technology Review 2007.<sup>10</sup> Developments in 2007 were very much a continuation of the progress reported for 2006 and are therefore not re-summarized here.

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<sup>9</sup> As of the end of 2007.

<sup>10</sup> See <http://www.iaea.org/OurWork/ST/NE/Pess/assets/ntr2007.pdf>.

## **B.2. Fusion**

International efforts for achieving fusion as a future energy source received strong commitment from seven International Thermonuclear Experimental Reactor (ITER) project parties (China, the European Union, India, Japan, the Republic of Korea, the Russian Federation, and the USA) when the ITER Joint Implementation Agreement (JIA) was finalized and signed in a ministerial meeting in Paris on 21 November 2006. The Agreement was subsequently ratified by all the respective Governments. The JIA entered into force on 24 October 2007, thus making the ITER International Fusion Energy Organization a legal entity. The IAEA has been associated with this major international initiative for over 20 years, and the ITER parties have expressed keen interest in maintaining continued involvement of the IAEA. The IAEA serves as an important international contact point for ITER parties and all Member States for activities related to education and training in fusion. Experts from smaller fusion devices can help influence the final design of fusion reactors by meeting regularly under IAEA auspices to discuss their technical achievements. The IAEA also provides a forum for international experts investigating power plant design based on magnetic confinement and alternative schemes. The future fusion demonstration power plant will use experience acquired by ITER.

With the view to accelerating the realization of fusion energy, EURATOM and Japan have agreed to work together under the 'Broader Approach' agreement over the next ten years. The infrastructure needed to progress further towards a demonstration facility for the production of electricity from fusion power includes the International Fusion Materials Irradiation Facility (IFMIF) to be used for testing and qualifying materials for fusion reactors.

The Fifth International Conference on Inertial Fusion Sciences and Applications, held in Japan in September 2007, highlighted fusion achievements using lasers, radiation or heavy ion beams as drivers for compressing the deuterium–tritium fusion pellet. The integration of an IAEA Technical Meeting into this international conference provided the possibility for experts, supported through a coordinated research project on inertial fusion energy, to present their work to a broad and experienced audience, including major institutions such as the US National Ignition Facility, the French Laser Megajoule project and the Japanese Fast Ignition Realization Experiment (FIREX) projects at the Institute of Laser Engineering in Osaka, Japan. The year 2008 marks the 50th anniversary of the disclosure of results of civilian nuclear fusion research at the second "Atoms for Peace" conference held in 1958 in Geneva. The 22nd IAEA Fusion Energy Conference, FEC-2008, will be held in October

2008 at the same venue, the Palais des Nations in Geneva, and is being co-hosted by Switzerland to commemorate the 1958 event.

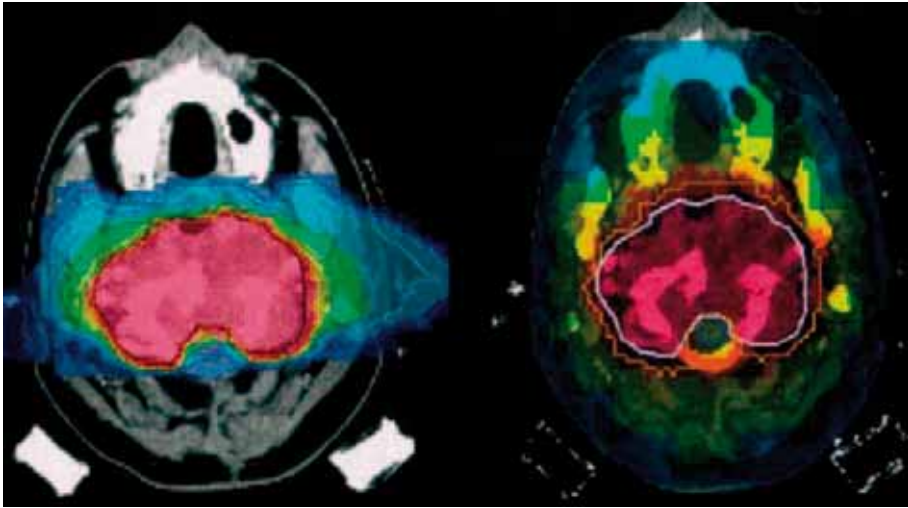
Interest in fusion activities is increasing in many countries. An example of this is the recent launch by the Brazilian Minister for Science and Technology of a Brazilian network of fusion research. This network will bring together the activities of different universities, research institutions and laboratories to establish priorities and foster international collaboration. Portugal hosted joint experiments on fusion allowing about 29 young international experts to use the Portuguese ISTTOK tokamak for experiments relevant to the future design of fusion experiments and remote participation in fusion experiments.

### **C. ATOMIC AND NUCLEAR DATA**

The International Conference on Nuclear Data for Science and Technology was held in Nice, France, from 22 to 27 April 2007. During the course of six days of intensive debate, special emphasis was placed on data needs for: innovative reactors and fuel cycles (safer, cleaner and more economical fission reactors); efforts to achieve fusion reactors (cf. ITER) and to test materials needed in such facilities (cf. International Fusion Material Irradiation Facility); accelerator driven systems (ADSs) designed for nuclear waste transmutation and energy production; medical applications, including radioisotope production, computer simulations of radiation doses to patients, and advanced cancer therapies using charged particles; and analytical techniques that are being adopted for cultural heritage diagnostics and materials composition analyses.

Scientists are collaborating in each of those areas, and national and international efforts are being made to clarify and resolve atomic and nuclear data issues for improved understanding and quantification in such studies.

A new project called EFNUDAT (European Facilities for Nuclear Data Measurements), an Integrated Infrastructure Initiative funded by the European Commission, was launched in Karlsruhe, Germany, on 11 January 2007. The main objective of EFNUDAT is to promote the coherent use and integration of infrastructure related services via networking, transnational access to participating facilities for nuclear data measurements and joint research activities. EFNUDAT will provide a convenient platform for the integration of all scientific efforts to generate high quality nuclear data measurements in support of waste transmutation studies and design studies for



*FIG. C-1. Comparison of a treatment plan with carbon ions (left panel) and with conventional X rays (right panel). The target volume is irradiated but the dose to healthy tissues for carbon ions is much lower. The accuracy of the planning depends on the reliability of the charged particle database (source: GSI, Germany).*

Generation IV systems that are being developed to reduce radioactive waste production in power generation.

Both the USA and OECD/NEA released new nuclear applications libraries in 2006/2007 (US ENDF/B-VII and JEFF-3.1.1, respectively) in which large quantities of new data were introduced to improve further the characterization and control of fission and fusion reactor operations. The data will be used to improve reliability and efficiency, and will assist in waste reduction. Data for the development of accelerator driven systems can also be extracted. These libraries, together with the Experimental Nuclear Reaction Data (EXFOR) database, are being used for non-destructive nuclear analytical techniques such as neutron activation analysis and ion beam analysis that are used for the chemical and isotopic characterization of valuable objects of which only a minute amount of sample is necessary.

In addition to traditional X rays and beta and gamma sources for treatment and diagnosis, the direct irradiation of patients with accelerator produced charged particles has become increasingly important. One advantage of charged particles is the avoidance of irradiation of healthy tissue (see Fig. C-1). Recognizing the need for accurate data to design and plan patient treatment facilities, the IAEA is encouraging the evaluation of charged particle interaction data for medical applications.

## D. ACCELERATOR AND RESEARCH REACTOR APPLICATIONS

### D.1. Accelerators

Construction of the world's first non-scaling fixed field alternating gradient (NS-FFAG) accelerator (Fig. D-1) has started at the Daresbury Laboratory in the United Kingdom. The NS-FFAG accelerator, invented in 1999, is anticipated to have a major impact as the next generation hospital-based clinical accelerators for proton and carbon ion beam treatment of cancers. It is smaller, simpler to operate, and cheaper than cyclotron and synchrotron cancer therapy counterparts. This electron beam NS-FFAG accelerator will provide information for the eventual design and construction of a prototype accelerator for medical applications, and knowledge to evaluate its potential as a proton driver for use in accelerator driven subcritical reactors, waste transmutation, and materials research. This first NS-FFAG is being designed by an international collaboration involving Brookhaven National Laboratory (BNL), the European Organization for Nuclear Research (CERN), Fermi National Accelerator Laboratory (Fermilab), Laboratory for Subatomic Physics and Cosmology (LPSC), TRIUMF, and the UK's accelerator science centres, and is expected to become operational in 2009.

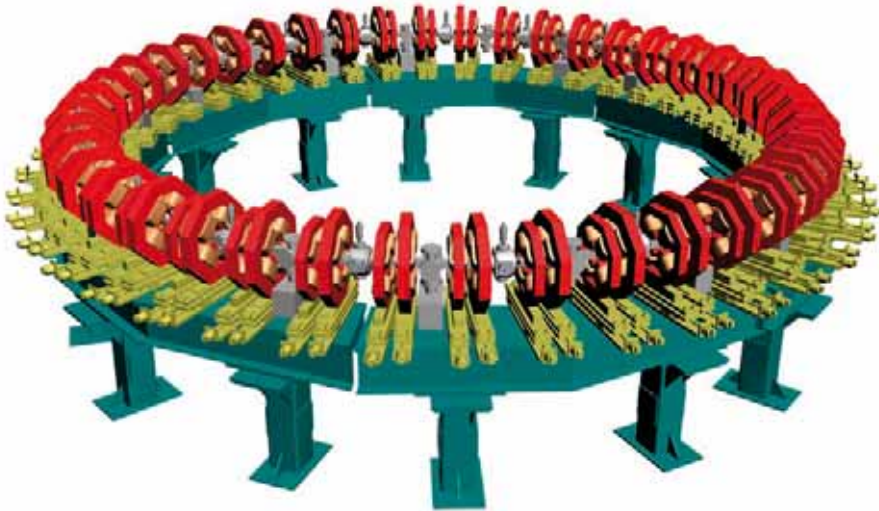


FIG. D-1. Conceptual layout of the NS-FFAG accelerator ring.



## D.2. Research Reactors

In France, construction of the 100 MW(th) Jules Horowitz materials test reactor started in March 2007. The reactor, which will be a key EU infrastructure facility to support nuclear power development, produce radioisotopes and irradiate silicon for electronic use, is being built by the French Atomic Energy Commission (CEA) and financed by an international consortium. Pending the availability of high density low enriched uranium (LEU) uranium–molybdenum (U–Mo) fuel, the reactor will start up using uranium silicide fuel enriched to 27%. In Belgium, development of a new accelerator driven irradiation facility, MYRRHA, is at an advanced stage. MYRRHA is intended to serve as a European multipurpose research facility to study, among other things, transmutation of high-level long-lived radioactive waste and the performance of innovative components and materials for future energy systems.

Regional cooperation was extensively discussed at the International Conference on Research Reactors: Safe Management and Effective Utilization, held in Sydney, Australia, 5–9 November 2007. The conference concluded, inter alia, that international collaboration had been successful in several examples, and was the key to success in meeting the needs of customers and maintaining financially strong institutions in the future; that consortia, coalitions and peer group networks could develop and maintain effective utilization; and that the IAEA should continue to facilitate formation of groupings of research reactor operating organizations, recognizing that no one model is suitable in all situations.

The Reduced Enrichment for Research and Test Reactors (RERTR) Programme, and other initiatives such as the Global Threat Reduction Initiative (GTRI), seek to convert research reactors using high enriched uranium (HEU) fuel to LEU fuel. Worldwide, 55 research reactors were converted to LEU fuel by the end of 2007 and another 46 are planned for conversion with existing qualified fuels. Development and qualification of very high density advanced U–Mo fuels, that still need qualification, are necessary to convert from HEU to LEU 28 additional research reactors. International coordination of the essential development and qualification of high density LEU fuels has progressed well, as presented in the annual meetings of the RERTR Programme and the International Topical Meeting on Research Reactor Fuel Management (RRFM) in 2007.

Efforts to address the shortcomings in behaviour of very high density U–Mo dispersion fuels especially at high power and temperature were reported in the *Nuclear Technology Review 2007*. Several potential remedies including changes to the fuel and matrix chemistry or replacement of the

aluminium matrix with another material, as well as an alternate strategy of elimination of the matrix altogether (monolithic fuel) are being investigated collaboratively by an International Fuel Development Working Group that includes Argentina, Canada, France, Germany, the Republic of Korea, the Russian Federation and the USA.

Results of the post-irradiation examination of dispersion U–Mo fuel miniplates irradiated in US tests showed that silicon additions of 2-5% drastically reduced the extent of interaction between the fuel and matrix and effectively solved swelling problems at the power and temperature conditions of the tests.

Results of French irradiation tests of full size U–Mo dispersion plates with ground or atomized U–Mo powder and different aluminium matrix compositions with or without the addition of silicon showed very good irradiation performance at high power level and burnup even without the addition of silicon to the matrix. This behaviour is, in principle, attributable to the presence of a protective oxide layer around the particles.

U–Mo monolithic fuel with a higher uranium density is required for the conversion of high performance research reactors and significant effort is being devoted to its development. Monolithic fuel miniplates have been irradiated with good results at both moderate power density to moderate burn-up and very high power density to high burn-up. Different fabrication techniques for U–Mo monolithic fuel are being developed and pursued.

## **E. NUCLEAR TECHNOLOGIES IN FOOD AND AGRICULTURE**

### **E.1. Crop Improvements**

Induced crop mutations have become the method of choice for developing superior crop varieties, resulting in the official release for cultivation of approximately 3000 mutant varieties (Fig. E-1). The ‘first generation’ mutants, in line with the breeding objectives of the times, addressed the need for enhanced yields through superior efficiencies in nutrient use and resistance to biotic and abiotic stresses. With the attainment of yield plateaux for the most important crops, emphasis in breeding programmes has now moved towards the introduction of added value traits that permit diversification of end uses, attract more income through greater

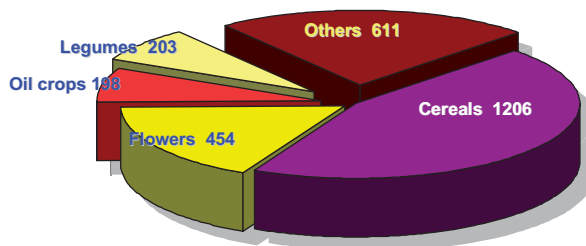


FIG. E-1. Mutant varieties (2007) Source: FAO/IAEA Mutant Varieties Database (<http://www-mvd.iaea.org>).

competitiveness and address specific dietary requirements. These traits require only subtle changes to hereditary factors (genes), a situation that is particularly suited for induced mutagenesis.

Recently released induced mutant crop varieties with enhanced quality traits, that meet the above specific needs, include two more nutritious barley varieties (reduced phytic acid content potentially increases bioavailability of iron, zinc and calcium), “Clearwater” and “Herald”. By using these two varieties in animal feeds, for example, farmers are making significant savings by avoiding the need to purchase expensive dietary supplements to counter the effects of phytic acid. The use of these mutants also contributes to a cleaner environment, as the pollution of ground and surface waters with excess phosphorus associated with livestock fed with barley varieties that are high in phytic acid is largely eliminated.

Induced mutations are also expanding potential uses of soybean by enhancing its nutritional value. The variety Sakukei 4, recently released in Japan, has the ability to fix nitrogen, and thus essentially becomes its own fertilizer, overcoming the need for other fertilizers. This translates into substantial savings for farmers. Other induced mutant soybean varieties recently released include the “Yumenori” variety, which has high content of the ‘good’ protein precursor glycine, and “Ichihime”, which is free of lipoxigenase, a naturally occurring plant enzyme involved in the genesis of diseases such as asthma and coronary heart diseases.

## E.2. Enhanced Biofuel Generation

Many countries have set targets and timescales for supplementing gasoline with fuel from renewable resources. The production of ethanol and biodiesel will need to be increased to meet those targets, many of which have been set for the near future. Amongst other endeavours this will require a switch from starch based to cellulose based ethanol production. The genetic

enhancement of biomass crops offers opportunities to improve both the overall yield of biomass and the efficiency of biomass conversion. An effective way to achieve these aims is through a mutation induction enhanced plant breeding programme, whereby the selection is based on individual genes as opposed to large chromosomal regions that contain the particular trait. Recently, the cell wall composition of maize was evaluated with a high-throughput genetics screen, resulting in a collection of mutants that can now be evaluated for biomass conversion efficiency. The mutant genes can be incorporated in a breeding programme, or the gene sequence can be used to identify natural variants of interest.

### **E.3. Improving Livestock Productivity and Health**

Nuclear technology applications that were developed to fulfil specific and unique requirements are increasingly used to obtain more and better livestock and livestock products. Current trends indicate that the techniques will play important roles in the improvement of animal nutrition, reproduction and health. Radioimmunoassay, for example, is now used for measuring the concentration of specific molecules in a biological sample, for labelling rumen microbes, for evaluating animal feeds, and for analysing the conversion of feed to nutrients and their uptake. The enzyme-linked immunosorbent assay (ELISA) is widely used for the evaluation, identification and surveillance of targeted antibodies for the detection of animal exposure to pathogens. Polymerase chain reaction (PCR), or PCR sequencing, is used for molecular detection and characterization of animal disease pathogens by direct labelling of DNA to select or confirm selected genomic traits that are desirable (leaner meat, more milk, disease tolerant, etc.), or to determine an animal's parentage or origin. Such new applications of nuclear technologies are continually finding their way into veterinary practices.

The use of stable isotopes, irradiated vaccines, and positron emission technology offer possibilities for the future. Stable isotopes continue to be used in animal production and health applications. Carbon-13 or nitrogen-15 labelling is used in methods to experimentally monitor the metabolism of carbohydrates, protein and nutrient uptake. A stable isotope labelled water (deuterium oxide) dilution technique is being increasingly used for the determination of lean body mass, fat content, body composition, total body water and milk intake by calves. The deuterium oxide concentration in body fluid is measured by isotope ratio mass spectrometry or, infrared spectroscopy. Isotope ratio mass spectrometry is also used in pathogenicity and other physiological studies and to non-invasively determine the geographical origin of animal products. By being able to accurately trace animal products to their

geographical origin, Member States may have more economic opportunities. For example, if a given disease can be eradicated in all but particular small regions of a country, the export of animal products from other areas may be justified if such products can be accurately traced to the disease-free zones. In addition, this approach has potential in determining the possible roles that wild animals play as carriers of animal diseases, for example the contribution from migratory birds towards the spread of avian flu from endemic to uninfected areas.

The inactivation of vaccines by irradiation produces dead pathogens that better mimic the immune induction pattern of live pathogens. This opens a new approach to immunization specifically for diseases such as malaria, foot-and-mouth disease, Rift Valley fever or neospora in cattle, as genetically engineered vaccines showed little success. Research has now started on irradiated vaccines for blood parasites in livestock.

Recent years have seen the transfer of many medical technologies for humans into veterinary purposes. Positron emission tomography (PET) is an example. Veterinarians are using PET for the diagnosis of tumours and other tissue irregularities in high value animals such as race horses and prize bulls. The use of PET can decrease costs and increase animal welfare by reducing the need for exploratory surgery.

#### **E.4. Insect Pest Control**

##### *E.4.1. SIT against Tsetse Flies*

Efforts to scale up the sterile insect technique (SIT) against the tsetse fly are being pursued in priority areas, including the Southern Rift Valley in Ethiopia. The first two modules of the large tsetse rearing and irradiation centre, located at Kaliti near Addis Ababa, of the Southern Rift Valley Tsetse Eradication Project, were officially inaugurated on 3 February 2007 (Fig. E-2). The inauguration followed the African Union's Pan African Tsetse and Trypanosomiasis Eradication Campaign Special Donors' Conference. The completed facility will consist of seven modules, and will eventually have a capacity to rear at least seven million tsetse females, which can produce about 700 000 sterile males per week, sufficient to cover areas between 4500 and 7500 km<sup>2</sup>. At Kaliti, there has been a steady increase in the tsetse fly colony size, but a substantial increase is still needed in order to reach the number of tsetse flies required to initiate the operational SIT phase. In May 2007, the first test releases of sterile male tsetse flies were successfully conducted to assess the performance in the field indicating that they survived and dispersed as required to carry out a future eradication programme.



FIG. E-2. Construction of the Tsetse Rearing and Irradiation Centre at Kaliti, Addis Ababa, Ethiopia.

FAO/IAEA standard operating procedures for mass rearing tsetse flies were recently finalized. This is a major contribution to the application of the SIT against tsetse flies, since it represents the first comprehensive outline of all procedures involved in colony initiation, mass-rearing, blood collection processing and storage, and quality control of sterile flies.

#### E.4.2. SIT against Fruit Flies

Among the most important insects interfering with international agricultural trade is the Mediterranean fruit fly *Ceratitidis capitata* (medfly). In order to overcome barriers to the export of fresh citrus fruit, Spain is implementing SIT in the Valencia region, which accounts for 80% of the country's citrus exports. The world's second largest medfly mass production facility was recently inaugurated in April in Valencia, Spain (Fig. E-3). The facility, Europe's first large scale insect production facility, marks a strategic step forward in area-wide integrated pest management for Valencia's agricultural community. The plant has the capacity to produce 500–600 million sterile male medflies per week, and paves the way for Spain to suppress medfly populations in a more environmentally friendly way. The investment will enable Valencia's fruit industry to cut down on the use of insecticides and to access new export markets.



FIG. E-3. The newly inaugurated Mediterranean fruit fly mass rearing facility in Valencia, Spain.

#### E.4.3. SIT against Moths

In Citrusdal, a valley in the Western Cape, South Africa, where some 6000 ha of land are used to produce citrus fruit for export, a pilot project has been in progress against the false codling moth *Thaumatotibia leucotreta* in collaboration with FAO and the IAEA. This is the most serious pest of citrus fruits in South Africa. The moth is difficult to control due to insecticide resistance, and represents a key international barrier to the export of citrus fruit. In view of the positive results achieved, the citrus industry has decided to resolve the problem by the introduction of the use of SIT and has committed to launching a commercial SIT based programme in the near future. The potential use of stable isotopes is being explored as an additional research tool to understand ecological processes of transboundary insect pests such as desert locusts in order to better comprehend the insect's behaviour. A better understanding of the biology and ecology of such migratory pests might ultimately contribute to the development of more efficient control strategies.

### E.5. Food Irradiation

Food losses caused by pests, contamination and spoilage are enormous. It is estimated that 42% of the production of the eight major food and cash crops of the world are lost to pests, with post-harvest losses adding a further 10%. Despite the use of modern food processing and distribution systems, foodborne diseases also pose a widespread threat to human health as well as being an important factor in reducing economic productivity in all countries. Ensuring the safety and quality of foods and agricultural commodities is therefore one of the essential dimensions of national responses to tackle the twin challenges of expanding urbanization and improved public health.

Food irradiation is a valuable tool to address the reduction of losses due to food spoilage and deterioration, the control of microbes and other organisms that cause foodborne diseases, and the fulfilment of sanitary and phytosanitary requirements<sup>11</sup>. In addition to the continuing use of irradiation for sanitary purposes, irradiation for phytosanitary applications, especially those applications related to quarantine measures, has increased. International standards and codes of practice have been developed to foster the application of this food processing technology in collaboration with the joint FAO/WHO Codex Alimentarius Commission and the International Plant Protection Convention.

## **F. HUMAN HEALTH**

### **F.1. Individualized Approach to Cancer Treatment through Nuclear Medicine**

Successful treatment of cancer requires a comprehensive understanding of the complex interaction among the various factors that lead to the growth of cancer. Understanding the specific properties of cancer in individuals at the cellular, genetic and molecular level is the key for prescribing patient specific treatment with much higher chances of cure. Molecular imaging in nuclear medicine through positron emission tomography (PET) has redefined and modernized the medical approach to cancer patient management. Classifying a cancer just by its anatomical location may be a reason why patients with what are thought to be the same cancers respond to treatment in radically different ways. There are now tools leading to an understanding of the molecular reasons for why patient responses can be so different. This is being translated into the selection of appropriate treatment regimens for patients. It has been discovered that cancers found in distant parts of the body may be more alike than two tumours originating in the same organ, depending on the type of the cancer causing mutations they harbour. Detailed knowledge of pathogenic processes provided by PET can also be exploited for rational drug design leading to targeted therapy.

In the field of cancer therapy, haematologists, paediatricians and oncologists are beginning to explore combined treatment approaches applying

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<sup>11</sup> Additional information is available in the annexes at the end of this report.



chemotherapy, immune modulating or cellular signal transduction modulating agents in combination with targeted tumour seeking molecules (peptides, antibodies or oligonucleotides) to improve the healing chances of cancer patients. Isotope enhanced radiotargeted treatment approaches have numerous advantages both for treating localized or disseminated solid cancer and for treating bloodborne malignancies.

## **F.2. Radiation Oncology**

Technological advances in treatment planning and radiation delivery have enabled the adoption of strategies to irradiate tumours with a three dimensional conformal radiation therapy (3D-CRT) approach and even highly conformal techniques such as stereotactic radiation therapy (SRT) or intensity modulated radiation therapy (IMRT). Conformal therapy describes radiotherapy treatment that creates a high dose volume shaped to closely ‘conform’ to the desired target volume while minimizing as much as possible the dose to critical normal tissues. The introduction of the most advanced techniques such as SRT and IMRT, as well as image guided radiation therapy (IGRT) and respiratory-gated radiotherapy (RGRT), have led to a better understanding of the importance of margins and organ movements. In addition, a major advance in the field of radiotherapy in recent years has been the introduction of functional imaging information into the process of treatment planning. For example, using PET scanning coupled with traditional computed tomography scanning yields images with biological/metabolic markers that may permit more appropriate tailoring of radiotherapy treatment fields and doses to individual patients and a better outcome to treatment.

The enthusiasm for these technologies derives from the assumption that further refinements in tumour localization, more precisely defined dose distributions, and greater individualization of dose prescriptions will improve the current levels of treatment outcome by reducing toxicity or achieving greater local control of tumours through dose escalation strategies. These approaches are being actively investigated worldwide.

Educational aspects are of paramount importance for the wide application of new technologies. Internet based ‘virtual’ teaching should help by reducing the overall costs and enable faster implementation of these technologies in daily clinical practice. At the same time, there is a global effort to raise the standard of education for medical physicists who support these new treatment technologies. Organizations have been created in many countries to define the competencies of medical physicists and to accredit their clinical residency training programmes.

In addition to external beam radiotherapy achievements, the recent development of high dose rate (HDR) cobalt-60 sources may allow modern HDR brachytherapy to be performed with replacement of the sources needed less frequently than with other sources. This should enable more cost effective radiotherapy and improve patient access to treatment. Regarding multi-modality treatments, several high quality clinical trials have reconfirmed that the addition of pharmaceutical agents to radiotherapy improves the survival of patients with many common cancers.

### **F.3. Nutrition**

The central role of nutrition to development has recently been re-emphasized by the World Bank in its publication entitled *Repositioning Nutrition as Central to Development: A Strategy for Large-Scale Action*.<sup>12</sup> The importance of investing in nutrition is highlighted by the growing international awareness that the magnitude of malnutrition will prevent many countries from achieving the United Nations Millennium Development Goals and by the growing evidence that there are solutions to the malnutrition problem. The excellent economic investments of nutritional interventions to combat malnutrition were highlighted during the Copenhagen Consensus<sup>13</sup>. According to the Consensus, the returns of investing in programmes to control infectious diseases, such as HIV/AIDS and malaria, and to combat malnutrition represent six out of the top dozen proposed interventions.

The role of nuclear techniques in the development and evaluation of nutritional interventions is well established, and many IAEA Member States are now benefiting from increased access to technical capacity in the use of stable isotope techniques in nutrition.<sup>14</sup> Recent trends indicate increased use of stable isotope techniques to address priority areas such as nutrition and HIV/AIDS, infant and young child feeding and micronutrient deficiencies. The use of a stable isotope technique, for example, to monitor changes in body composition (body fat versus muscle mass) during nutritional interventions can contribute important information to optimize care, treatment and support to people living with HIV/AIDS and is of particular relevance in the context of increased access to anti-retroviral treatment in resource-poor settings.

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<sup>12</sup> See <http://siteresources.worldbank.org/NUTRITION/Resources/281846-1131636806329/NutritionStrategy.pdf>.

<sup>13</sup> See <http://www.copenhagenconsensus.com/>.

<sup>14</sup> Additional information is available in the annexes at the end of this report.

In addition, stable isotope techniques are being used in several countries to estimate intake of human milk in breastfed infants and to assess the time of introduction to other foods and fluids. It can therefore be used to monitor interventions to promote exclusive breastfeeding for 6 months, followed by introduction of appropriate complementary foods and continued breastfeeding, as recommended by the World Health Organization.

Stable isotope techniques are also currently used to develop and evaluate strategies to combat micronutrient deficiencies. For example, stable isotope techniques can be used to evaluate iron bioavailability from different compounds as an important step in the development of a food fortification strategy and to monitor changes in vitamin A status in individuals benefiting from vitamin A provided via food fortification and supplementation.

## **G. ENVIRONMENT**

### **G.1. Improving Detection of Radionuclides for Terrestrial Environmental Assessment**

Field gamma spectroscopy has numerous applications, including estimation of radioactivity in surface soils, assessment of gamma radiation fields (and hence dose rate), and location of orphan sources. In the case of a nuclear accident with widespread distribution of artificial radionuclides in the environment, aerial measurements are an important tool for rapid and large scale nuclide specific determination of soil contamination. Detectors based on sodium iodide crystals or high purity germanium crystals are commonly used. The former have the advantages of ruggedness and high detection efficiency, but the disadvantage of low energy resolution. They are routinely used in the survey of relatively large areas, for example using airborne or vehicle mounted systems, and in assessment of natural radionuclide activities under difficult field conditions, for example on uranium mining sites. Use of the Global Positioning System (GPS) to provide accurate location data, along with developments in data analysis techniques, have resulted in significant improvements in data analysis from such surveys in recent years.

Germanium based detectors are commonly used when identification of individual radionuclides is important. Improvements in high purity germanium crystal production in recent years have meant that larger crystals can now be produced, resulting in improved detection efficiencies. There is, however, a

requirement to cool the detector with liquid nitrogen, which remains a practical difficulty when using these detectors in the field.

## **G.2. Quality of Measurement Results**

Physical and chemical measurements (including nuclear analytical techniques) are used for estimating the quality and fitness for purpose of traded goods. The quality of measurement results needs to be assured and demonstrated in order for them to be accepted as part of the decision making process. Factors contributing to assurance of quality include an appropriate measurement infrastructure (involving national metrology institutes and the availability of necessary calibration standards) as well as the availability of quality control tools such as reference materials<sup>15</sup>.

## **G.3. Application of Nuclear Technologies in Marine Environmental Sustainability**

### *G.3.1. Expanding Applications of Radioassay in Seafood Safety*

Ciguatera fish poisoning (CFP) is caused by the ingestion of tropical reef fishes that have accumulated toxins produced by harmful algae. These toxins, which may be measured by radioassay, can induce severe gastrointestinal, neurological and cardiovascular disorders. In the past, ciguatera fish poisoning in humans had been restricted to tropical island communities, but with increases in seafood trade, worldwide seafood consumption and international tourism, the populations at risk are worldwide. CFP incidences in the tropics vary between 10 000 and 50 000 cases per year. A radioassay technique is now being used in French Polynesia to quantify ciguatoxin in marine foods, including giant clams and fish, and to study its transfer through tropical marine food chains. In order to address this increasing concern, a coordinated research project on the use of radioassay technology to quantify ciguatoxins in fish has been initiated by the IAEA, which will also be complemented by assistance to Member States through technical cooperation projects.

### *G.3.2. Climate Change and Ocean Acidification*

Atmospheric levels of carbon dioxide (CO<sub>2</sub>) are increasing due to the combustion of fossil fuels (petroleum, gas, coal) and deforestation. Yet

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<sup>15</sup> Additional information is available in the annexes at the end of this report.



*FIG. G-1. A new facility to assess the effects of ocean acidification on larvae of commercial fish at the IAEA's Radioecology Laboratory, Monaco.*

atmospheric CO<sub>2</sub> levels would be even higher if it were not for the ocean, which has absorbed about one third of this human produced CO<sub>2</sub>. As a result, ocean levels of CO<sub>2</sub> are also increasing, and because CO<sub>2</sub> is an acid, ocean pH is dropping. This 'ocean acidification' is likely to adversely affect many marine organisms, particularly corals and shell builders, such as oysters, mussels and molluscs, and may affect entire marine food webs, impacting on natural biodiversity and aquaculture (Fig. G-1). The Intergovernmental Panel on Climate Change has recently highlighted this as a critical gap in knowledge.<sup>16</sup>

Ocean acidification may also affect solubility of pollutants, such as heavy metals, thereby affecting seafood safety. Marine isotopes such as those for boron, have been used to determine past changes in ocean pH, and how they differ from the present human driven perturbation. Another isotope, calcium-45, has provided a key tool to measure rates of calcification in corals whose reefs provide fish habitat and breeding grounds, defence against storms and erosion, and the foundation of a multi-billion dollar tourism industry. The IAEA is helping Member States to use isotope studies and numerical models to better understand and project how ocean acidification will alter marine resources. For example, applied radioecological studies are being conducted for expected levels of high CO<sub>2</sub> and low pH, using calcium-45 and other isotopes to help unravel the effects of ocean acidification on commercially important organisms such as fish larvae and molluscs.

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<sup>16</sup> See [http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1\\_Print\\_SPM.pdf](http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_SPM.pdf).

## H. WATER RESOURCES

Groundwater meets more than half of the world's freshwater demands. This proportion is as high as 90% in water scarce countries with arid or semi-arid climates, and in developing countries with large scale irrigated agriculture.

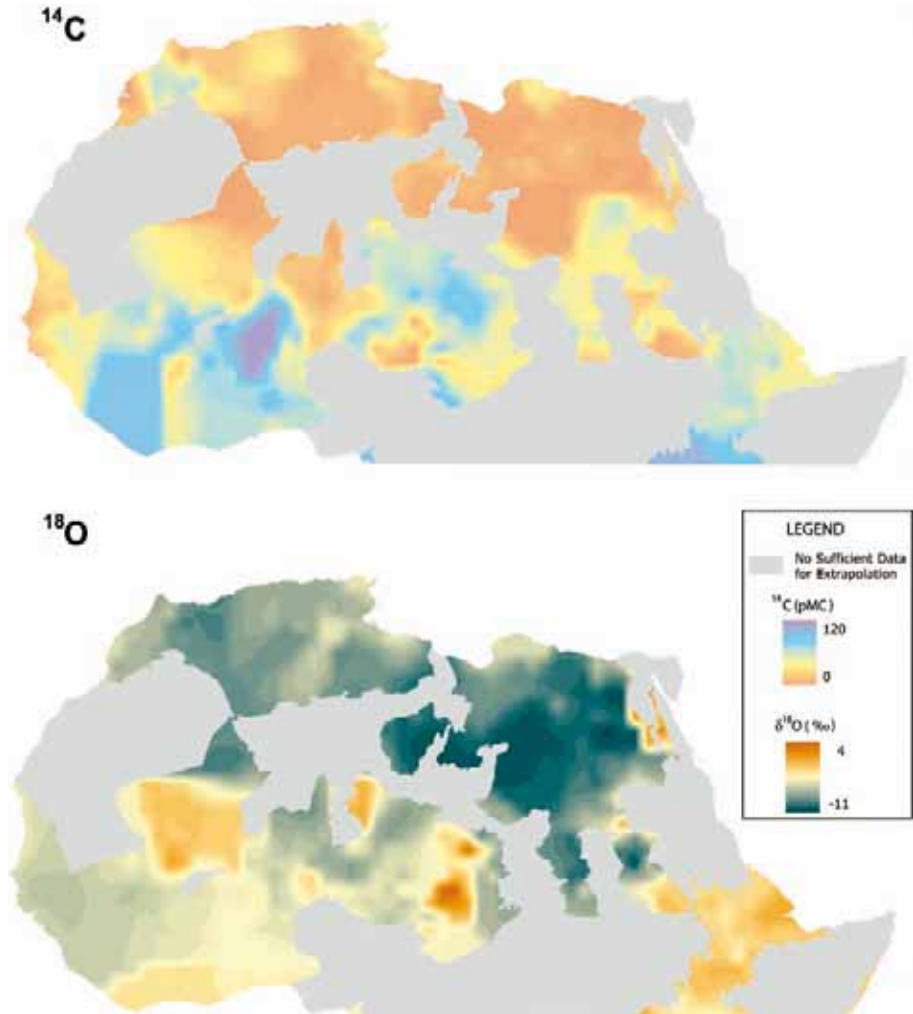


FIG. H-1. Carbon-14 and oxygen-18 content in groundwater in northern Africa from the recently published IAEA Atlas of Isotope Hydrology. The low carbon-14 values show the extent of 'very old' groundwater that was recharged under wetter climates thousands of years ago.

The looming impacts of climate change on freshwater availability make groundwater an even more critical resource and requires its judicious use. Observations over many years are required to assess and manage aquifers used for groundwater development. Such information is scarce in most parts of the world. Isotope data provide a window into the natural groundwater systems and a time and space integrated set of information on its functioning, enabling groundwater assessment and management without significant investments of time and resources.

Recognizing this important application of isotope data, a number of countries are taking steps to broaden the availability of isotope data at a national scale. The IAEA is producing a series of atlases with a synthesis of isotope data collected from groundwater related technical assistance in Member States over the past fifty years. Most of these groundwater isotope data have not been easily available until now.

The first atlas focuses on Africa and contains data from more than 10 000 isotope samples. As can be seen in Fig. H-1, the isotope data easily show the extent of old groundwater, presently non-renewable with ages in excess of about 10 000 years, in the northern Africa region. The low (more negative)  $\delta^{18}\text{O}$  values indicate that recharge in many parts of northern Africa occurred mainly under cooler climate conditions than exist in the present day. This groundwater occurs in major transboundary aquifer systems such as the Nubian aquifer between Egypt, the Libyan Arab Jamahiriya, Chad and Sudan, and its shared management is critical for human development in this region.

## **I. RADIATION TECHNOLOGY**

### **I.1. Radioisotope Production**

The availability of reliable supplies of well established radioisotopes for sustainable medical and industrial applications, as well as the development of new products for emerging requirements, continue to attract worldwide attention. In addition to industry, several national centres in Member States are actively engaged in this area. The share of technetium-99m and fluorine-18 in diagnostic imaging continues to remain at around 80% and 10%, respectively, of the nearly 25 to 30 million procedures performed in 2006. In the case of products for radionuclide therapy, the increasing popularity of the more easily and widely producible lutetium-177 and a novel generator system for

yttrium-90 based on electrochemical separation from strontium-90 are two notable developments in 2007. Another important development in 2007 was the emerging interest in the establishment of new facilities for the production of molybdenum-99 using LEU targets in some Member States. An important meeting of all the stakeholders currently involved in the production of this radioisotope took place in Sydney, Australia, in December 2007 that was co-organized by the National Nuclear Security Administration (NNSA) of the US Department of Energy and the Australian Nuclear Science and Technology Organisation (ANSTO). The meeting report identifies all the aspects to be addressed as well as the support needed to facilitate the use of LEU target technology without affecting the supplies of molybdenum-99 and thereby reducing reliance on HEU for the large scale production of that radioisotope. In Australia, regular production of molybdenum-99 on a large scale using LEU targets is slated to commence in 2008.

## I.2. Natural Polymers

Natural polymers exist in many forms, and many are amenable to radiation processing to produce valuable products (see Fig. I-1). Such natural polymers include starch (in potato and corn), cellulose (in plants and trees),

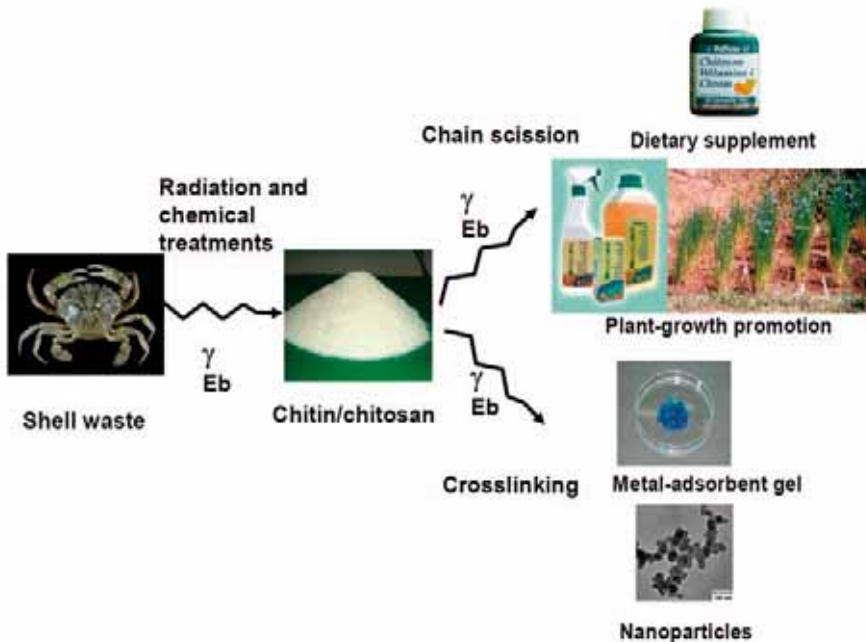


FIG. I-1. Radiation processing of natural polymers.



chitin (in shrimps, crabs and lobsters), alginates (in algae) and polypeptides such as silk, keratin and hair. These natural polymers are non-toxic, biodegradable and harvestable at low cost. Radiation processing offers a clean and additive-free method for the preparation of value added new materials based on these natural polymers. The products from chitin, for example, can be used as hydrogel wound dressings, non-bedsore mats, face cleansing cosmetic masks, drug delivery devices, and adsorbents of pollutants, such as metal ions, dye, proteins, solid particles and others. The low molecular weight products show antibiotic, antioxidant and plant-growth promoting properties.

Radiation processing of natural polymers is emerging as a promising area whereby the unique characteristics of polymeric materials can be exploited for practical applications in medicine, cosmetics, agriculture, biotechnology and environmental protection.

### **I.3. Hazardous Bio-contaminants**

The use of ionizing radiation for the inactivation of microbes is an established technology in food hygienization, radiation sterilization of medical products and biological tissues, and on a larger scale, for the treatment of sewage sludge. More recently, the use of radiation technology to lower the threat from biological contaminants such as anthrax in mail has been demonstrated. These results showed the utility of ionizing radiation for addressing threats such as the deliberate spread of biological contaminants.<sup>17</sup> The major advantages of the use of radiation technology compared with other methods lies in its ability to treat materials from small scale to a very large scale, and that the required dose delivery to the target object/area is the only parameter that needs to be controlled. The results reported so far indicate that some additional aspects should be addressed in the further development, as for example the handling and treatment of the contaminated products and training for field operations.

### **I.4. Computer Automated Radioactive Particle Tracking**

A technique called ‘computer automated radioactive particle tracking’ (CARPT) is now a recognized method to investigate complex multiphase flows (e.g. gas and liquid) in chemical, petroleum and bio-engineering industries. CARPT uses a small gamma ray emitting tracer particle of the correct density

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<sup>17</sup> NOJI, E.K., Bioterrorism: A ‘new’ global environment health threat, *Global Change Human Health* **2** 1 (2001) 46–53.

and size capable of moving with the phase to be investigated and a number of gamma radiation detectors located strategically around the chemical reactor to trace the position of the particle and in turn the phase movement reliably.

The tracking method is non-invasive and provides the dynamic features of the particular phase of interest. The data obtained on flow pattern, velocity, turbulence, etc., help optimize the processes in pilot plant level and in turn, provide evidence for making decisions on final designs for actual plant scale operations.<sup>18</sup> The petrochemical industries, which use fluidized beds and bubble columns, and manufacturing products based on bio-processes, will be the major beneficiaries from the use of CARPT.

A further improved option is to use a positron emitting tracer for particle tracking. The technique, called 'positron emitting particle tracking' (PEPT), offers the additional advantage of the coincidence detection of positron annihilation radiation, leading to greater accuracy in tracking the tracer particle even in high speed flow systems commonly encountered in some industrial systems. The overall goal of CARPT and PEPT is to ensure more efficient and effective industrial processes.<sup>19</sup>

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<sup>18</sup> BHUSARAPUL, S., AL-DAHMAN, M.H., DUDUKOVIC, M.P., Solids flow mapping in a gas–solid riser: Mean holdup and velocity fields, *Powder Technol.* **163** 1–2 (2006) 98–123.

<sup>19</sup> BAKALIS, S., COX, P.W., RUSSELL, A.B., PARKER, D.J., FRYER, P.J., Development and use of positron emitting particle tracking (PEPT) for velocity measurements in viscous fluids in pilot scale equipment, *Chem. Eng. Sci.* **61** 6 (2006) 1864–1877.

## Annex I

### ENSURING FOOD QUALITY AND SAFETY

#### I-1. Introduction

Food losses caused by pests, contamination and spoilage are enormous. It is estimated<sup>20</sup> that 42% of the production of the eight major food and cash crops of the world are lost to pests, with post-harvest losses adding a further 10%. Despite the use of modern food processing and distribution systems, foodborne diseases still pose a widespread threat to human health as well as being an important factor in reducing economic productivity in all countries.

Ensuring the safety and quality of foods and agricultural commodities is therefore one of the essential dimensions of national responses to tackle the twin challenges of expanding urbanization and improved public health. Food contaminants, such as mycotoxins and radionuclides, as well as pesticides and veterinary drug residues, may have negative effects on human health as well as adversely affect the environment. The establishment of scientifically sound and accepted international standards can help to ensure the production of safe, high quality foods as well as facilitate international trade. The utilization of appropriate technologies and quality management systems through the application of good agricultural and manufacturing practices also enables countries to improve the availability of wholesome and nutritious foods and to increase their foreign exchange earnings through greater access to international and domestic food commodity markets.

The role of the analytical laboratory in the application of good production practices throughout the food chain, as opposed to the more traditional end-product testing of products, is also being strengthened with a view towards ensuring food safety and the reduction at their source of hazards arising from chemical and microbiological contamination. These activities entail the development of analytical methods and procedures that enable governments to evaluate the impact of their application of good production practices, including the identification and use of environmental indicators related to water and soil. To help meet these needs, protocols have been developed for the use of radiolabelled compounds to optimize different steps,

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<sup>20</sup> OERKE, E.-C., DEHNE, H.-W., SCHÖNBECK, F., WEBER, A., *Crop Production and Crop Protection – Estimated Losses in Major Food and Cash Crops*, Elsevier, Amsterdam (1994).

and estimate measurement uncertainty, during the development of analytical techniques used in regulatory programmes for residues of pesticides and other contaminants in food and environmental samples.

Parallel with these developments has been the establishment of legal and regulatory infrastructure at the international, national and local levels aimed at improving the environmental management of agricultural systems so as to ensure the efficient and safe use of agricultural production inputs, while also having in place emergency action procedures to minimize the risk of contamination arising from nuclear accidents. Collaborative efforts between UN organizations and other relevant governmental and non-governmental agencies through current joint activities are a critical aspect of these activities, for example, collaboration between FAO and the IAEA for emergency planning and response to nuclear emergencies and radiological events affecting agriculture.

The IAEA works in close collaboration with FAO, WHO and others to be at the forefront of international research and coordination efforts dedicated to food safety issues. These efforts include the promotion of public health, international trade, and economic development in Member States through contributions to the accelerating expansion in the use of food irradiation techniques, the creation of international food safety standards, and the harmonization of Member State legislation regarding food safety.

## **I-2. Food Irradiation**

In response to increasing consumer demands for safe, wholesome and nutritious foods, many countries have introduced stricter sanitary and phytosanitary controls on the food industry. The increasing relevance of these controls for consumers and policy makers alike has resulted in a heightened interest in food irradiation as a valuable technique for dealing with food safety issues. Food irradiation can destroy the microbes that carry disease, reduce the need for harmful chemicals used to control insect pests in fruits and vegetables, and serve as a useful addition to conventional food processing technologies (such as pasteurization, curing and drying) that are used to preserve and extend the shelf-life of foods.

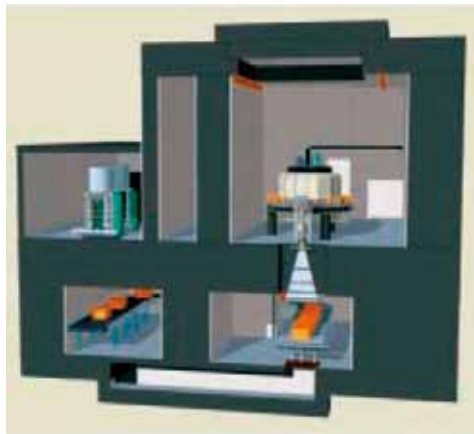
Sanitary applications of food irradiation have long been used to target harmful foodborne microorganisms such as *Salmonella* and *E.coli*, primarily in animal products such as poultry, seafood and beef. However, a recent rise in outbreaks of foodborne diseases traced to produce is leading to concerted efforts in some countries to expand the use of these applications to fruits and vegetables.

Food irradiation is also a valuable tool to address losses due to food spoilage and deterioration, the control of microbes and other organisms that cause foodborne diseases, and the fulfilment of sanitary (human health) and phytosanitary (plant health) requirements. In addition to the continuing use of irradiation for sanitary purposes, many countries have increased their use of irradiation for phytosanitary applications, especially those applications related to quarantine measures. International standards and codes of practice have been developed to foster the application of this food processing technology in collaboration with the Joint FAO/WHO Codex Alimentarius Commission (Codex) and the International Plant Protection Convention (IPPC).

### *I-2.1. The Food Irradiation Process*

Food irradiation is a process of exposing either packaged food or food in bulk to precisely controlled amounts of ionizing radiation. The process is entirely automated, involving no human exposure to radiation sources. It is also not sensitive to temperature, meaning it can be carried out in a climate controlled environment to keep food fresh. Most importantly, irradiation does not increase radioactivity levels in food or otherwise make it dangerous for human consumption. Applications of irradiation doses may be categorized according to three ranges:

- **Low dose applications (up to 1 kGy):** Sprout inhibition in bulbs and tubers; delay in fruit ripening; insect disinfestation including, quarantine treatment and elimination of foodborne parasites.



*FIG. I-1. Electron beam irradiator.*

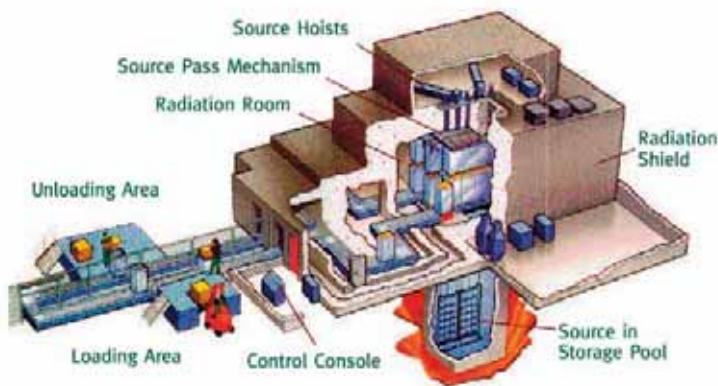


FIG. I-2. Gamma irradiator.

- **Medium dose applications (1–10 kGy):** Reduction of spoilage microbes to improve the shelf-life of meat, poultry and seafood under refrigeration; elimination of pathogenic microbes in fresh and frozen meat, poultry and seafoods; reduction of the number of microorganisms in spices to improve hygienic quality.
- **High dose applications (above 10 kGy):** Sterilization of packaged meat, poultry and products which can be stored without refrigeration; sterilization of hospital food; product improvement for increased juice yield or improved rehydration.

Food irradiation is normally applied by electron beams/X rays (Fig. I-1) or with the use of cobalt-60 (gamma irradiation) (Fig. I-2).

Research has not shown any adverse safety issues from food irradiation techniques, culminating in the revision in 2003, of the relevant Codex and IPPC standards and codes.<sup>21</sup> Overall, the response to food irradiation from national authorities has been positive, and when consumer concerns are addressed through sound information campaigns and the provision of mandatory food product labelling, there is steady progress in the public acceptance and implementation of these techniques.

To date, health and safety authorities in over 60 countries worldwide have approved the irradiation of over 60 kinds of foodstuffs. These include

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<sup>21</sup> Joint FAO/WHO Codex Alimentarius Commission General Standard for Irradiated Foods, as well as the associated Code of Practice for Radiation Processing of Food. The Guidelines for the Use of Irradiation as a Phytosanitary Measure were also finalized by the Interim Commission for Phytosanitary Measures.

spices, grains, poultry, beef, seafoods, fruits, vegetables and other food products. An estimated 500 000 tonnes of various foods are treated annually in approximately 180 gamma irradiation facilities that use radioactive sources such as cobalt-60 and caesium-137, as well as in about a dozen electron beam facilities.<sup>22</sup>

Phytopsanitary applications of irradiation target insect pests, such as fruit flies, which can infest and destroy harvested grains and produce. Though the value of these applications was first recognized in the early 1970s, particularly as a quarantine treatment, rising health, safety and environmental concerns related to insecticide use have considerably magnified interest in these techniques.

In 1989, the US Animal and Plant Health Inspection Service published the first rule to allow the use of irradiation as a phytopsanitary treatment and in January 2006, the US regulatory framework was expanded to approve the treatment of imported fruits and vegetables. To date, India, Mexico and Thailand have already signed Framework Equivalence Work Plans to allow for the export of irradiated fresh fruits to the USA. Although the USA is presently the only country applying irradiation as a quarantine treatment on a commercial scale (4000 tonnes annually), other countries, such as Australia and New Zealand, have carried out initial market trials with irradiated fresh fruits.

Future research and development of sanitary and phytopsanitary techniques is expected to focus on complex foods such as prepared meals; the application of higher doses of radiation along with other complementary and supplementary technologies, such as controlled atmosphere packaging; high pressure processing; antimicrobial compounds and edible coatings, and the prevention of allergic reactions to foods.

The IAEA supports research and development in food irradiation techniques to assist Member States in obtaining the necessary expertise and equipment to apply them, and to foster international efforts to establish guidelines for the use of radiation for sanitary and phytopsanitary purposes. The IAEA collaborated with the IPPC in the development of *Guidelines for the Use of Irradiation as a Phytopsanitary Measure* to cover specific irradiation doses for generic groups of insect pests. Further efforts will focus on the urgent need to increase training for quarantine inspectors of national plant organizations, to continue research on insect groups sensitive to irradiation, and to study the tolerance of certain fruits to irradiation.

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<sup>22</sup> For more detailed information, see the IAEA's Clearance of Irradiated Foods Database at <http://nucleus.iaea.org/NUCLEUS/nucleus/Content/Applications/FICdb/FoodIrradiationClearances.jsp?module=cif>.

### **I-3. Emergency Preparedness and Response to Nuclear Emergencies Affecting Agriculture**

Emergency planning and response to nuclear emergencies and radiological events is of growing importance in joint international activities, particularly with regard to increasing the capabilities of relevant organizations' ability to respond to such events. International cooperation is facilitated through the mechanisms pursuant to the relevant IAEA conventions, namely the Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency. In this context, FAO, in particular, has declared pursuant to Article 14, paragraph 5(c) of the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency that it is competent to "... advise governments on measures to be taken in terms of the agricultural, fisheries and forestry practices to minimize the impact of radionuclides and to develop emergency procedures for alternative agricultural practices and for decontamination of agricultural, fisheries and forestry products, soil and water".

FAO actively participates in the IAEA sponsored Interagency Committee on Response to Nuclear Accidents (IACRNA), whose purpose is to coordinate the arrangements of the relevant international intergovernmental organizations for preparing for and responding to nuclear and radiological emergencies. IACRNA considers, among other issues, the implementation of Cooperative Arrangements between FAO and the IAEA related to nuclear emergencies.<sup>23</sup>

9.5. Other collaborative activities under these conventions have helped to ensure the successful adoption of the revised *Codex Guideline Levels for Radionuclides in Foods Contaminated Following a Nuclear or Radiological Emergency for Use in International Trade*.

### **I-4. Seafood Safety Research**

Radiotracer and radioassay nuclear techniques are particularly useful for generating information on the biokinetics and food chain transfer of metals and toxins in marine organisms, including those that are consumed as seafood. Such information could be better linked to analyses that support risk based management decisions with respect to the safety assessment of commercially important seafoods intended for human consumption. In support, the IAEA has initiated research on applications of radiotracer and radioassay

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<sup>23</sup> See <http://www-naweb.iaea.org/nafa/emergency/index.html>.



technologies to seafood safety risk analysis to generate data on priority contaminants in seafood organisms with regard to human consumption, sale and export, and to assess the application and relevance of these experimentally derived and field based data to the management of these contaminants in seafoods. The specific research objectives include:

- The integration of current studies on the application of nuclear techniques into the study of the bioaccumulation and food chain transfer of contaminants in seafoods, with risk management decisions in relation to assessment of their suitability for human consumption;
- The identification of scientific data needed on the bioaccumulation of priority contaminants in seafoods through linkages with international standardization bodies;
- The generation of data that are relevant to the management of contaminants in seafoods through the application of radiotracer, radioassay and related nuclear technologies.

It is envisioned that these studies will assist in the improvement of safety and suitability of commercially important seafoods intended for human consumption. They may also assist in any future international standardization processes through expert bodies for the potential establishment of maximum levels for contaminants already evaluated (lead, cadmium) as well as contaminants not evaluated to date (harmful algal blooms, persistent organic pollutants and other toxins).

## **Annex II**

### **STABLE ISOTOPE TECHNIQUES TO DEVELOP AND MONITOR NUTRITION PROGRAMMES**

#### **II-1. Introduction**

The central role of nutrition to development is emphasized by the growing international awareness that the magnitude of malnutrition as a global health problem will prevent many countries from achieving the United Nations Millennium Development Goals. The urgent need for effective nutritional interventions is clearly indicated by the current global situation where, on the one hand, 170 million children are underweight and undernutrition is an important factor in more than half of all child deaths worldwide and, on the other hand, more than a billion adults are overweight. “The double burden of malnutrition”, i.e. overlapping under- and overnutrition, results in a very heavy burden on health systems in countries where treatment of diet related non-communicable diseases will be increasingly needed at the same time as undernutrition is still prevalent. In particular, infants and young children in resource poor settings are vulnerable to the devastating effects of undernutrition and poor health as demonstrated by the fact that 99% of all young children dying in 2001 (10.6 million) lived in low and middle income countries and poor nutrition contributed to 1 out of 2 deaths.

Improved nutrition represents a high priority area as part of the development agenda in low and middle income countries. The IAEA assists Member States in their efforts to develop effective, evidence-based interventions to combat malnutrition in all its forms by nuclear techniques, in particular stable isotope techniques, and complements work by other UN agencies, in particular WHO and UNICEF.

#### **II-2. Stable Isotope Techniques in Nutrition**

Stable, that is, non-radioactive isotopes of an element and the ability to measure these isotopes by mass spectrometry were first recognized in the 1920s [II-1]. Following a long history of use in research, stable isotopes are increasingly being used in the wider nutritional context. In part, this has stemmed from the inappropriateness of the use of radioisotopes in vulnerable population groups such as infants, children, and pregnant or lactating women. Secondly, the stable isotopes of carbon, hydrogen, nitrogen and oxygen have been commercially available and in relatively good supply in recent years. In

addition, the sensitive, specific and precise analytical instrumentation for the measurement of stable isotopes, isotope ratio mass spectrometry (IRMS), is now more widely available. For example, the IAEA equipped three laboratories in Africa and Asia with IRMS dedicated to nutrition projects during 2007. However, due to the high establishment and maintenance costs of an IRMS facility there is increasing interest in the use of Fourier transform infrared spectrometry (FTIR) for applications based on the use of deuterium. During the last few years, the IAEA has facilitated the establishment of a number of FTIR units in strategic locations in Member States, in particular in Africa, and contributed significantly to capacity building of personnel through various education and training initiatives.

There is a wide range of stable isotope techniques used in nutrition, however, the scope of this Annex is limited to an overview of three of the most widely used techniques with particular relevance to the development and monitoring of nutritional interventions globally. These techniques include the doubly labelled water technique of deuterium ( $^2\text{H}$ ) and oxygen-18 ( $^{18}\text{O}$ ) to assess total energy expenditure, the use of  $^2\text{H}$  for the estimate of total body water and assessment of body composition as well as the deuterium oxide “dose-to-mother” technique to assess human milk intake in breastfed infants. The stable isotopes of hydrogen ( $^2\text{H}$ ) and oxygen ( $^{18}\text{O}$ ) are present in the body, food and water; about 0.015% of all hydrogen is deuterium, while approximately 0.20% of all oxygen is  $^{18}\text{O}$ . Thus, an adult man weighing 70 kg with 40 kg of body water contains almost 80 g  $^{18}\text{O}$  water and about 6 g deuterium. Consequently, body cells are accustomed to molecules containing  $^2\text{H}$  and  $^{18}\text{O}$  at natural abundance levels.

### **II-3. The Nutrition Context: The Double Burden of Malnutrition**

The 5th *Report on The World Nutrition Situation* [II-2] estimated that childhood and maternal underweight alone are responsible for 138 million disability adjusted life years lost or 9.5% of the global burden of disease. However, many parts of the developing world are undergoing a rapid transition and the combined effects of industrialization, urbanization, economic development and globalization are having a significant impact on the health and nutritional status of these populations [II-3, II-4]. The main consequences of changes in diet and lifestyle patterns include an increase in chronic non-communicable diseases such as diabetes mellitus, cardiovascular disease, hypertension, stroke, osteoporosis, some cancers, and related conditions such as obesity. Obesity is a major public health problem in all industrialized countries and a burgeoning problem in developing countries and a key risk

factor in the progression of chronic and non-communicable diseases. The WHO has projected increasing obesity rates over the next 20 years [II-5].

The unique characteristics of the stable isotope techniques discussed in this annex make these methods highly suitable for development and evaluation of interventions to address the urgent need to improve nutrition throughout the life cycle. These techniques are state-of-the-art methodologies to monitor changes in body composition, total energy expenditure and human milk intake in breastfed infants and thus provide tools to monitor the effects of altered diet and physical activity as well as interventions specifically targeted to improve infant nutrition. The IAEA has fostered the more widespread use of these techniques in Member States through support to national and regional nutrition projects via the technical cooperation programme, and the development and transfer of technical expertise through numerous coordinated research projects addressing priority areas in nutrition.

#### **II-4. Body Composition Assessment**

The most common approach in body composition assessment is to divide body mass into two compartments, fat mass and fat-free mass. The three commonly recognized primary body composition assessment techniques are densitometry, elemental analysis and the measurement of total body water. Densitometry involves the estimation of body density which has conventionally been made by underwater weighing. More recently, air displacement plethysmography has provided a simpler alternative. Both densitometry approaches are laboratory based and therefore not suitable for use in field settings. Elemental analysis techniques, including total body in vivo neutron activation analysis and total body potassium analysis, are also limited in terms of wider application. Dual energy X ray absorptiometry is a widely used body composition method although not commonly used in field studies. The third primary body composition measurement technique is the assessment of total body water. The technique is based on the assumption that the water content of fat free mass is relatively constant (approximately 73.2% in adults) and that a negligible amount of water is associated with fat in adipose tissue.

Total body water assessment using stable isotope labels is the criterion method of body composition analysis and ideally suited for nutrition applications in field settings. Less exacting techniques, including anthropometry and bioelectrical impedance, have been used in large nutrition interventions and population studies with validation against total body water in a representative sample.

#### *II-4.1. Deuterium Oxide Dilution Technique for the Assessment of Body Composition*

Deuterium oxide ( $^2\text{H}_2\text{O}$ ) and  $^{18}\text{O}$  labelled water ( $\text{H}_2^{18}\text{O}$ ) are both used for body composition assessment, however, due to substantial differences in cost, the technique of choice is deuterium oxide dilution. The labelling of water molecules with deuterium enables the measurement of the dynamic character of body water. After consuming a dose of  $^2\text{H}_2\text{O}$ , the deuterium labelled water is distributed throughout the body water pool and commonly reaches a steady state concentration in approximately 3–5 hours. The body water pool size, or deuterium dilution space, can be measured based on the concentration of deuterium oxide in body water and the exact dose of deuterium labelled water consumed. Comparisons are made between pre-dose and post-dose samples of urine (IRMS only) or saliva (IRMS or FTIR).

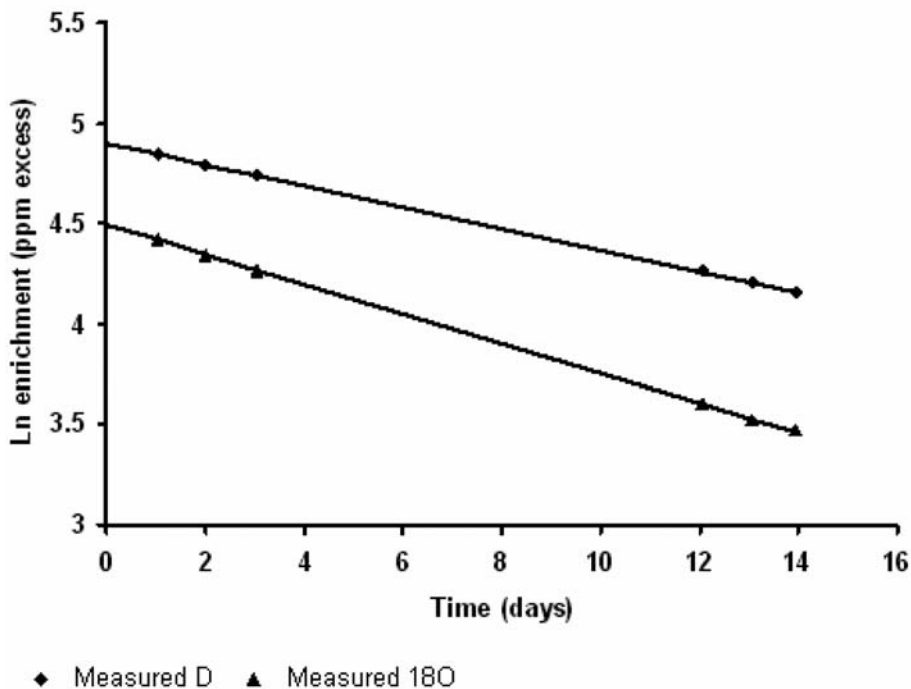
### **II-5. Assessment of Total Energy Expenditure**

A number of methods, including food records, indirect calorimetry and the doubly labelled water technique, have been used to estimate energy expenditure in people. Whole room calorimetry is considered a ‘gold standard’ for measuring 24 hour energy expenditure. However, spontaneous physical activity (more recently termed non-exercise activity thermogenesis), and movement in general, is severely limited in such an environment. Energy expenditure measurement in room calorimeters is strictly controlled, but the environment is very artificial.

#### *II-5.1 The Doubly Labelled Water (DLW) Technique for the Assessment of Total Energy Expenditure*

Unlike 24 hour energy expenditure measurement in a room calorimeter, the DLW technique is non-invasive, non-restrictive and enables the assessment of total energy expenditure under free living conditions. Following the discovery of the application of the DLW technique for the determination of energy expenditure [II-6], the technique has become the gold standard for the measurement of total energy expenditure. The technique is ideal for use in nutrition interventions in any field setting.

Using the DLW technique, average energy expenditure is normally assessed over a period of 14 days. Participants drink a dose of water containing the doubly labelled water which is rapidly distributed and mixed with hydrogen and oxygen in body water. As the body expends energy, hydrogen and oxygen are lost from the body; oxygen is lost more quickly as it is present in carbon



Ln = natural logarithm

FIG. II-1. Graph of stable isotope elimination in a multipoint DLW protocol. (source: data from Christine Slater, UK).

dioxide and water. The rate of decline of both isotopes in urine samples over the course of the study is used to calculate carbon dioxide production and energy expenditure. Figure II-1 illustrates the elimination of both isotopes over 14 days, the lines representing a best-fit between samples measured at discrete time-points.

The best way to measure physical activity energy expenditure is to combine the gold standard DLW technique for the estimation of total energy expenditure (and average daily energy expenditure), with indirect calorimetry to measure basal or resting metabolic rate [II-7]. A recent report by FAO/WHO on energy requirements [II-8] is based on the DLW technique combined with appropriately validated heart rate methodology to establish energy requirements in children 2–18 years of age in both developed and developing countries. This report referenced the DLW technique as the optimal measurement approach for total energy expenditure of individuals in normal daily living conditions. The report also suggested that other methods of energy

expenditure measurement in children should be validated against the DLW technique.

The IAEA is currently supporting projects on body composition assessment and total energy expenditure to address a wide range of priority areas in nutrition, including childhood obesity, acute severe malnutrition and HIV/AIDS in Latin America, Asia and Africa.

## **II-6. Nutrition during Early Life**

Exclusive breastfeeding for six months, followed by the introduction of appropriate complementary foods and continued breastfeeding, as recommended by WHO [II-9], are cornerstones in infant nutrition. However, only limited information is available on the quantities of human milk consumed and the time of introduction of other foods into the infants' diet, in particular in developing countries. The lack of information is, at least partly, due to the difficulties involved in measuring intake of human milk. By conventional technique, infants are weighed before and after each feed, "test weighing". This technique is obviously time consuming and can disturb the normal feeding pattern. In addition, in many settings, infants are nursed frequently — "on demand" — including during the night, resulting in severe practical limitations to the use of "test weighing".

### *II-6.1. Deuterium Oxide "dose-to-mother" Technique to Assess Intake of Human Milk in Breastfed Infants*

By using a stable isotope technique — "deuterium oxide dose-to-mother technique" — these practical problems can be overcome as the normal feeding pattern is not influenced and the average volume of human milk, consumed by the baby over a period of 14 days, is measured [II-10]. Furthermore, the method is non-invasive as the dose of deuterium oxide is consumed orally by the mother and only samples of urine or saliva are collected for analysis. Briefly, after intake of deuterium oxide by the mother in a glass of water, deuterium is mixed with the mother's body water and ingested by the baby via human milk (Fig. II-2). By measuring the disappearance of the stable isotope from the mother and its appearance in the baby (Fig. II-3), the intake of human milk can be calculated. Information about whether the infant has consumed water from sources other than human milk can be obtained at the same time and the mother's body water content can be measured. Based on total body water content, the mother's fat free mass and fat mass can be estimated to provide important information about the nutritional status of the lactating mother.



1. Mother drinks  $^2\text{H}_2\text{O}$
2. Baby consumes  $^2\text{H}_2\text{O}$  in human milk
3. Saliva in both mother and baby is enriched with  $^2\text{H}_2\text{O}$

FIG. II-2. Dose-to-mother technique of assessing human milk intake.

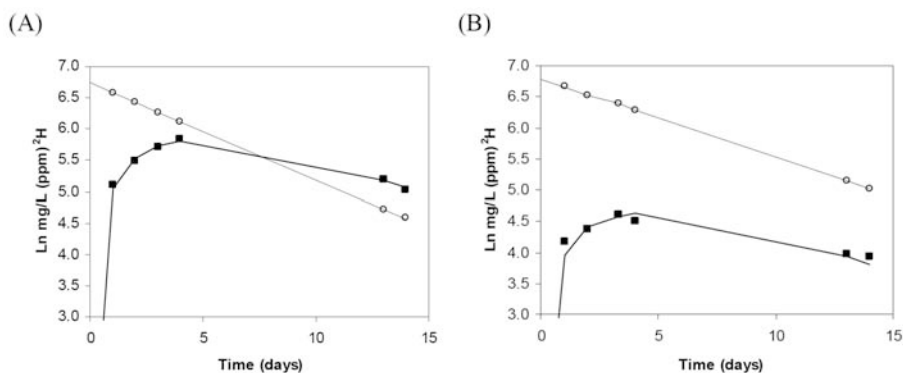


FIG. II-3.  $^2\text{H}$  concentration in body water (saliva) collected from mother ( $\circ$ ) and baby ( $\blacksquare$ ). Source: data from Les Bluck, UK.

Differences in the deuterium concentration in saliva collected from two mother–baby pairs illustrated in Fig. II-3 are evident. Modelling of the data reveal that baby A consumed considerably more human milk and only a small amount of water from sources other than human milk as compared to baby B who consumed less human milk than water from sources other than human milk.

The IAEA has supported projects using the stable isotope technique to assess human milk intake in breastfed infants over a period of several years, and thus contributed significantly to progress in this important area. The “dose-to-mother” stable isotope technique has been used in a wide range of field settings and experience with the technique as well as analytical equipment (FTIR) is now available in many countries.



## II-7. Conclusions

The well established stable isotope techniques outlined in this review have been utilized in a wide range of nutrition contexts. However, there are significant opportunities for more widespread use. For example, the stable isotope technique to assess human milk intake can be used to optimize nutrition interventions for improving the nutrition, health and well-being of infants and young children in developing countries. In addition, the use of stable isotopes such as deuterium and  $^{18}\text{O}$  is crucial in the development and evaluation of nutrition interventions regarding body composition and energy expenditure, including in the determination of nutrition and physical activity recommendations compatible with healthy lifestyles for the global population.

For more information about the IAEA's activities in human nutrition, please visit: <http://www-naweb.iaea.org/nahu/nahres/default.shtm>

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## Annex III

### REFERENCE MATERIALS FOR TRADE AND DEVELOPMENT: QUALITY AND COMPARABILITY

#### III-1. Introduction

Scientific measurements are a basic input to decisions made in many areas of human activity. In particular, physical and chemical measurements are used for estimating the quality and fitness for purpose of traded goods such as food, pharmaceutical products, ores and chemical products. Measurement results also play an important role in the areas of human health (diagnostics and treatment), environmental protection, and exploitation of water, mineral and energy resources. In all of these areas the quality of associated measurement results needs to be assured and demonstrated in order for them to be accepted as part of the decision making process. Laboratories are experiencing increased demand in the area of quality assurance for traded goods, in particular, due to the growth in international trade (Fig. III-1).

This is where metrology, standardization and conformity assessment play important roles. They are the pillars of knowledge for developing a technical infrastructure, and thereby enabling sustainable development and full participation in international trade. To this end there is an international measurement

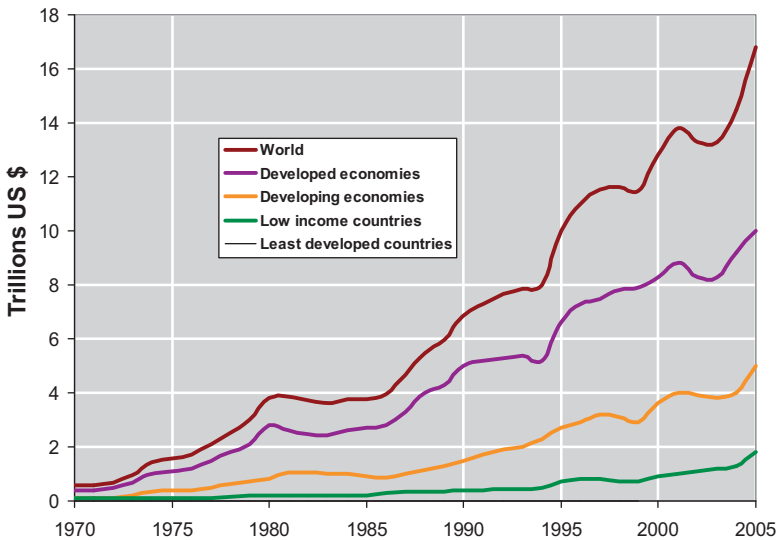


FIG. III-1. Development of world trade, in trillions of US \$. Source: UNCTAD.



FIG. III-2. Schematic presentation of the current international and regional measurement and standardization infrastructure (this figure is not exhaustive and does not cover the national level.)

infrastructure that works closely together in order to promote a worldwide metrology system (Fig. III-2), supported by international standardization and harmonization activities, by national metrological infrastructure, certification and accreditation bodies and at the laboratory level by appropriate quality management, including quality assurance and quality control.

In many areas comparability is the main quality component of measurement results. This term describes the property of measurement results which enables them to be compared independent of the time, place, analyst and procedure used. It involves the assurance of metrological traceability. Other quality characteristics of importance are accuracy, reproducibility and measurement uncertainty, which give an indication of whether or not the measurement results are actually fit for their intended use. These quality characteristics underpin confidence in analytical measurement results and help avoid unnecessary duplicate measurements, which are still often present in the export and import of goods.

### III-2. Tools for Assuring and Checking Measurement Results

The basic tools used by laboratories to assure and demonstrate the quality of their measurement results include the following:

- Use of standardized methods for sampling and analysis;
- Proper calibration of measuring instruments;
- Routine quality control practices;
- Regular participation in interlaboratory comparisons and proficiency tests.

### III-2.1. Standardized Methods for Sampling and Analysis

Sampling is an integral part of the measurement process, and can strongly influence the comparability of the final measurement results based on the use of agreed sampling procedures. Sampling should result in a representative sample, which often will be composed of spot samples selected according to the specific sampling strategy.

Sampling of the environment is especially complex due to its non-homogeneous nature, the number of environmental compartments needing to be sampled (soil, water, biota, atmosphere, etc.) and the large number of characteristics which may need to be measured on the samples. The effect of a lack of harmonized approaches to sampling was evident after the Chernobyl accident in 1986 as the different sampling strategies used at the time made a geographical comparison of results difficult. As a result, the International Commission on Radiation Units and Measurements and the International Union of Pure and Applied Chemistry (IUPAC) have recently published guides on sampling in the environment to help address this issue [III-1, III-2]. A well characterized and geostatistically stable sampling site, such as the one presented in Fig. III-3, can be used for assessing sampling strategies and

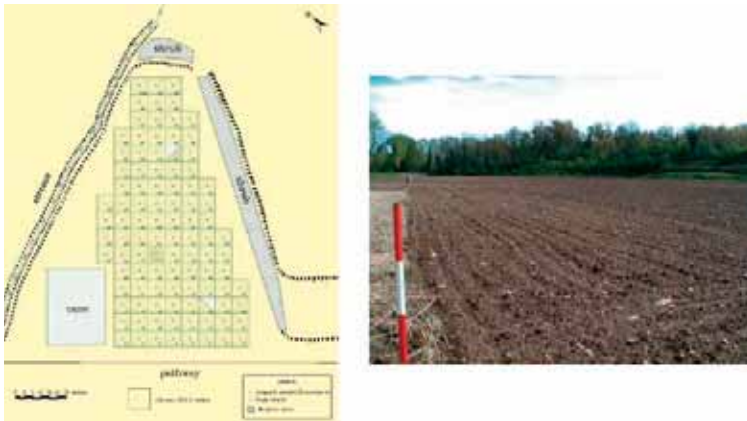


FIG. III-3. A reference sampling site for soil at Friuli, Italy. The schematic presentation shows a sampling grid used in the site characterization process.

uncertainties associated with different sampling techniques. Such sites will be needed in the future and proficiency testing in sampling has become an important activity in recent years [III-3].

The need for standardized methods for sampling and analysis for radioactivity in the environment was one of the reasons for the creation of the ALMERA (Analytical Laboratories for the Measurement of Environmental Radioactivity) network, which is coordinated by the IAEA, and makes available to Member States a worldwide network of analytical laboratories capable of providing reliable and timely analysis of environmental samples in the event of an accidental or intentional release of radioactivity. The network is a technical collaboration of institutions, and provides an operational framework to link expertise and resources, in particular when transboundary contamination is expected or when an event is of international significance [III-4, III-5].

### *III-2.2. Reference Materials*

Reference materials are materials for which one or more properties are well established. They are used for calibration of an apparatus; for the assessment of a measurement method; for establishing traceability of measurement results and for determining the uncertainty of these results [III-6]. Their application provides direct information on the quality of the measurement results in a laboratory. The final responsibility for selection and correct application of appropriate reference material will always rest with the users. They therefore need to be properly informed and aware of the characteristics and limitations of the selected reference material.

Matrix reference materials are a type of reference material with a relatively complex matrix such as soil, fish flesh or milk powder (Fig. III-4). Differences in the types of reference materials influence the possible methods for their characterization and certification, as well as their utilization in the analytical process.

A majority of matrix reference materials are characterized through inter-laboratory comparisons, meaning that the assigned property values are established from the average of laboratory results. Therefore metrological traceability of these values can normally be claimed only to the respective laboratory intercomparison, and not to any other point of reference. Trends in the reference materials area depend in part on the development of new analytical techniques, of which two aspects should be mentioned. The first is the development of new, especially micro and nano, techniques. The second is the development of non-destructive analytical techniques involving solid sampling, such as neutron activation analysis (NAA), X ray fluorescence



FIG. III-4. IAEA reference materials (fish flesh and soil) characterized for radionuclides.

(XRF) and gamma spectrometry. In both cases there is only a limited variety of appropriate reference materials presently available characterized for chemical element composition, radionuclide content, and stable isotopes ratios suitable for use with such techniques thus additional efforts are needed.

The role of nuclear and nuclear related analytical techniques in the development of new materials is significant. Among others, mass spectrometry techniques, NAA, micro X ray fluorescence, and alpha spectrometry, may be applied in the characterization process. An important step in this respect is the recent recognition of instrumental neutron activation analysis (INAA) as a potentially primary method of measurement by the Consultative Committee for Amount of Substance: Metrology in Chemistry [III-7].<sup>24</sup> Characterization by primary methods of measurement (for example, by gravimetry, coulometry or isotope dilution mass spectrometry) may lead to the preparation of reference materials of highest metrological quality – materials that can be used as calibrants. Calibrants are usually pure materials (pure substance or element), transferred by the end user into the physical and chemical form appropriate for insertion into the measurement device. All such transformations, however, may influence the uncertainty of measurement results. Therefore another important field is the development of matrix reference materials that could be used as calibrants.

<sup>24</sup> See <http://www.bipm.org/en/committees/cc/ccqm/>.

In the case of non-destructive measurement techniques, the availability of matrix type calibrants would compensate for many uncertainty sources when test samples of similar composition and density as a calibrant are measured. It is expected that the trend towards preparation of such matrix materials useable as calibrants will grow. Preparation of such materials may be achieved using one of two broad approaches. The first is spiking of a base matrix with a standard which is metrologically traceable to SI units [III-8]. The second approach is characterization of the original material through a characterization campaign involving a small number of expert laboratories, such as national metrology institutes.

One measurement area in which the first pilot studies have recently been initiated is the area of stable isotope ratio determination. A pilot CCQM-P75 study, titled Stable Isotope Delta Values of  $^2\text{H}$ ,  $^{13}\text{C}$ ,  $^{15}\text{N}$  and  $^{18}\text{O}$ ,  $^{34}\text{S}$  in Methionine, coordinated by the Institute for Reference Materials and Measurements, is the first that tackles metrology issues for stable isotope measurements of light elements. The participation of laboratories from 18 countries demonstrates a strong interest and the need for this type of comparison.

Stable isotope ratio measurements are important in the study of water resources, agriculture and the environment. In this area the IAEA prepares and maintains a stock of relevant reference materials. The best known of these are the Vienna Standard Mean Ocean Water (VSMOW) and the Standard Light Antarctic Precipitation (SLAP), which fulfil the function of primary measurement standards for hydrogen and oxygen isotope ratios. For a better understanding of the role of primary measurement standards, one can compare the role of VSMOW and SLAP with the function of the primary kilogram prototype stored at the Bureau International des Poids et Mesures (BIPM) in Paris, which defines the international mass scale [III-9]. Both VSMOW and SLAP are materials established to define a certain unit, whether for mass or for a stable isotope ratio of elements. However, while the primary kilogram is an artifact kept under controlled conditions and only subsequently calibrated secondary standards are further used in the calibration process, VSMOW is an exhaustible material sent out in small portions to laboratories for their calibration.

Recently, in an international effort coordinated by the IAEA, the original and almost exhausted VSMOW was replaced by a successor material called VSMOW2. The isotopic composition of the original VSMOW was reproduced nearly perfectly. This was achieved by mixing three different water samples characterized by the world's leading stable isotope measurement laboratories (Fig. III-5). The uncertainty of the calibration is much smaller than the uncertainty of measurement that a field laboratory can normally achieve



### Raw water for VSMOW2 production

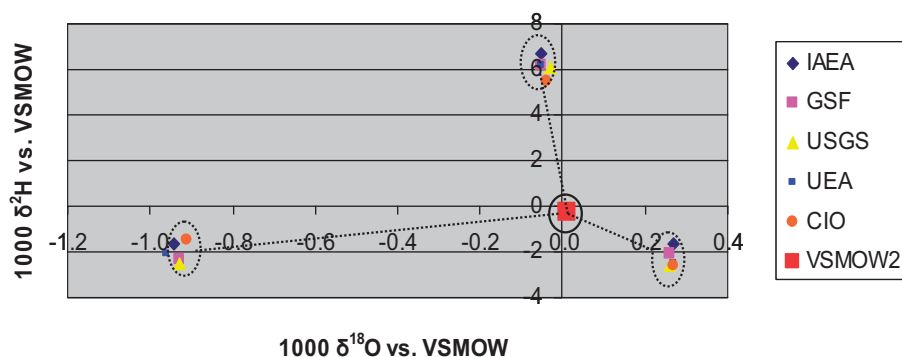


FIG. III-5. The measurement results for three water samples used in the preparation of VSMOW2.

(indicated by the blue circle). In other words, VSMOW2 can be used as a direct replacement without any need for adjustment of measurement results due to the calibrant used. Hence comparability of measurement results is assured.

Several similar efforts were undertaken in the last few years to recalibrate existing reference materials for improved consistency of assigned values, coordinated by the US National Institute for Standards and Technology (NIST), the IUPAC and the IAEA.

The importance of these activities is shown by a recently initiated project of the Commission of Isotopic Abundances and Atomic Weights<sup>25</sup>, the international body for atomic weights data of all elements, to compile a list of available reference materials for all elements to improve the situation in areas and elements without proper internationally accepted reference materials. In this context a project was also launched recently at NIST to develop new reference materials for transition zone elements (copper, iron, etc.) for new kind of mass spectrometers using ultra-low amounts of sample for analysis.

#### III-2.3. Interlaboratory Comparisons — Proficiency Tests

Interlaboratory comparisons and proficiency testing are methods for regularly assessing the accuracy of the analytical data produced by laboratories. Proficiency testing schemes operate by providing participating laboratories with samples containing specified material but the actual quantity of the

<sup>25</sup> See <http://www.iupac.org/divisions/II/II.1/index.html>

substance to be analysed in the material is known only to the organizers. The laboratory analyses the samples, preferably as part of their normal routine, and reports the results to the scheme organizers. The laboratory is then provided with a report showing how closely their results agree with the accepted value, and where necessary, can then take appropriate action to improve performance.

Regular participation in a proficiency testing scheme provides independent verification of the analytical competence of a laboratory and shows a commitment to the maintenance and improvement of performance. It demonstrates to the public, customers, accreditation bodies, regulators and management that analytical procedures are under control and gives analysts confidence that the service which they provide will withstand scrutiny.

The results generated in proficiency testing may be used for the purpose of a continuing assessment of the technical competence of the participating laboratories. With the advent of “mutual recognition” it is of importance that laboratories participate in proficiency testing schemes to provide an interpretation and assessment of results which is transparent to the participating laboratory and its “customer”.

### **III-3. Conclusions**

The acceptance of information provided by analytical chemical laboratories strongly depends on quality measures implemented during the process of data generation. Increasing demands on laboratories to demonstrate the quality of their work leads in the direction of greater formalization in this field, including requirements that laboratories be accredited.

The importance of matrix reference materials has been recognized by international organizations such as WHO, WMO, FAO, OECD, UNEP and WTO (TBT: Technical Barrier to Trade) as well as the EU. The producers of reference materials are increasingly requested to adopt ISO Guide 35 (Certification of Reference Materials) and receive ISO Laboratory accreditation (ISO Guide 43). They face new challenges due to the more complex nature of production, such as increased requirements due to new analytical methods, low levels of analytes (measurands), and newly required analyte species. Nuclear analytical techniques are in many cases uniquely able to help address these challenges.

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## Annex IV

### DEVELOPMENT OF ADVANCED REPROCESSING TECHNOLOGIES

#### IV-1. Introduction

Currently, about 10 500 t HM (tonnes of heavy metal) of spent fuel are discharged annually from nuclear power reactors worldwide. Although this spent fuel still contains substantial fissionable material (uranium and plutonium) that can be reprocessed and recycled as fuel, only 15% is currently reprocessed. For most of nuclear power's history, reprocessing and recycling of the separated U and Pu in fast reactors has been the favoured strategy for the back end of the fuel cycle. While most countries have adopted a 'wait and see' strategy on this matter, some countries have decided, due to proliferation concerns and a lack of economic stimulus, to regard the spent fuel as waste and prefer to dispose of it after 30–40 years of storage without reprocessing. Lately, however, in some of these countries there has been a resurgence of interest in reprocessing and recycling as key components of developing future sustainable nuclear energy systems [IV-1, IV-2].

The main purpose of reprocessing is to better utilize natural resource by recycling the remaining uranium and plutonium, thus reducing demands on fresh uranium mining and milling and ensuring a more sustainable and long term use of nuclear energy. Reprocessing and recycling in fast reactors has the potential to reduce the uranium demand per kW·h by a factor of 50–100. Reprocessing of fuel from light water reactors and gas cooled reactors and recycling of the separated plutonium as mixed oxide (MOX) fuel is today commercially available. (Table IV-1).

Figure IV-1 shows how the relative radiotoxicity<sup>26</sup> of the different components of spent nuclear fuel varies over time. For the first 100 years after spent fuel is discharged, its radiotoxicity is determined by the fission products. It is then determined by plutonium. If the plutonium is removed, the minor actinides determine the long term radiotoxicity. It should be noted that both scales are logarithmic.

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<sup>26</sup> Radiotoxicity is calculated by dividing the radioactivity (Ci) of a nuclide in the spent fuel by the maximum permissible concentration (Ci/m<sup>3</sup>) of that radionuclide in drinking water.

TABLE IV-1. COMPOSITION OF SPENT FUEL FROM THERMAL REACTORS: ASSOCIATED ISSUES AND PLAUSIBLE SOLUTIONS

| Constituent  | Composition in percentage | Issue  | Disposition path   |
|--|---------------------------|--|--|
| Uranium  | ~95–96                    | An energy resource.  | Separated uranium could be recycled as fuel in reactors.   |
| Plutonium  | ~1.0                      | An energy resource, but also the major contributor to long term radiotoxicity (and heat-load) of the waste. Separated Pu constitutes a major proliferation concern.        | Separated Pu could be recycled in reactors as fuel. Proliferation concerns could be reduced by not separating pure Pu.   |
| Minor actinides (MAs) primarily Np, Am and Cm      | ~0.1                      | Important contributors to long term radiotoxicity of the waste. Proliferation concerns exist concerning separated Np.  | MAs can be burnt alone or in combination with Pu in fast reactors.   |
| Stable or short lived FPs (fission products)       | ~3–4                      | Some FPs such as Cs and Sr are the primary contributors to the short term radiotoxicity and heat source in the waste. Other FPs, e.g. noble metals, could become valuable. | Storage of high level waste (HLW) for a few hundred years or separation of Cs and Sr for separate disposal after a few hundred years of storage. Separated Cs has industrial applications. |
| Long lived fission products (LLFPs), e.g. Tc and I | ~0.1                      | Contributors to the long term radiotoxicity of the waste.  | No industrial process to limit the problem has been developed.   |

In comparison with direct disposal of spent fuel, present day reprocessing also provides some positive effects on the remaining radioactive waste that needs disposal. These include the following:

- **Long term radiotoxicity is reduced.** This reduces long term concerns for the repository, which could simplify the repository design and increase public acceptance.
- **Long term heat production is reduced.** This increases the capacity of a repository, as the packaging density in most cases is determined by the heat load.
- **The volume of high level waste is reduced.**

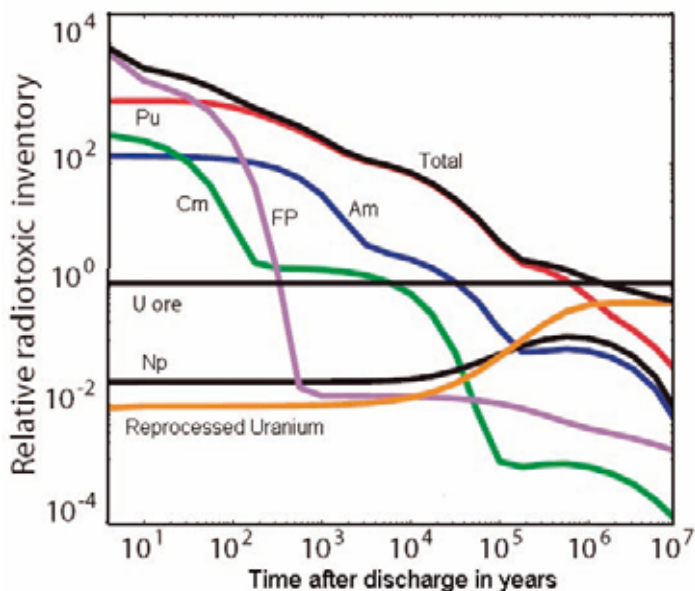


FIG. IV-1. Relative radiotoxicity of the different components in spent nuclear fuel from a light water reactor irradiated to 41 MW·d/kg U with respect to the radiotoxicity of the corresponding uranium ore [IV-3, IV-4].

These effects can be further enhanced in advanced reprocessing systems, where minor actinides are also separated with the purpose of burning them, thereby further reducing the long term radiotoxicity and heat load in the remaining waste. In addition, some valuable fission product materials, e.g. caesium and platinum group metals, could be extracted for industrial use. Heat reduction is mainly achieved by removing the caesium and strontium followed by plutonium and americium.

#### IV-2. Purex: Current Industrial Reprocessing Technology

All current commercial reprocessing plants use the PUREX<sup>27</sup> process. It was developed for civil applications during the 1960s, following experience gained from military programmes.

In the PUREX process (which is summarized in Fig. IV-2), the spent fuel is first chopped into small pieces and then dissolved in nitric acid and subjected to a solvent extraction process using tri-n-butyl phosphate (TBP). Uranium

<sup>27</sup> PUREX: plutonium–uranium extraction.

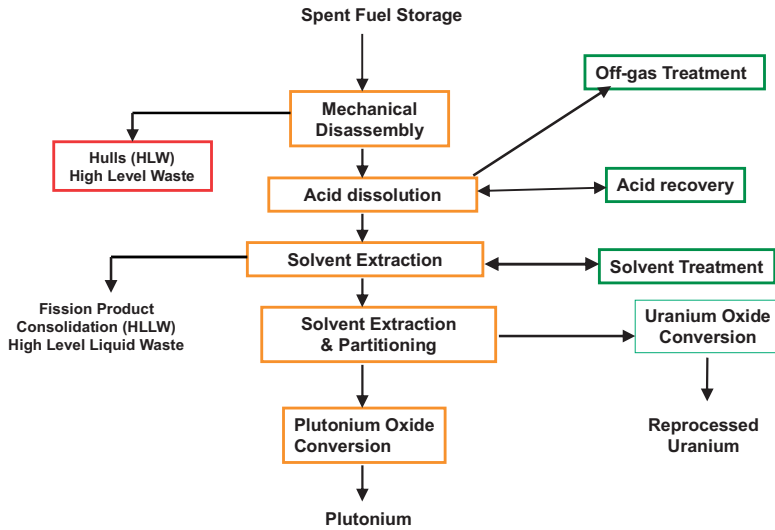


FIG. IV-2. Key steps in the PUREX process.

and plutonium are selectively taken up in the TBP phase resulting in good separation from the rest of the fission products and minor actinides,<sup>28</sup> which are retained in the initial acid medium. The U and Pu are then separated in multistage extraction cycles and purified. The present state of the art in PUREX reprocessing provides a 99.9% separation of U and Pu. In some variants of the PUREX process the Pu is co-precipitated with uranium to avoid the separation of pure plutonium. This is the case in the Japanese reprocessing plant at Rokkasho. The waste stream (the liquid high level waste) that contains fission products, minor actinides and activation products, is processed and vitrified, i.e. mixed with glass material to form a borosilicate glass, and encapsulated in a steel container.

In a PUREX reprocessing facility the spent fuel is thus separated into its four components: uranium, plutonium, high level waste containing fission products and other transuranic elements, and metallic waste from the fuel rods and assemblies.

The PUREX technology is actively used on a large scale in France, Japan, India, the Russian Federation and the United Kingdom. It is used to reprocess uranium and MOX fuel from different types of reactors (LWRs, PHWRs, GCRs and LMFRs<sup>29</sup>) and also fuel with different chemical forms and enrich-

<sup>28</sup> The main minor actinides are neptunium, americium and curium.

<sup>29</sup> LWR: light water reactor; PHWR: pressurized heavy water reactor; GCR: gas cooled reactor; LMFR: liquid metal cooled fast reactor.

ments, e.g. from research reactors. Around 90 000 t HM have been reprocessed in civilian reprocessing facilities. The current annual industrial reprocessing capacity is around 4600 t HM globally, and it is expected that an additional 2000 t might be added in the next ten years.

### **IV-3. Developments in Reprocessing Technologies**

The current generation of reprocessing plants has been continuously improved in regard to the following [IV-5]:

- (a) Flexibility (adaptations to increased burnup, MOX treatment);
- (b) Reduction of effluent discharges and impacts on the environment;
- (c) Reduction of occupational exposure (e.g. during preventive maintenance and inspections);
- (d) Reductions in waste volumes (of both HLW and intermediate level waste (ILW));
- (e) Simplification of the process (e.g. through reducing the number of cycles needed);
- (f) Increased safety through reduced criticality hazards, and better proliferation resistance through real time accounting of nuclear materials.

Nevertheless, reprocessing systems still have to address some more challenging concerns, namely:

- (a) Proliferation issues associated with producing separated plutonium;
- (b) Issues associated with HLW, owing to the presence of minor actinides and long lived fission products (LLFP);
- (c) Economics and costs;
- (d) Processing of transuranic-rich fuels that are being developed for future advanced nuclear reactors.

Much of the ongoing development work for reprocessing technologies deals with these issues. The economic competitiveness of reprocessing and recycling of fissile materials depends on the price of natural uranium and on the possible gains from reduced demands for repositories.

Collaborative international efforts are under way, including INPRO and GIF<sup>30</sup>, for developing innovative reactors and fuel cycles that are competitive

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<sup>30</sup> INPRO; International Project on Innovative Nuclear Reactors and Fuel Cycles; GIF: Generation IV International Forum.



and safe, with simplified procedures for managing radioactive waste and with features to increase the proliferation resistance of nuclear material. Similar to the evolution of innovative nuclear reactor development, reprocessing technology is evolving in stages.

New wet processes are under development in which also the minor actinides and some LLFPs are separated for later destruction (incineration) in different types of reactors, including fast reactors and accelerator driven systems. Other methods are also being developed in which plutonium is never separated in a pure form but always mixed with minor actinides for proliferation resistance. In a longer time perspective different dry reprocessing technologies are also being developed, e.g. pyro-processing, which could provide benefits in terms of economics, size and fuel cycle flexibility through their higher radiation resistance. Several different lines of development are being considered and tested on a laboratory scale. In some cases the step towards industrial implementation is fairly short, while others will require substantial work before they can be introduced at an industrial level. The following section gives some examples of advanced processes.

#### *IV-3.1. Wet Process Developments*

For wet processes there are two different lines of approach: (i) advanced separation of different components in the high level liquid waste (HLLW) generated by the PUREX process (advanced separation), or (ii) changing the chemistry in the first separation step so that only uranium is separated, while keeping plutonium, minor actinides and fission products in the waste solution for later processing (e.g. UREX<sup>31</sup>).

##### *IV-3.1.1. Advanced Separation*

The purpose of the ongoing development work on advanced separation methods is to remove minor actinides and some fission products from the HLLW in order to reduce the radiotoxicity and heat load in the final HLW. The minor actinides will be incorporated in reactor fuel for transmutation (nuclear incineration), while the separated fission products are conditioned for long term storage or separate disposal.

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<sup>31</sup> Uranium Extraction.

The processes typically involve the following steps:

- Recovering minor actinides (MA) and lanthanide fission products;
- Purifying the MAs from the lanthanides;
- Individually separating the MAs;
- Recovering Cs and Sr.

Several processes using different types of extractants and solvents have been studied in different countries and tested in hot facilities. Some examples are listed in Table IV-2. Each process uses its specific extractant and solvent. Very high separation efficiencies will be required to reduce the long term radiotoxicity of the remaining HLLW by a significant factor. In addition to high separation efficiency the minimization of secondary process waste, e.g. by using amides instead of phosphorous reagents, is also an important goal.

Figure IV-3 shows the stepwise combination of different processes developed by CEA in France. For the first 'post-PUREX' step, the co-extraction of minor actinides (americium and curium) and lanthanides, the DIAMEX process is used [IV-7]. In the second step, SANEX, the actinides are separated from the lanthanides, and in the third step americium is separated from curium. A process called SESAME is under development for this. In the last step caesium and strontium are extracted from the remaining waste stream.

During current reprocessing operations, neptunium is partly discharged with the fission products into the HLLW and partly associated with the U and

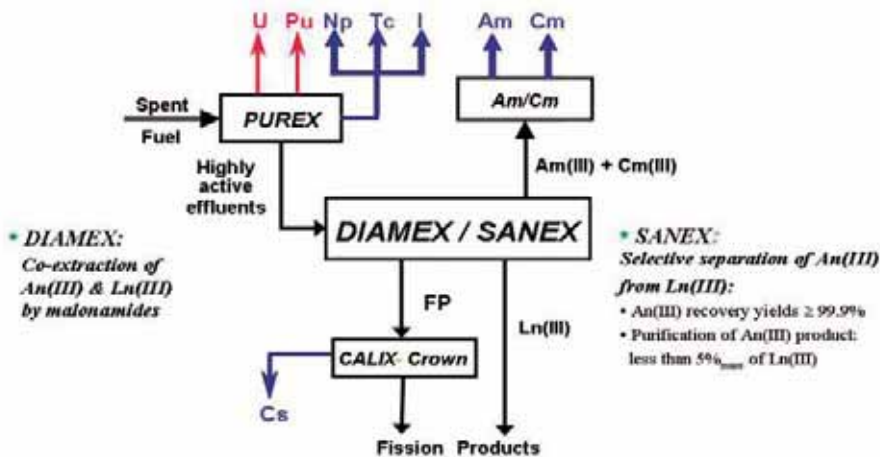


FIG. IV-3. One of the strategies for treating PUREX raffinate under development at the Commissariat à l'énergie atomique (CEA), France.

TABLE IV-2: REVIEW OF ADVANCED AQUEOUS PARTITIONING METHODS [IV-1, IV-6–IV-10]

| Process  | Purpose  | Country   | Special aspects   |
|----------|--|---|---|
| DIAMEX   | Extraction of minor actinides and lanthanides from HLLW                                  | France  | <b>Diamide Extraction Process</b><br>Solvent based on amides as alternate to phosphorous reagent<br>Generates minimum organic waste as the solvent is totally combustible         |
| TODGA    | ditto  | Japan   | <i>Tetra-octyl-diglycol-amide</i><br>Amide similar to DIAMEX  |
| TRUEX    | Transuranic elements ( <i>TRU</i> )<br>Extraction from HLLW                              | USA,<br>Russian Federation,<br>Japan, Italy,<br>India             | Extraction by using Carbamoyl Methyl Phosphine Oxide (CMPO), together with TBP  |
| SANEX-N  | Selective Actinide Extraction process for group separation of actinides from lanthanides | France,<br>Germany<br>(Institute for Transuranium Elements (ITU)) | Process for separating actinides from lanthanides from HLLW by using neutral N-bearing extractants, such as Bis-triazinyl-pyridines (BTPs)  |
| SANEX-S  | Selective Actinide Extraction process for group separation of actinides from lanthanides | China,<br>Germany,<br>India                                       | Use of acidic S-bearing extractants, for example synergistic mixture of Cyanex-301 <sup>a</sup> with 2,2-bipyridyl  |
| TALSPEAK | Selective Actinide Extraction process for group separation of actinides from lanthanides | USA,<br>Sweden  | <i>Trivalent Actinide Lanthanide Separation by Phosphorus Extractants and Aqueous Komplexes</i><br>Use of HDEHP as extractant and DRPA as the selective actinide complexing agent |

TABLE IV-2: REVIEW OF ADVANCED AQUEOUS PARTITIONING METHODS [IV-1, IV-6–IV-10] (cont.)

| Process   | Purpose   | Country                                     | Special aspects  |
|-----------|---|---|--|
| ARTIST    | Selective Actinide Extraction<br>process for group separation of actinides from lanthanides | Japan                                       | Amide-based Radio-resources Treatment with Interim Storage of Transuranics<br>This process comprises: (1) Phosphorus-free branched alkyl monoamides (BAMA) for separation of U, Pu; (2) TOGDA for actinide and lanthanide recovery and (3) N-donor ligand for actinide/lanthanide separation   |
| SESAME    | Selective Extraction and Separation of Americium by Means of Electrolysis                   | France, Japan                               | Process for separating Am from Cm by oxidation of Am to Am(VI), subsequent extraction with TBP for separation from Cm  |
| CSEX      | Cs Extraction   | USA, France                                 | Using Calix-crown extractants  |
| CCD - PEG | Extraction of Cs and Sr from the raffinate  | Czech Republic, EU, Russian Federation, USA | Chlorinated cobalt dicarbollide and Poly-ethylene glycol (CCD-PEG) in sulfone based solvent is planned for extraction of Cs and Sr from UREX raffinate   |
| SREX      | Sr Extraction   | USA   | Using dicyclohexano 18-crown-6 ether   |
| GANEX     | Uranium extraction followed by group extraction of all actinides                            | France                                      | Group recovery of all actinides based on branched amide compound N,N-di-(2-ethyl-hexyl)-iso-butanamide (DOiBA) and subsequent DIAMEX/SANEX   |
| UREX +    | Uranium Extraction + other processes for further separation                                 | USA   | A series of five solvent-extraction flow sheets that perform the following operations: (1) recovery of Tc and U (UREX); (2) recovery of Cs and Sr (CCD-PEG); (3) recovery of Pu and Np (NPEX); (4) recovery of Am, Cm, and rare earth fission products TRUEX; and (5) separation of Am and Cm from the rare earth fission products (Cyanex 301). |

<sup>a</sup> Cyanex refers to compounds belonging to the family of organo-dithio-phosphinates ( $R_2PS_2^-$ ).

Pu stream. The purification of U and its separation from Np is achieved in the second extraction cycle of the PUREX process. An advanced PUREX process, PARC (PARTitioning Conundrum), is being developed with the main objective of separating Np and Tc in the first extraction cycle.

#### IV-3.1.2. Pure Uranium Separation

As an alternative to PUREX based processes a series of new processes are being developed that separate uranium (UREX) while keeping plutonium, minor actinides and fission products in the waste solution [IV-10]. Subsequently all actinides can be recovered as a group. Also, caesium and strontium can be separated. These UREX based separation processes have become one of the key emphases in the US Department of Energy's Advanced Fuel Cycle Initiative (AFCI), which provides the technical foundation for the Global Nuclear Energy Partnership (GNEP). A similar process, GANEX<sup>32</sup>, is being developed in France.

#### IV-3.2. Pyrochemical Processes

Pyrochemical processes were first investigated in the 1950s as an alternative to PUREX to increase the radiation resistance and stability of material used in extraction processes. An initial pyrochemical process was constructed at the Experimental Breeder Reactor II (EBR-II) in the USA during the 1950s. Later many concepts for pyrochemical partitioning were developed, and in some cases pilot plants were built and operated. The techniques were based on using metals and salts at high temperatures: melt-refining, volatilization, gas–solid reaction, fractional precipitation, vacuum distillation, electro-deposition, electro-refining, electro-winning<sup>33</sup> and others. This technology, which has a lower separation factor, can possibly decrease reprocessing costs, nonetheless, by taking advantage of the ability of fast reactors to use fuel with more impurities than would be acceptable in thermal reactors. The advantages of some of these pyro-processes are:

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<sup>32</sup> Group ActiNide Extraction.

<sup>33</sup> Electro-winning and electro-refining processes are standard metallurgical processes for extracting and purifying metals. In electro-winning a current is passed from an inert anode through a liquid leach solution containing the metal so that the metal is deposited onto the cathode. In the electro-refining process, as the current passes through the anode, which is made of impure metal, the metal dissolves into the solution and gets deposited as refined metal onto the cathode.

- Adaptability to reprocess spent fuels, including MA based fuels, with shorter cooling periods (this advantage relates principally to future fuel cycles);
- Ability to co-recover actinides largely in a single process;
- Compact plants that can accept several forms of fuel;
- Very short turn-around time for the fuel, and associated cost savings from the resulting reduction of otherwise large fissile materials inventories;
- Generation of minimum amounts of transuranic waste;
- Very high intrinsic proliferation resistance for the fissile materials owing to:
  - Limited purity of the end product, which limits its direct use in nuclear weapons;
  - A built-in isotopic barrier because of the presence of isotopes with high decay heat, high spontaneous neutron yield and lethally high radiotoxicity;
  - Co-location of reprocessing and fuel fabrication facilities with the reactor.

However, the main challenges facing pyroprocesses are the requirement for an oxygen- and moisture-free plant environment, and the need to develop materials that will not only withstand high radiation levels but have excellent resistance to high temperature corrosion in molten metals and molten halide salts.

The common features of pyrochemical processes are dissolution of spent fuel elements in a molten salt bath around 500 to 800°C, followed by some degree of selective recovery of constituent elements for recycling or conditioning. Semi-industrial scale reprocessing technologies based on electro-refining processes (ERPs) were developed in the USA in the 1980s for U as well as (U, Pu) metal fuels. Likewise, for UOX and MOX fuels the Russian Federation has developed the electro-winning process combined with remote vibro-pack technology for fuel rod fabrication. These were tested in fast reactors in the 1990s. A schematic diagram of the electro-refining cell and a flowsheet for the ERP are shown in Fig. IV-4(b).

In the molten salt refining process developed in the USA, the spent metallic fuel (U–Zr or U–Pu–Zr alloys) is chopped into small pieces and loaded in the anode basket of an electro-refining cell with, as the electrolyte, molten LiCl/KCl eutectic mixtures at around 773K. A cylindrical rod of low carbon steel is used as the cathode. CdCl<sub>2</sub> is added to the electro-refining cell to transfer most of the actinides and fission products as chlorides to the electrolyte bath. On passing a current through the cell, the uranium in the anode forms uranium ions in the molten salt electrolyte and then the uranium

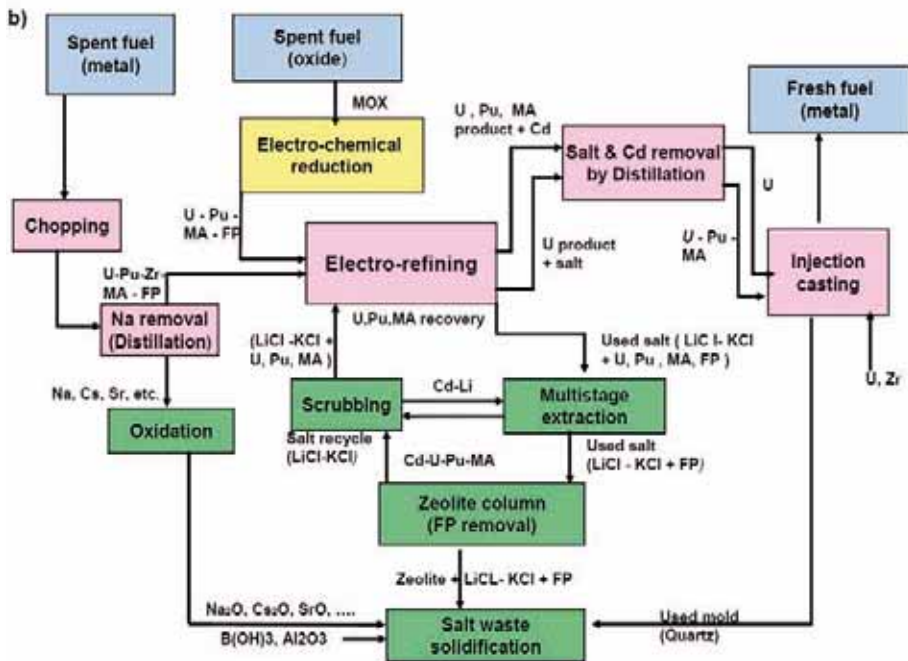
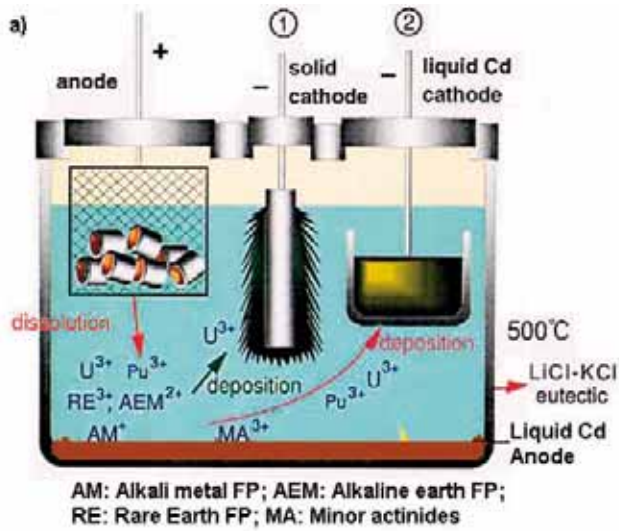


FIG. IV-4. (a) Schematic of an electro-refining cell; and (b) the process flow sheet for an electro-refining process under development at Idaho National Laboratory (INL), USA, Japan Atomic Energy Agency (JAEA), and the ITU, EC.

is reduced and deposited as uranium metal on the cathode. After uranium recovery, the solid cathode is replaced by a liquid cadmium cathode. Under this condition, electrolysis leads to co-deposition of U, Pu, MAs as well as some lanthanide elements into the liquid cathode. More reactive fission products remain dissolved in the salt phase. Fission products less reactive than actinides, namely noble metals and zirconium, are not dissolved and remain in the anode basket (see Fig. IV-4(a)).

Recent technological development efforts [IV-11] in the USA range from laboratory scale studies of new processing concepts, such as the electrolytic reduction of spent LWR oxide fuel, to the engineering scale demonstration of high-throughput uranium electro-refining. Japan has a laboratory scale facility for electro-refining metallic fuel [IV-12]. In addition, development work is under way on extracting transuranic elements (TRUs) by pyrochemical methods from HLLW generated from the PUREX process applied to LWR fuels. Other IAEA Member States (China, the Czech Republic, France, India and the Republic of Korea,) as well as the EC/ITU, have also embarked on some of these pyrochemical methods on a laboratory scale. At the Research Institute of Atomic Reactors (RIAR) at Dimitrovgrad, Russian Federation, the recycling of fuel at tonnage scale has been successfully demonstrated using a pyrochemical method based on the electro-winning process as part of demonstrating a closed fuel cycle with MOX fuels for the BOR-60 fast reactor. Another promising method is fluoride volatilization for processing the TRU-rich fuels or targets that are being considered for a future generation of dedicated burner reactors or accelerator driven systems (ADSs).

The development of pyrochemical processes requires also the development of state of the art equipment that is suitable for applying such processes at an industrial scale. The path to industrial utilization is thus perhaps longer for the pyro-processes than for the advanced aqueous processes.

#### **IV-4. Synergistic Combination of Different Fuel Cycles**

There are several research efforts looking for ways in which different fuel cycles, both existing and future, can efficiently complement one another for sustainable nuclear energy development. Aqueous processing methods have very high throughputs and sufficient industrial maturity to handle large volumes of discharged fuels from LWRs. However, they are less suitable for reprocessing fast reactor fuel with short turnaround times. Pyrochemical processes can handle spent fuels with short cooling times as well as with very high MA content in a significantly smaller processing facility. Furthermore, these processes can recycle TRU waste, thus reducing the volume of TRU waste that needs disposal. Due to impure product recovery, the process is very



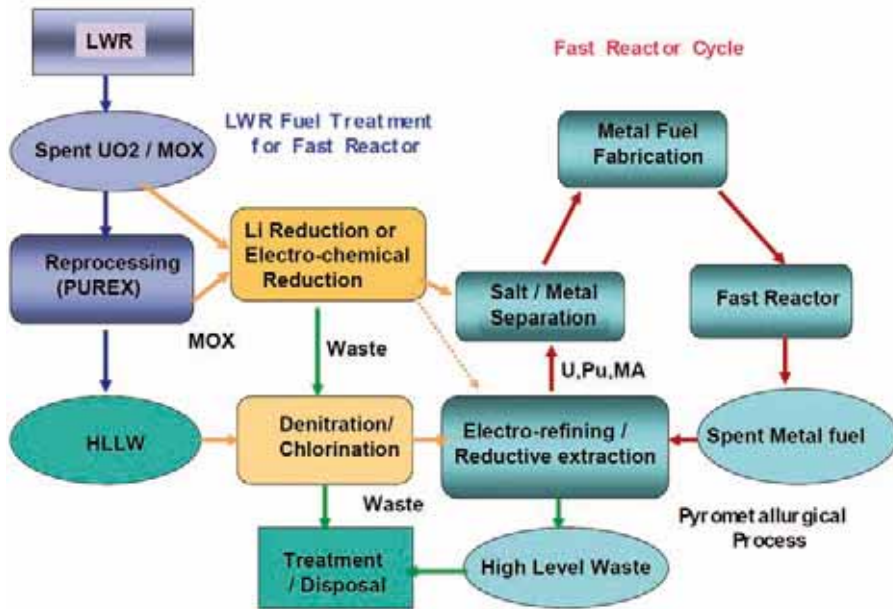


FIG. IV-5. Actinide recycling system by integrating oxide fuel treatment and the recovery of actinides in HLLW.

much proliferation resistant. Thus, synergistic combinations of aqueous partitioning steps with pyrochemical processing, as depicted in Fig. IV-5, could be a promising option in the future.

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## **Annex V**

### **INSTRUMENTATION AND CONTROL SYSTEMS IN NUCLEAR POWER PLANTS: A TIME OF TRANSITION**

Instrumentation and control (I&C) systems are the nervous system of a nuclear power plant. They monitor all aspects of the plant's health and help respond with the care and adjustments needed.

Progress in electronics and information technology (IT) has created incentives to replace traditional analog I&C systems in nuclear power plants with digital systems, i.e. systems based on computers and microprocessors. Digital systems offer higher reliability, better plant performance and additional diagnostic capabilities. Analog systems will gradually become obsolete in the general IT shift to digital technology. About 40% of the world's operating reactors have been modernized to include at least some digital I&C systems. Most newer plants also include digital I&C systems.

Digital I&C systems have posed new challenges for the industry and regulators, who have had to build up the methods, data and experience to assure themselves that the new systems meet all reliability and performance requirements. In general, countries with more new construction of nuclear reactors have had greater incentives and opportunities to develop the needed capabilities. Other countries are still in the process of doing so.

#### **V-1. Status and Examples of Digital I&C Systems in Nuclear Power Plants**

Nuclear power plants rely on I&C systems for protection, control, supervision and monitoring. A typical unit has approximately 10 000 sensors and detectors and 5000 km of I&C cables. The total mass of I&C related components is of the order of 1000 t. This makes the I&C system one of the heaviest and most extensive non-building structures in any nuclear power plant.

No globally comprehensive statistics are available on the numbers of plants with fully analog, fully digital or hybrid I&C systems. However, approximately 40% of the world's 439 operating power reactors, accounting for nearly all of the 30 countries with operating nuclear power plants, have had some level of digital I&C upgrades to at least important safety systems. From another perspective, 90% of all the digital I&C installations that have been done have been modernization projects at existing reactors. Ten per cent have been at new reactors. Of the 34 reactors currently under construction around the

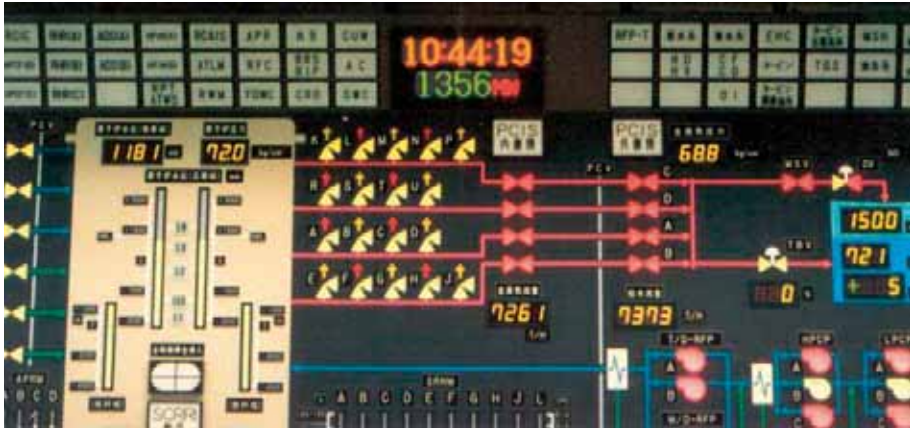


FIG. V-1. Section of main control panel in the Kashiwazaki-Kariwa-6 and -7 ABWR (1350 MW(e)).

world, all of those for which construction began after 1990 have some digital I&C components in their control and safety systems.

In Japan, the first fully digital I&C system was integrated into the Kashiwazaki-Kariwa-6 advanced boiling water reactor (ABWR) in 1996, followed shortly by Kashiwazaki-Kariwa-7 (see Fig. V-1). Similar digital I&C systems are used in Hamaoka-5. Tomari-3, which will feature the first all-digital reactor control room, is scheduled to begin operation in 2009.

In China, Qinshan Phase III, with two 700 MW(e) CANDU reactors, and Tianwan-1 and -2, with two 1000 MW(e) WWERs, have fully digital I&C systems, including both the safety and control systems, and partly computerized, i.e. hybrid, human–system interfaces (HSIs). China’s high temperature gas cooled experimental reactor, the HTGR-10, also has fully digital safety and control I&C systems, plus a hybrid HSI in its main control room.

In the UK, at Sizewell B, a 1250 MW(e) PWR, all automatic functions of the safety I&C systems are digital, and in the main control room, all the qualified displays used in the HSI are computerized.<sup>34</sup>

In the Russian Federation, Kalinin-3, which was commissioned in 2004, is the first WWER-1000 equipped with digital I&C safety systems and digital process control systems. In addition, both its main and emergency control rooms have hybrid HSIs (Fig. V-2(a)). A dynamic simulator was also installed (Fig. V-2(b)) for the purpose of testing control functions.

<sup>34</sup> The phrase “qualified displays” refers to dedicated display equipment with the high performance and dependability needed for safety applications.



FIG.V-2. (a) Main data control room of Kalinin Unit 3; (b) dynamic simulator of Kalinin Unit 3.

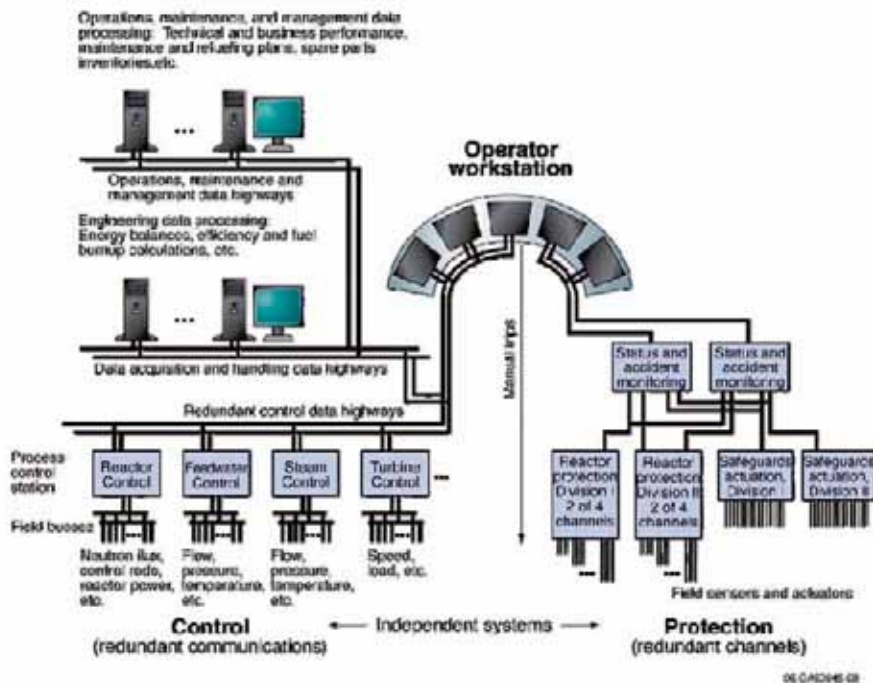


FIG.V-3. Typical I&C architecture for a plant with a digital I&C system for control and an analog I&C system for safety (labelled “protection” in the figure) (source: US National Research Council).

In the Republic of Korea, three 1000 MW(e) PWRs are under construction (Shin-Kori-1 and -2 and Shin-Wolsong-1), all with fully digital I&C safety and control systems and hybrid HSIs in the control rooms.

In the USA, 1978 was the last year in which construction started on a reactor that eventually came on-line. The United States Nuclear Regulatory Commission (NRC) has, therefore, not had the same experience with digital I&C systems as have regulators in China, India, Japan and the Republic of Korea, where the expansion of nuclear power is centred. Partly as a result, digital systems have not yet been approved for use as safety systems in operating US nuclear power plants. Figure V-3 is a simplified illustration of a US case where the I&C systems for controlling the plant, on the left side of the figure, are digital (computers, digital data networks, automatic calculations, and microprocessor-based sensors), and the I&C systems for safety, labelled “protection” on the right side of the figure, are analog. The figure also illustrates the features of independence, redundancy and diversity that are essential in I&C systems and are outlined below.

## **V-2. I&C Basics and the Reasons for Shifting from Analog to Digital I&C Systems**

I&C systems are installed throughout a nuclear power plant and are vital parts of normal, abnormal and emergency operations. Typically plants have both main and secondary (emergency) control rooms from which most I&C systems are operated. Some I&C functions are critical for assuring nuclear safety (e.g. reactor shutdown systems). Others influence safety to varying degrees. And still others, which are more related to production and maintenance, may have no impact on nuclear safety (e.g. I&C functions for turbine diagnostics, fluid level controllers in the turbines, or the turbine hall crane).

I&C systems are the nervous system of the plant, and they affect every aspect of plant operation. Their components and functions include the following:

- Sensors interfacing with the physical processes within a plant and continuously taking measurements of plant variables such as neutron flux, temperature, pressure and flow;
- Control, regulation and safety systems that process measurement data to manage plant operation, optimize plant performance and keep the plant in a safe operating envelope;
- Communication systems for data and information transfer through wires, fibre optics, wireless networks or digital data protocols;
- HSIs to provide information and allow interaction with plant operating personnel;
- Surveillance and diagnostic systems that monitor sensor signals for abnormalities;

- Actuators (e.g. valves and motors) operated by the control and safety systems to adjust the plant's physical processes;
- Status indicators of actuators (e.g. whether valves are open or closed, and whether motors are on or off) providing signals for automatic and manual control.

In the control room, the I&C systems and the plant operators meet at the HSI. The designs of HSIs, whether digital (e.g. digital displays and touch screens), analog (gauges, knobs, switches and push-buttons) or hybrid (some of both), must go beyond IT electrical engineering to include human factors engineering and ensure both that the operators get the most out of the I&C system and, in a sense, the I&C system gets the most out of the human wisdom of the operators. The next section elaborates on HSI technologies.

Perhaps faster than any other part of nuclear power plants, I&C technology is continuously advancing. Yet the majority of I&C equipment in nuclear power plants was designed more than 30 years ago with analog and relay components, and in some cases rudimentary digital technology. Although analog I&C systems have served the above functions satisfactorily for many decades, a substantial amount of this original I&C equipment already is or soon will be obsolete. Much is approaching or has exceeded its original life expectancy.

Approaching obsolescence means a decreasing availability of replacement parts, decreasing supplier support (or even the loss of the supplier to the nuclear industry), a lack of functional capabilities needed to satisfy current and future needs, and a lack of experienced staff for maintenance and engineering. This can lead to degraded reliability and availability, and a compensatory increase in operation and maintenance (O&M) costs to maintain acceptable performance. Older technology also limits possibilities for adding new beneficial capabilities to the plant. New technology, in contrast, provides opportunities to improve plant performance, HSI functionality, and reliability; to enhance operator performance and reliability; and to address difficulties in finding young professionals with education and experience with older analog technology.

Ageing, by itself, can also reduce performance. If the I&C system has a high failure rate, especially if the consequences are unacceptable or unnecessarily challenge protection systems, then it should have high priority for modernization. In addition, the need for ever higher reliability and availability may require newer technologies with capabilities not possible or practical with older technology.

Approaching obsolescence and ageing may thus make the effort to maintain or increase the reliability and useful life of existing I&C systems

greater in the long run than that of modernizing or replacing them completely with new digital or hybrid systems. Finally, potential regulatory updates might require modernization.

I&C modernization should be performed in the context of, and in support of, the overall plant goals, objectives, and internal and external commitments. These include commitments to licensing authorities, staff and other stakeholders. The goals and objectives of the plant will be driven substantially by utilities' long and short term business plans.

An adequate assessment of the expected length of a plant's remaining lifetime is crucial. In extreme cases, the decision is obvious. If a unit is to be shut down and decommissioned very soon, there is no justification to modernize any of its significant systems, including I&C. On the other hand, when the plant's lifetime is extended through licence renewal and the existing systems cannot continue to support the plant, modernization is required. A nuclear power plant that operates for 60 years, as 48 reactors in the USA are now licensed to do, could outlive its original I&C system by a factor of three, shifting first from analog to digital I&C systems, and then subsequently to even more advanced digital I&C systems.

In between the extremes, those making the decision can benefit from the experience of other plants that have already modernized their I&C systems. Such experience covers cost-benefit analyses, design and selection of equipment, licensing requirements, qualification methods and project management. Importantly, O&M experience from other plants is valuable for determining the goals for a new system, the scope of the project and the system's design.

### **V-3. Control Rooms and Human-System Interface Technologies**

The HSI in the control room is where plant information is translated into required operator action. It is critical to safe operation. Computerizing an HSI means incorporating features such as computerized procedures, digital displays, touch screen interfaces, pointing devices (like a mouse), and large screen overview displays. Computerization allows more tasks to be done by operators sitting at their workstations without moving about the control room.

HSI modernization is an integral part of I&C modernization in general. Because computerization is phased, control rooms at plants that have been modernized are hybrid, incorporating some analog features and some digital features (Fig V-4(a) and (b)).

HSI computerization offers advantages similar to those of digital I&C systems. It allows more efficient operations and maintenance due to the HSI providing operators with a more comprehensive and detailed understanding of





FIG. V-4. (a) Sweden's Oskarshamn unit 1 MCR before modernization in 2003; (b) after modernization.

operating conditions. This leads to improved power plant availability and safety and reduced operating costs through the avoidance of transients, forced outages and unnecessary shutdowns. More precise controls and modelling allow increased power plant efficiency and output. New digital systems also have additional capabilities including self-diagnostic capabilities, simple recalibration, screening and validation of input signals.

Shifting to an increasingly computerized HSI requires retraining operators and revising operation and maintenance procedures. However, it is also an opportunity to take advantage both of certain features of digital systems and of improved understanding of human cognitive processing. Control rooms and their HSIs can be designed, operated and maintained to better match with human cognitive processing abilities and thus increase performance and reduce the likelihood of human errors.

To this end, it is important that control room modernization be a continuous and iterative process with feedback from intended users, who should be involved in all phases. Human factors verification and validation play an important role both in the design and development of individual subsystems and in their integration and installation in the complete system. Human factors verification refers to the comparison of detailed design features against those given in specifications. Human factors validation refers to overall performance testing to check for safe, error-free and efficient performance.

#### V-4. Classification of I&C Systems

I&C systems are classified based on the safety importance of the functions and systems they support. The nuclear industry's graded approach to safety stipulates that greater attention is given to systems and equipment that are important to safety than to systems that have less or no safety impact. In practice, this principle is implemented using a classification or categorization

TABLE V-1. COMPARISON OF DIFFERENT CLASSIFICATION SYSTEMS

|                                    |  |                              |            |                                 |
|------------------------------------|--|------------------------------|------------|---------------------------------|
| National or international standard | Classification to the importance to safety |                              |            |                                 |
| IAEA                               | Systems important to safety                |                              |            | Systems not important to safety |
|                                    | Safety system                              | Safety related system        |            |                                 |
| IEC 61226                          | Category A                                 | Category B                   | Category C | Unclassified                    |
| France N4                          | 1E   | 2E                           | IFC/NC     |                                 |
| European utility requirements      | F1A (Automatic)                            | F1B (Automatic and manual)   | F2         | Unclassified                    |
| Russian Federation                 | Class 1 (beyond DBA <sup>a</sup> )         | Class 2 (safety system, DBA) | Class 3    | Class 4                         |
| UK                                 | Category 1                                 |                              | Category 2 | Unclassified                    |
| USA (IEEE)                         | 1E   | Non-nuclear safety           |            |                                 |

<sup>a</sup> DBA: design basis accident.

document which lists every system and component and assigns it to a safety class or category. Different countries and international organizations use different categorization schemes. For example, the International Electrotechnical Commission (IEC) categorization defines three safety categories, A, B and C, while the US Institute of Electrical and Electronics Engineers (IEEE) only distinguishes between safety and non-safety systems. The IAEA has generally adopted a three level distinction between safety systems, safety related systems and non-safety systems. Table V-1 illustrates how categories used in different classification systems overlap. All classification systems essentially provide the same guidance concerning priorities for I&C modernization, for assuring that safety is never compromised and for allocating resources for testing, verification and validation.

Examples of systems important to safety, using the IAEA classification, are:

- Reactor protection systems;
- Engineered safety features actuation systems (ESFAS), e.g. emergency core cooling and feedwater;
- Safe shutdown systems, e.g. for the fast insertion of absorber rods or injection of neutron absorbing liquid;

- Emergency power supply and diesel generator control systems;
- Information systems important to safety, e.g. displays in the main control room or the neutron flux in-core monitoring system;
- Interlock systems important to safety;
- Reactor control and access control systems;
- Some data communications systems;
- Essential auxiliary supporting systems, e.g. heating, ventilation and air conditioning.

## **V-5. Challenges of Digital I&C Systems**

Digital equipment with improved performance has had an important influence on I&C systems design in many major industries. However, in nuclear power plants digital technology has been adopted more slowly, especially for safety I&C systems. For good reason, the nuclear industry has an inherently conservative approach to safety, and substantial effort is required to provide the necessary evidence and analysis to ensure that digital I&C systems can be used in safety-critical and safety related applications. That effort has been made in countries where it has been justified by recent new construction and by national policies supportive of expanding nuclear power. In other countries industry and regulatory approval of digital safety I&C is less advanced. In both cases, designers and regulators will need to make continuing mutual adjustments at least until digital I&C systems become the universal norm, and probably longer as the technology keeps developing. Designers have to design to existing regulations, which are often still based on analog systems. Regulators have to adjust to the new technology to make sure a country benefits, efficiently and safely, from any advantages it offers in terms of greater reliability, lower costs or greater safety.

For industry adoption and regulatory approval, three features of digital I&C systems are distinctive. First, a digital I&C system has more connections among its many components and is simply more complex than its analog predecessor. Second, the digital system is more dependent on software. Third, the overall dependence on computers raises the importance of cyber security.

The first two of these features, complexity and software dependence, introduce new possibilities for common cause failures.

### *V-5.1. Common Cause Failures*

The greater complexity of digital I&C systems and the greater interaction among subsystems increase the possibility that a latent fault can exist in the system that could be triggered and propagate, thus causing the system to not

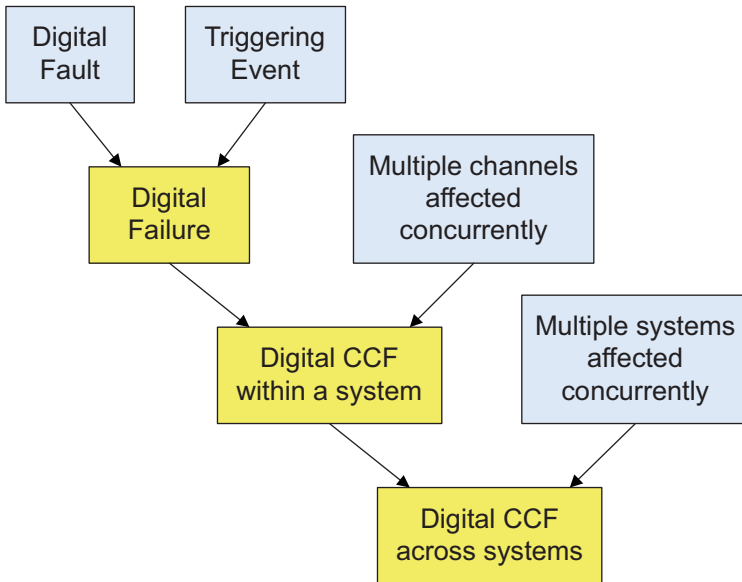


FIG. V-5. Conditions for a common cause failure in a digital I&C system.

perform as expected. The fact that the generation of software can be prone to failures, and the possibility that copies of the same software might be used in redundant channels of a safety system, create an additional potential for common cause failures.

For a potentially unsafe common cause failure to occur, a number of developments must happen at once, as illustrated in Fig. V-5. The system must have a fault; a triggering event must activate the fault; channels that are supposed to be independent must be affected concurrently; the result must have an affect on safety; and multiple systems must share the same fault(s) and be susceptible to the same trigger concurrently.

Concern about similar common cause failures did not exist for earlier analog safety systems because it was assumed that any common cause failure that did occur would be due to slow, distinct processes like corrosion or a part prematurely wearing out. The same cannot be assumed for systems dependent on software.

There are three complementary ways to prevent common cause failures, all of which contribute to defence in depth. They are diversity, redundancy and independence. Diversity means that, for a particular function, two or more redundant systems or components with different attributes are included in the design. In practice, it may mean using different components based on different designs and principles, from different vendors. Redundancy means that

alternative systems and components are included, so that any one can perform the required function if the others fail. Independence prevents the propagation of failures and common cause failures due to common internal plant hazards. Independence is achieved by electrical isolation, physical separation and independence of communications between systems.

Additional diversity, redundancy and independence, however, also increase a system's complexity and raise the possibility that the additional complexity may pose a larger risk of human errors in design, operation and maintenance than the common cause failure they were intended to avoid. To compensate, one way to simplify the design, manufacture and use of digital I&C systems is to use pre-qualified 'commercial off-the-shelf' (COTS) hardware and software components that have been thoroughly tested and evaluated for nuclear power plant applications.

Whichever mix of these approaches is taken to reducing possible failures, the overall risk of a digital I&C system needs to be assessed, quantified and managed using probabilistic safety assessment (PSA) methods. This will become increasingly straightforward as experience with digital I&C systems grows, as the data on their performance in all conditions expand, and as associated PSA models are further developed.

#### *V-5.2. Cyber Security*

Nuclear power plant I&C systems are generally isolated from external communication systems. Nonetheless, particularly the computers used in safety and safety related systems must be very well protected from possible intrusions. But other computers must be protected as well. The computers used to control the plant are essential to ensure the continuity of power production. The computers used to control access to sensitive areas are needed both to prevent unauthorized access that might be part of an attack, and to ensure authorized access both for safety and security reasons. Computers that store important and sensitive data have to be protected to ensure that those data are not erased or stolen.

Possible cyber attacks could be associated with business espionage, technology theft, a disgruntled employee, a recreational hacker, a cyber activist, organized crime, a nation State, or a terrorist organization. Four categories of possible cyber attacks have to be considered: (1) unauthorized access to information (loss of confidentiality); (2) interception and change of information, software, hardware (loss of integrity); (3) blocking data transmission lines and/or shutting down systems (loss of availability); and (4) unauthorized intrusion into data communication systems or into computers (loss of reliability).

Computer security is built from a consideration of these possible threats and the development of a design basis threat (DBT), defined within the context of computer security, that typically involves both insiders and outsiders. A significant difficulty is that the complexity of computer systems sometimes makes it difficult to identify possible sequences that could introduce important threats. The tools for identifying threats and building barriers include both technical tools, such as intrusion detection, virus scanners and encryption, and administrative tools such as the application of security zones, security management systems, passwords and biometric identification.

Experience gained from cyber security in other sensitive fields, such as the military, national security, banking, and air traffic controls is valuable both for improving cyber security at nuclear power plants with digital I&C systems and for demonstrating that cyber defences can consistently stay ahead of cyber attacks. But, as with safety and other areas of security, cyber security is an area where no one can rest on his or her laurels. Continued success requires continuous vigilance and continuous improvement.

## **V-6. Emerging Technologies**

Digital I&C systems are expected to continue as an area of rapid technological development. Future designs of NPPs will require new solutions both in sensing technologies and in digital control. Advanced sensors, detectors, transmitters and data transmission lines are needed to meet the requirements imposed by the operating conditions of new designs (e.g. high temperatures and high flux) and the harsh environment of ‘beyond design basis’ conditions. Additional monitoring and diagnostic systems will need to be developed, making use of on-line condition monitoring techniques, reactor noise analysis for incipient failure detection, wireless sensor networks and communication, and integrated remote operation.

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## ANNEX VI

### STATUS OF FAST REACTOR RESEARCH AND TECHNOLOGY DEVELOPMENT, DESIGN, CONSTRUCTION, OPERATION AND DECOMMISSIONING

#### VI-1. Introduction

##### VI-1.1. *Why Fast Reactors?*

When neutrons are generated during the fission process in a reactor they have high energy and are moving fast. Reactors that operate using these fast neutrons are called fast reactors. When fast neutrons hit  $^{238}\text{U}$  atoms, there is a high likelihood that they are absorbed and that a new atom (after several decays) is produced,  $^{239}\text{Pu}$ , which is a new fissile material. This process is called 'breeding' if more fissile material is produced during the operation of the reactor than is consumed for the production of energy.

Thermal reactors, which are the most common, use a different approach. The neutrons are first slowed down by a moderator, either water or graphite, in the reactor core. When the fast neutrons hit atoms or molecules of the moderator, their speed is reduced. Slow neutrons have a high probability of being absorbed by  $^{235}\text{U}$  atoms, which then leads to fission. Reactors that operate on the basis of slower neutrons are called thermal reactors, which constitute — with few exceptions — all reactors in operation today.

Fast reactors need a high concentration of fissile material to sustain a chain reaction. There are thus strong incentives to extract all fissile material left in the spent fuel and recycle it in new fuel elements. This is called 'closing the fuel cycle'.

Thermal reactors, which mostly use water as both a moderator and coolant and have been used on a large scale, have benefited from major improvements in reliability and economics gained from operating experience.

Nearly all operating nuclear power plants use thermal reactors which can utilize only a small fraction of the energy in uranium. They use mainly the isotope  $^{235}\text{U}$ , which is only about 0.7% of natural uranium. The world's identified conventional uranium resources of about 5.5 million tonnes are adequate to fuel today's reactors for roughly another 100 years.

However, fast breeder reactors can use effectively all the energy in uranium by converting the fertile isotope  $^{238}\text{U}$ , which is 99.3% of natural uranium, into the fissile isotope  $^{239}\text{Pu}$ . Thermal reactors can also convert fertile to fissile material, but breeders can do it in a way that produces more fissile

material than is consumed. With fuel reprocessing to retrieve fissile material from the spent fuel, the result is an increase in the energy potential of natural uranium by a factor of about 60.

Finally, the fast neutrons in fast reactors make it possible to use or transmute certain isotopes that cannot be used in thermal reactors and thus normally become part of thermal reactors' waste burden. These are trans-uranium nuclides and some long lived fission products. By eliminating these isotopes, fast reactors can contribute to reducing the environmental burden of spent fuel, which further enhances the long-term sustainability of nuclear energy. In recognition of the fast reactor's importance to the sustainability of nuclear power, there is currently renewed worldwide interest in fast reactor technology development.

### *VI-1.2. A Short History of Fast Reactor Development*

Fast reactor research and technology development programmes started in a number of countries in the 1940s and early 1950s. The USA was the first to construct an operational fast reactor, with Clementine becoming critical in 1946. The first kilowatt-hours of nuclear electricity in history were produced in December 1951 by a fast reactor, the EBR-I in Idaho<sup>35</sup>, after which the US programme continued with basic R&D and construction of fast reactors of increasing power (EBR-II, FERMI and FFTF).<sup>36</sup> At essentially the same time, the USSR (BR-10, BOR-60), the UK (DFR) and France (RAPSODIE) also began development programmes and built their own experimental fast reactors. A few years later, Germany and Japan started national development programmes and constructed experimental fast reactors, JOYO and KNK, respectively. Thereafter, the pace of fast reactor development picked up steadily until most programmes reached a peak around 1980.

At this point experimental reactors were operating in many countries, providing R&D tools (mainly as irradiation facilities) for various prototype and commercial sized fast reactor development programmes, e.g. Phénix and Superphénix in France, SNR-300 in Germany, MONJU in Japan, PFR in the UK, CRBR in the USA, as well as BN-350 and BN-600 in the USSR. While interest was increasing in developing countries, the next ten years saw a gradual

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<sup>35</sup> The water cooled, graphite moderated, 30 MW(t) (5 MW(e)) AM-1 reactor in Obninsk, USSR, delivered the first nuclear electricity to the grid in 1954.

<sup>36</sup> EBR: Experimental Breeder Reactor; FFTF: Fast Flux Test Facility; DFR: Dounreay Fast Reactor; PFR: Prototype Fast Reactor; CRBR: Clinch River Breeder Reactor.



decline in fast reactor activities in most developed countries. By 1994, the US Government had decided to cancel the CRBR and shut down the FFTF and EBR-II. In France, Superphénix was shut down at the end of 1998; SNR-300 in Germany was completed but not put into operation; and KNK-II was permanently shut down in 1991. In the UK, PFR was shut down in 1994, as was BN-350 in Kazakhstan in 1998. At the time, there was simply no compelling need for fast breeder reactors, so most development programmes either proceeded at a reduced scale or stopped. Today, however, renewed interest in nuclear power has heightened awareness of the medium and long term benefits of fast reactors with a closed fuel cycle.

## **VI-2. Challenges for Fast Reactor Development**

The most important challenges for fast reactors are in the areas of cost competitiveness, enhanced safety, non-proliferation and public acceptance. With the exception of public acceptance challenges, these translate into technology development challenges, i.e. the development of innovative reactor, fuel and fuel cycle (reprocessing and fabrication) technology. Some examples are briefly summarized below.

Cost competitiveness can be achieved through simplification, series construction, extension of reactor lifetimes, increased thermodynamic efficiency, reduction of component structural requirements and increased component reliability. Many of these are related to fast reactor core, fuel, coolant and component design. Simplification can be achieved, for example, by eliminating the intermediate heat transfer system. R&D to this end focuses on, on the one hand, gas cooled fast reactors and gas turbines and, on the other, lead cooled fast reactors. Using helium or lead as a coolant avoids two problems with sodium (the coolant in most fast reactor designs), which are the production in the core of the activation product sodium-24 and the fact that sodium reacts violently with water. These problems necessitate an intermediate sodium-sodium circuit to separate the primary sodium from the steam generator. In contrast, helium is not activated in the core, and neither helium nor lead reacts chemically with water. Thus, the use of helium or lead as a coolant allows simplified fast reactor designs without intermediate heat removal systems.

Lead cooled loop type fast reactors can also be simplified relative to sodium cooled reactors since lead, unlike sodium, does not react with water. This simplifies steam generator design in lead cooled fast reactors. In helium cooled fast reactors, the steam generator can be eliminated altogether, which reduces costs, by using helium turbines.

R&D includes the development of high burnup fuels and of advanced structural materials. For high burnup fuels, the most limiting factor is the

cladding material. Currently, stainless steel claddings are state of the art and have made it possible to achieve burnup values as high as 200 GW-d/t HM. However, new oxide dispersion strengthened (ODS) steels with increased high temperature oxidation characteristics are being developed. These would both allow longer reactor cycles and lifetimes, and increase thermodynamic efficiency. Efficiency could be further increased in lead or helium cooled fast reactors, which allow higher outlet temperatures than in sodium cooled reactors. In addition to their contribution to cost reductions, long life cores can contribute to proliferation resistance by reducing, perhaps to nearly zero, the number of times the reactor needs to be opened up for refuelling.

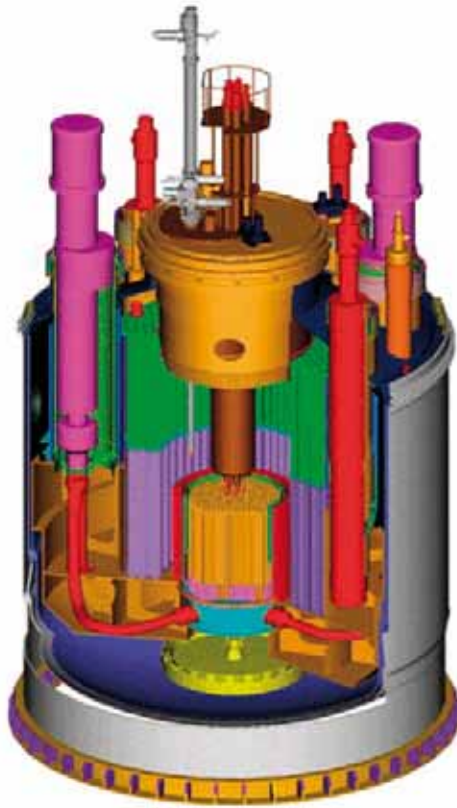
R&D to improve fast reactor safety focuses on reducing the positive reactivity effect due to loss of coolant (known as the void effect). While the neutronics sensitivity of sodium cooled cores to coolant loss can be reduced by various design measures, lead and lead-bismuth eutectic cooled fast reactors offer inherent characteristics that ensure smaller positive void reactivity effects. Specifically, they do not react chemically with water, and they have higher boiling temperatures, 1743°C and 1670°C for lead and lead-bismuth eutectic, respectively, compared to 880°C for sodium.

### **VI-3. Current Status: Fast Reactor Research and Technology Development, Design, Construction, Operation and Decommissioning**

#### *VI-3.1. National Fast Reactor Programmes*

In **China**, the 25 MW(e) sodium cooled, pool type Chinese Experimental Fast Reactor (CEFR) is under construction, with first criticality foreseen for mid-2009 and grid connection in mid-2010. CEFR (Fig. VI-1) is a 65 MW(t) sodium cooled, pool type experimental fast reactor fuelled with mixed uranium-plutonium oxide. The fuel cladding and reactor block structural material is Cr-Ni austenitic stainless steel. CEFR has two main pumps and two loops for each of the primary, secondary and tertiary circuits. The CEFR block is composed of the main vessel and the guard vessel supported from the bottom on the floor of the reactor pit, which has a diameter of 10 m and a height of 12 m. The reactor core and its support structure are supported on lower internal structures, while the two main pumps and four intermediate heat exchangers are supported on upper internal structures.

The next two stages in the Chinese fast reactor development programme consist of the construction of a 600 MW(e) prototype fast reactor (CPFRR), for which design work started in 2005, and a 1000–1500 MW(e) demonstration fast reactor (CDFRR).



*FIG. VI-1. CEFR block scheme.*

**France** has built and operated the 238 MW(e) prototype fast breeder reactor Phénix and the industrial size 1200 MW(e) demonstration fast breeder reactor (FBR) Superphénix. Both reactors have mixed oxide (MOX) fuel in the core, are sodium cooled and have a loop type primary system. Phénix became critical in 1973. It is still in operation and has provided operating experience with a complete prototype fast breeder reactor power station. In 2006, Phénix's annual availability and load factors were 78% and 56%, respectively. Two more operating cycles (representing about 250 equivalent full power days (EFPD)) are planned in Phénix before the reactor is finally shut down in 2009. These will allow completion of irradiation tests in support of France's transmutation R&D programme and will support research on future innovative designs.

The operation of Superphénix confirmed the suitability of the main design and technological choices for an industrial size sodium cooled fast

reactor, and substantial experience was gained in the areas of design and engineering technology. The decision to shut down Superphénix was based on the unfavourable economics of fast reactors given the slow growth in global nuclear capacity and low uranium prices during the 1990s. The permanent shutdown of Superphénix was formalized on 31 December 1998, 20 years in advance of the plant's design lifetime. Decommissioning started in 1999.

Prospective studies for future reactor systems are being carried out by the French Commissariat à l'énergie atomique (CEA) and its industrial partners. These will define the French medium and long term (beyond 2040) R&D strategy in the area of innovative nuclear systems. The strategy will have three complementary objectives: (i) the development of sodium or gas cooled fast reactors (GFRs) and the associated closed fuel cycle to ensure, in the long term, sustainable energy supplies through breeding and, in the medium term, to manage actinides in the spent fuel from light water reactors (LWRs); (ii) the development, in close collaboration with industrial partners, of key technologies for the nuclear production of hydrogen and the supply of high or very high temperature heat for industrial applications; (iii) further optimization of LWRs (through innovative fuels, high conversion cores, and reactor systems) to ensure the most efficient use of nuclear power prior to the anticipated availability around 2040 of fourth generation fast neutron systems that are mature enough for industrial deployment. R&D priority is given to fast neutron nuclear systems with a closed fuel cycle, specifically the sodium cooled fast reactor (SFR) and the GFR. These are generally recognized to be the most capable of meeting sustainability goals that include optimal use of natural uranium resources and minimized production of long lived radioactive waste.

**India** has limited uranium resources, but about 32% of the world's thorium (Th) reserves. India has therefore developed a three stage nuclear energy development programme, from heavy water reactors (HWRs) using natural uranium, through fast reactors using U and Pu, to a Th based advanced reactor system.

The uranium available for power generation in India is about 60 000 t. If this were used in pressurized heavy water reactors (PHWRs), as is done currently in India, it could produce nearly 330 GW(e)/a of electricity. This is equivalent to about 10 GW(e) of PHWRs running at a lifetime capacity factor of 80% for 40 years. The same amount of uranium, with multiple recycling using FBRs, could provide about 42 200 GW(e)/a assuming utilization of 60% of heavy metal. This is equivalent to an installed nuclear capacity of 530 GW(e) operating for 100 years at a lifetime capacity factor of 80%. India's thorium reserves, which are greater than its uranium reserves, are estimated at about 225 000 t. With multiple recycling through the appropriate reactor systems, these could produce about 150 000 GW(e), which could satisfy India's energy



FIG. VI-2. PFBR construction. Photo courtesy of Indira Gandhi Centre for Atomic Research.

needs for many centuries. The expected total installed electric capacity in India in 2050 is about 1500 GW(e). Theoretically, this could be met, and fuelled from domestic resources for at least the next 100 years, through India's three stage programme noted above: (i) PHWRs to make use of available uranium, (ii) fast reactors to convert thorium into  $^{233}\text{U}$ , and (iii) advanced reactors (thermal and fast) to convert thorium into  $^{233}\text{U}$  with the fissile material from steps i and ii.

Today, India is operating the Fast Breeder Test Reactor (FBTR), constructing the Prototype Fast Breeder Reactor (PFBR), and performing research and technology development for the deployment of an industrial scale FBR. FBTR is a 40 MW(t), 13.2 MW(e), mixed carbide fuelled, sodium cooled, loop type fast reactor with two primary and two secondary sodium loops. First criticality was achieved in October 1985. The reactor is mostly used as an irradiation facility for testing fuel and fuel elements and to gain operational experience with a liquid metal cooled fast reactor.

PFBR is a 500 MW(e), pool type, sodium cooled fast reactor with two primary pumps, four intermediate heat exchangers (IHXs) and two secondary loops. There are eight integrated steam generator (SG) units (four per secondary loop) producing steam at 766 K and 17.2 MPa. Four dedicated safety grade decay heat exchangers (SGDHR) are provided to remove the decay heat directly from the hot pool. The hot and cold pool sodium temperatures are 820 K and 670 K, respectively.

PFBR is now under construction at Kalpakkam. Manufacturing of components is progressing well, and the official PFBR commissioning date is September 2010. Figure VI-2 shows the construction of the PFBR containment building as of May 2007.

After PFBR commissioning, India's Department of Atomic Energy is planning to construct four 500 MW(e) FBRs with improved economics and

enhanced safety. Features chosen to improve the economics include building pairs of reactors as twin units, reducing the main vessel diameter, incorporating an in-vessel purification system, reducing the height of the components supported on the top shield as well as of the entire reactor assembly by an improved design of the top shield, using the most cost efficient materials for construction, enhancing burnup to reduce fuel cycle costs, reducing the construction time from seven to five years, extending the designed lifetime from 40 to 60 years, and designing for a higher capacity factor. With these features, the targeted unit energy cost is 50 mils, compared to 80 mils for PFBR. As for enhanced safety features, the most important are reliable shutdown systems incorporating passive features, a passive decay heat removal system, a rationalization of design basis events to arrive at a lower number of anticipated events, the possible elimination of core disruptive accidents, and elaborate in-service inspection and repair provisions. MOX fuel is the choice for these first four fast breeder reactors. However, for subsequent FBRs, metallic fuel would allow a higher breeding ratio and a faster expansion of nuclear power. Metallic fuel could already be introduced in one of the first four reactors once the technology, especially the fuel fabrication technology, is sufficiently mature.

**Japan's** Atomic Energy Commission (AEC), in October 2005, issued a Framework for Nuclear Energy Policy that reiterated the significance of developing fast reactors and their associated fuel cycle technology. In March 2006, the Council for Science and Technology Policy of the Cabinet Office selected, in its third term Science and Technology Basic Plan, fast reactors and their associated fuel cycle technology as a key technology of national importance. Subsequently, the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and the Ministry of Economy, Trade and Industry (METI) published proposed action plans to develop nuclear technologies. In response to these proposals and a review by the MEXT Advisory Committee on the R&D in the Nuclear Energy Field of results of Phase-II of a Feasibility Study on Commercialized Fast Reactor Cycle Systems, the AEC issued in December 2006 the Basic Policy on R&D of FBR Cycle Technologies over the Next Decade. Its most salient points are as follows:

- MEXT, METI and the Japan Atomic Energy Agency (JAEA) will cooperate with electricity utilities, manufacturers and universities to promote R&D regarding the selected concept, and to produce, by 2015, the conceptual designs of commercial and demonstration FBR cycle facilities that can satisfy performance criteria regarding safety, economic competitiveness, reduction of environmental burden, high efficiency in

the utilization of nuclear fuel resources and enhancement of resistance to nuclear proliferation.

- JAEA shall resume operations of the prototype fast breeder power reactor MONJU in fiscal year 2008, on the precondition of safety, while promoting mutual understanding with local residents on safety issues. The goal is that, within approximately ten years of restarting MONJU, JAEA will both demonstrate MONJU's reliability as an operational fast reactor power plant and establish sodium handling technologies. After that, MONJU will be utilized for R&D activities aimed at the commercialization of fast breeder technology.
- Government and R&D organizations will also promote both the exploration and proof of principle activities of innovative concepts for realizing alternative FBR cycle technologies, as well as wide ranging relevant basic and fundamental R&D activities, utilizing their various research facilities including the experimental fast reactor JOYO.
- MEXT, METI, JAEA, utilities and manufacturers will develop a roadmap for the commercialization of FBR cycle technologies to enable the promotion of effective long term R&D and to facilitate the smooth transition to the demonstration phase of FBR cycle technologies. The roadmap will specify both the requirements for the FBR cycle technology demonstration facilities, for which the conceptual design is to be proposed in 2015, and the activities during the demonstration and commercialization phases, including a plan to achieve the construction of these demonstration facilities within the decade after 2015.

The experimental fast reactor JOYO has an MK-I breeder core and first achieved criticality in 1977. Since then, it has provided a valuable irradiation bed for advanced fuels and materials, and for improvements in fast reactor safety and operation. Future plans for using JOYO's enhanced irradiation capabilities include developing fuels and materials, enhancing safety, and irradiating fuel containing minor actinides and long lived fission products. Since future fast reactor development work will focus on extending fuel lifetimes, JOYO will be used for tests to develop high burnup uranium-plutonium MOX fuel and other innovative fuels, advanced fuel fabrication processes (e.g. vibration packing or 'VIPAC'), and long life control rods.

MONJU, shown in Fig. VI-3, is a sodium cooled, mixed uranium-plutonium oxide fuelled, loop type prototype fast power reactor rated at 280 MW(e) (714 MW(t)). MONJU's first criticality and grid connection were achieved in April 1994 and August 1995, respectively. However, in December 1995 a sodium leak occurred in the secondary heat transport system during pre-operational testing at a 40% power level. After two years of cause



*FIG. VI-3. MONJU. Photo courtesy of JAEA.*

investigations, comprehensive safety reviews, and the necessary licensing, the permit for plant modification for countermeasures against sodium leaks was issued in December 2002 by METI. In February 2005, after receiving approval from the governor of Fukui Province, JAEA started preparatory modification work. The main modification work was approximately 94% complete by March 2007. The functional testing of the modified systems began in December 2006. Comprehensive system function tests are also planned because of the length of time the plant was shut. MONJU's restart (i.e. first criticality) is scheduled for 2008.

The conclusion of the Feasibility Study on Commercialized Fast Reactor Cycle Systems that began in July 1999 was that the most viable technology options for commercialization were: the plutonium–uranium MOX fuelled, sodium cooled FBR, with fuel fabrication based on simplified pelletizing, and with advanced aqueous reprocessing. The runner-up concept, deemed equally viable for commercialization but more uncertain in its social and technical aspects, was a metallic plutonium–uranium fuelled, sodium cooled FBR, with fuel fabrication based on injection casting, and with electro-refining reprocessing. In 2006, JAEA launched the Fast Reactor Cycle Technology Development (FaCT) project focused on R&D for the first, most viable concept.



In the **Republic of Korea**, fast reactor technology development dates back to 1992 when the Korea Atomic Energy Commission approved a long term R&D plan for a sodium cooled fast reactor. In February 2007, the development of the conceptual design of KALIMER-600, an advanced sodium cooled fast reactor concept was completed by the Korea Atomic Energy Research Institute (KAERI). The core is loaded with single enrichment metal fuels and configured without blanket assemblies. To achieve power flattening in the single enrichment core the current design contains different cladding thicknesses in the inner, middle and outer core regions. KALIMER-600 is a pool type reactor, which has a large heat capacity and can reduce any rapid transients caused by reactor trips. The heat transport system consists of a primary heat transport system (PHTS), an intermediate heat transport system (IHTS), a residual heat removal system (RHRS) and a steam generating system (SGS). The PHTS consists of the PHTS pump, intermediate heat exchangers (IHXs) and all the internal structures within the reactor and the containment vessel. The PHTS pump is a centrifugal mechanical pump. The IHTS consists of piping and an electromagnetic pump. The RHRS has three layers and consists of the passive decay heat removal circuit (PDRC), the intermediate reactor auxiliary cooling system (IRACS), and the steam/feedwater system. When normal decay heat removal is not available through the steam/feedwater system, the operator can activate the IRACS. The IRACS is operated by closing the SG isolation valve and by opening the IRACS isolation valve. Then the air heat exchanger (AHX) of the IRACS dumps heat to the atmosphere. In the event of a station blackout, the KALIMER-600 design relies on the PDRC. The PDRC is a pure passive system relying exclusively on natural convection phenomena, without any operator action and active components.

The main features of the mechanical design in KALIMER-600 are the seismically isolated reactor building, the reduced total pipe length of the IHTS, the simplified reactor support and the compact reactor internal structures.

In the **Russian Federation** there are two fast reactors in operation, the experimental reactor BOR-60 at Dimitrovgrad, and BN-600, the commercial Unit 3 of the Beloyarsk nuclear power plant. BOR-60 has been in operation for more than 36 years. While also producing heat and electricity, BOR-60 is used for material tests, isotope production, and fast reactor equipment tests. The reactor has an operational licence until 31 December 2009, and lifetime extension activities are currently under way.

BN-600 (Fig. VI-4) has been in operation for more than 27 years. BN-600 is the largest operating fast reactor power unit in the world. It is a sodium cooled loop type reactor using MOX fuel, and its safety performance and operating reliability have been excellent. As of 31 December 2006, BN-600 had



*FIG. VI-4. BN-600 at the Beloyarsk nuclear power plant site. Photo courtesy of the Institute of Physics and Power Engineering.*

produced more than 100.4 TW·h of electricity, of which 4.13 TW·h were generated in 2006. In 2006, BN-600's load factor was 78.6%, while the average load factor since 1983 is 74.2%. The design lifetime of the BN-600 reactor plant expires in April 2010, and lifetime extension activities are also under way for this reactor.

BN-800 is under construction also at the Beloyarsk site. BN-800 is a sodium cooled, uranium–plutonium MOX fuelled fast reactor. Although originally designed for 800 MW(e), BN-800's design power has been increased to 880 MW(e) while the thermal power remains unchanged (at 2100 MW) through optimizing the third circuit, improving the turbine parameters, and eliminating steam extraction for heating. These and other design improvements have also extended the reactor's lifetime from 30 to 40 years. The pouring of concrete for the foundations of the reactor compartment and turbine hall has been completed. Manufacturing of large components (e.g. the main and safety reactor vessels, and primary circuit sodium tanks) has started. Commissioning of BN-800 is foreseen for 2012. Vibro-packed fuel is being considered on the basis of successful testing in BN-600.

The Russian Federation's advanced fast reactor research and technology development programmes are currently focused on the development of advanced sodium cooled fast reactors and of fast reactors cooled by heavy liquid metal coolants (i.e. lead and lead–bismuth).

The development of advanced sodium cooled fast reactors involves two main activities: R&D work to develop the conceptual design of a large commercial fast sodium cooled reactor (BN-1800), and the conceptual development of a small, modular and transportable two circuit sodium cooled

fast reactor with a gas turbine (BN GT nuclear co-generation power plant (NCPP)).

In the area of heavy liquid metal cooled fast reactors, work is concentrated on R&D for the lead cooled BREST OD 300 reactor, and on development work for the basic design of the lead–bismuth cooled ‘SVBR-75/100 reactor facility (RF)’. The BREST OD 300 design substantiation work covers coolant technology, material studies and safety issues.

In the **United States of America**, the Department of Energy’s NP2010 programme facilitates the deployment of advanced light water reactors (ALWRs) while its Global Nuclear Energy Partnership (GNEP) seeks to develop, demonstrate and deploy advanced technology for recycling spent nuclear fuel that provides important waste management and proliferation benefits, including no separation of plutonium. The development of fast reactor technology is a major part of this strategy. Using sodium cooled fast reactors with a closed fuel cycle could also result in better utilization of the US geological repository. The GNEP fuel cycle strategy is based on expanded nuclear power production in ALWRs with the spent fuel separated into several components for tailored waste management. The transuranium nuclides would be recycled to be consumed in advanced reactors for further power production. Fast reactors would be utilized for closed recycling and ‘burning’ of these materials. The development of recycled fuels and the management of the waste from ALWRs and fast reactor recycling are additional important technological challenges. The overall strategy focuses on waste management and non-proliferation benefits.

### *VI-3.2. International Fast Reactor Programmes*

The challenges of developing fast reactors and the closed fuel cycle exceed in many cases the capabilities of individual countries. To pool international experience, expertise and resources, several international initiatives have been established to jointly evaluate and develop promising options.

The Generation IV International Forum (GIF) is a joint initiative of 13 countries. Six innovative reactors have been selected for further development and potential deployment by about 2030. Three of these design concepts are fast reactors cooled by sodium, lead (or lead–bismuth ) or helium. A fourth, the supercritical water reactor, includes an option to use fast neutrons. GIF was created in May 2001 to lead the collaborative efforts to develop the next generation of nuclear power plants. It first established development goals (specifically sustainability, economics, safety and reliability, proliferation resistance and physical protection) and a roadmap for deployment around

2030. Current development work is focused on materials, systems and components.

The IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) is a discussion forum for experts and policy makers on all aspects of nuclear energy planning as well as on the development and deployment of innovative nuclear energy systems (INSS). It currently has 28 Members and brings together technology holders, users and potential users to consider jointly the international and national actions required for achieving desired innovations in nuclear reactors and fuel cycles. INPRO pays particular attention to the needs of developing countries. INPRO has developed a methodology for assessing INSS and completed assessment studies in which the methodology was applied by interested Member States. For example, a joint assessment study of a closed nuclear fuel cycle with fast reactors (CNFC-FR) was done by Canada, China, France, India, Japan, the Republic of Korea, the Russian Federation and Ukraine in 2005–2007. The study assessed the CNFC-FR against sustainability criteria to determine milestones for deployment and to establish a framework for collaborative R&D. The study helped identify elements of the fast reactor technology development strategy that would meet sustainable development requirements of nuclear power. Currently, the IAEA coordinates and supports collaborative projects identified by INPRO Members to address technology improvement in the areas of safety, economics, environmental impacts, waste, proliferation resistance and infrastructure.

GNEP is an initiative by the USA, which, as part of its efforts described earlier, seeks to develop cooperative efforts to expand the use of nuclear energy. GNEP had 19 members as of the end of 2007, and its current approach is to develop industry-led prototype facilities for fast reactor and LWR spent fuel separation relatively quickly, i.e. by about 2020. These facilities would demonstrate the innovative technologies and design features important for subsequent commercial demonstration plants and would substantiate fuel cycle benefits. Concurrently, a DOE laboratory-led technology development and research programme will continue. This will focus on innovative fuel cycle technologies including fuel development for recycling. For fast reactor research, the critical focus will be on capital cost improvements, principally through design simplifications, new technology and advanced simulation.

#### **VI-4. Conclusions**

Many scenarios of possible energy futures foresee an important role for nuclear power. While some explore the impacts of a nuclear phase-out, others envision a major growth in nuclear power's share of the world energy mix. A growing world population, continued economic development, concerns about

greenhouse gas emissions, rising fossil fuel prices and energy supply security are the main drivers of current rising expectations for nuclear power. To make nuclear power a truly long term option, fast reactors are needed to produce new fissile material and to reduce the amount of waste and its impact on the environment. The fast reactor concept is not new; several reactors have operated in various countries. Globally fast reactors did not break through commercially because demand for new fissile material was lower than had been anticipated, and the fast reactor was not economic for electricity production. However for some countries, notably India, the restricted availability of uranium has made fast reactors more attractive in the short term.

Currently, several fast reactor concepts are being developed with various coolants and fuel cycles. Major challenges are still to reduce costs and to develop materials and fuels for commercial operation. Different types of reactors and fuel cycles may be appropriate in different countries.

The various fast reactor research and technology development programmes are not uniform because they reflect different needs. The renewed interest in fast reactors, as indicated by increased funding and the many national and international fast reactor research and technology development activities, is driven to different degrees by resource scarcity, security of supply considerations and waste management concerns.

## Annex VII

### NUCLEAR POWER AND NON-POWER APPLICATIONS IN THE CONTEXT OF CLIMATE CHANGE

#### VII-1. Introduction

Nuclear technology's potential contribution to reducing climate change risks is currently dominated in the public perception by nuclear power. The complete nuclear power chain, from resource extraction to waste disposal including reactor and facility construction, emits only 1–6 grams of carbon equivalent per kilowatt-hour (g Ceq/kW·h). This is about the same as wind power and hydropower, including construction and component manufacturing. All three, together with solar power, are well below coal, oil and natural gas (60–460 g Ceq/kW·h) even taking account of carbon capture and storage.

But non-power nuclear applications also have a role to play in improving climate science, better understanding potential impacts of climate change, adapting to climate change, and developing mitigation alternatives in addition to nuclear power. Relative to nuclear power, the roles of these non-power applications are less significant at present, but they offer promise of becoming more widespread. While there is essentially no mention of any individual non-power application in the Fourth Assessment Report (AR-4) of the Intergovernmental Panel on Climate Change (IPCC), published in 2007, the report deals extensively with areas in which non-power applications play an important role in developing technological solutions, such as agriculture, water resource management, and ecosystem assessment and sustainability. For example, isotopic techniques for understanding ocean dynamics and for reconstructing past climates using records stored in ice cores are hardly mentioned in the AR-4, but they are fundamental to much of the science upon which the report's conclusions are based.

This annex summarizes two important developments in 2007–2008 in international efforts to limit the risks of climate change. The first, the publication of AR-4, concerns climate science and the shared understanding of the scientific community of climate change trends, impacts, adaptations and mitigation. The second, the 13th Conference of the Parties (COP-13) to the UN Framework Convention on Climate Change (UNFCCC), concerns climate policy. A summary of AR-4 is presented according to the three working groups of the IPCC: Working Group I (WG I) addresses climate science, Working Group II (WG II) addresses impacts and adaptation, and Working Group III

(WG III) addresses mitigation. Included after each of these three sections is a summary of pertinent nuclear applications and their relevance to that section.

## **VII-2. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change**

### *VII-2.1. WG I: The Physical Science Basis [VII-1]*

WG I's report noted that over the past few years observations and related modelling of greenhouse gases, solar activity, land surface properties and some aspects of aerosols have led to improvements in the quantitative estimates of radiative forcing (the measure of the influence various factors exert in altering the balance of incoming and outgoing energy in the Earth-atmosphere system). Carbon dioxide (CO<sub>2</sub>) is the most important anthropogenic greenhouse gas. Its global atmospheric concentration has increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005. This far exceeds the natural range over the last 650 000 years (180 to 300 ppm). Moreover, the annual increase in carbon dioxide concentration from 1995 to 2005 averaged 1.9 ppm per year, which is the highest such increase since the beginning of continuous direct atmospheric measurements.

The improved understanding of anthropogenic influences on the climate system suggests, with very high confidence, that the global average net effect of human activities since the mid-19th century is a global mean temperature increase of 0.76°C (with an uncertainty range of 0.57°C to 0.95°C). The WG I report concludes, "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level". Over the past half century, most of the observed increase in global average temperatures is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.

In the near term future (over the next two decades), a warming of about 0.2°C per decade is projected for a range of emission scenarios presented in the Special Report on Emissions Scenarios (SRES) [VII-2]. Due to the inertia in the climate system, a further warming of about 0.1°C per decade is expected even if the concentrations of all greenhouse gases and aerosols were stable at their 2000 levels. Over the long term, continued GHG emissions at increasing rates, as projected by most recent global energy studies such as the OECD-IEA World Energy Outlook 2007 [VII-3], would cause further warming and induce increasingly larger changes in the global climate system during the 21st century and beyond. The WG I report summarizes the best estimates and likely ranges for global average surface air warming for the six main SRES emissions

scenarios. At the lower end of the spectrum, for a sustainability oriented high efficiency, low energy demand scenario, the best estimate is a 1.8°C increase in global average temperature, with an uncertainty range between 1.1°C and 2.9°C. At the other extreme, the estimated warming for a rapid economic growth pathway relying predominantly on fossil fuels is 4.0°C, with an uncertainty range between 2.4°C and 6.4°C.

#### VII-2.1.1. Nuclear Applications Relevant to the Physical Science Basis

Environmental radionuclides, both naturally occurring and anthropogenic, as well as stable isotopes, are used to test and verify global models of atmospheric circulation patterns, ocean circulation patterns and precipitation patterns, in addition to the hydrological cycle. They thus underlie much of the modelling of these processes that is the basis for WG I's conclusions. Palaeoclimatology and the historical connections it identifies between high GHG concentrations and climate change are also an important basis for WG I's conclusions. Stable isotopes in the Earth's natural archives of marine sediments, ice cores and corals provide a critical method of determining past environmental conditions, including temperature, salinity, acidity, humidity, biodiversity and circulation. Isotopes of hydrogen, oxygen and carbon, together with other isotopes are also used to date and obtain information on palaeo-environmental conditions from non-marine climatic archives such as glaciers, lake sediments, tree rings, stalactites and stalagmites and groundwater. Specifically, oxygen isotopes are used to reconstruct historical atmospheric temperatures, making them valuable tools for climate change studies and models.

The use of isotopes to understand the role of the oceans in climate change and the impact of climate change on marine ecosystems was reported in greater detail in Annex III of the Nuclear Technology Review 2007. That report described the use of radiocarbon ( $^{14}\text{C}$ ), tritium ( $^3\text{H}$ ) and other isotopes to analyse the major currents that transport and redistribute heat, carbon and nutrients throughout the oceans, and the use of carbon-13 ( $^{13}\text{C}$ ), nitrogen-15 ( $^{15}\text{N}$ ), phosphorus-32 ( $^{32}\text{P}$ ) and other isotopes to map ocean productivity and track the transfer of  $\text{CO}_2$  to seawater, marine biota and organic compounds. It also described the role of radioisotope and stable isotope analyses in palaeoclimatology, the study of climate change over the Earth's entire history.

Both environmental radionuclides and stable isotopes are useful in developing and validating the general circulation models (GCMs) and chemical transport models (CTMs) used in analysing the buildup and circulation of greenhouse gases (GHGs) in the atmosphere. GCMs simulate the mixing of the atmosphere, and CTMs predict the behaviour of chemical species in the



environment. Improvement and validation of GCMs and CTMs requires the comparison of their predictions with measured data, and radionuclides are useful for this purpose as they are present in trace amounts, have a range of half-lives and chemical properties, and are produced in a variety of locations in the environment.

Radon ( $^{222}\text{Rn}$ ) is an inert gas that escapes from soil into the atmosphere at ground level and has a half-life of 3.82 days, which is comparable to the lifetimes of short lived atmospheric pollutants such as nitrogen oxides ( $\text{NO}_x$ ), sulphur dioxide ( $\text{SO}_2$ ), carbon monoxide ( $\text{CO}$ ) and ozone ( $\text{O}_3$ ), and the atmospheric residence time of water and aerosols. This timescale is also comparable to many important aspects of atmospheric dynamics, making radon a useful tracer for studying atmospheric processes at local, regional or global scales.

Useful radionuclides for testing CTMs include isotopes of lead ( $^{210}\text{Pb}$ , half-life 22.3 years) and beryllium ( $^7\text{Be}$ , half-life 53.2 days).  $^{210}\text{Pb}$  is produced in the troposphere from the decay of  $^{222}\text{Rn}$ , while  $^7\text{Be}$  is produced from the action of cosmic rays in the stratosphere and upper troposphere. Both of these radionuclides attach to, and thereby mirror the behaviour of, circulating particles in the atmosphere.

Stable isotopes of oxygen, nitrogen, carbon, and heavier elements have been used in botanical and biological investigations and are increasingly considered useful in ecological studies.

Precipitation and the role of the hydrological cycle in climate change can be analysed using stable isotopes and the methods of isotope hydrology. An important resource is the 45 year old Global Network for Isotopes in Precipitation (GNIP), operated jointly by the IAEA and the World Meteorological Organization (WMO) (Fig. VII-1). It is a unique source of information that contributes to the predictive capacity of climatic and hydrological models as well as to the proper calibration of historical climate reconstructions on millennial and longer timescales.

#### *VII-2.2. WG II: Impacts, Adaptation and Vulnerability [VII-4]*

WG II's report describes observational evidence from all continents and most oceans that many natural systems are already being affected by regional climate changes, particularly temperature increases.

Observed changes in the hydrological cycle include increased runoff and earlier spring peak discharge in many glacier and snow-fed rivers and the warming of lakes and rivers in many regions. Terrestrial biological systems show poleward and upward shifts in ranges in plant and animal species. Observed changes in marine and freshwater biological systems include shifts in

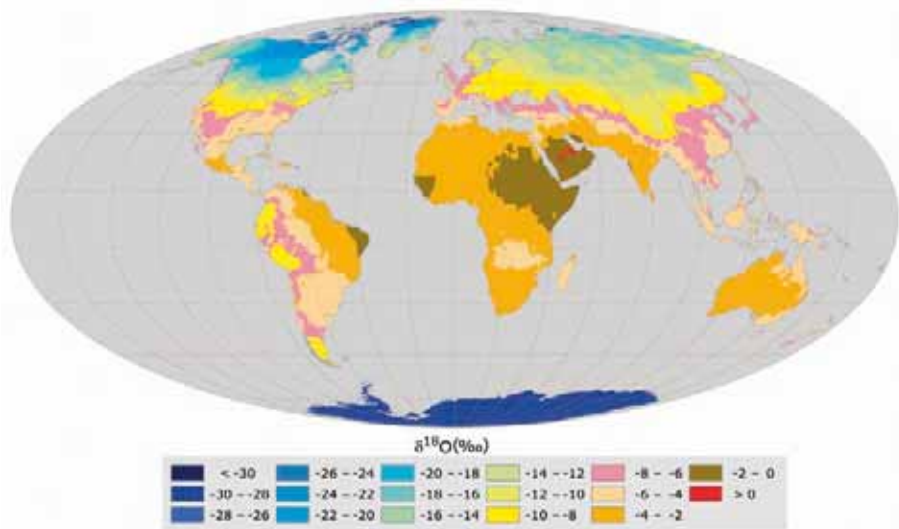


FIG. VII-1. Distribution of stable isotopes ( $^{18}\text{O}$ ,  $^2\text{H}$ ) obtained from the IAEA/WMO Global Network of Isotopes in Precipitation are used for isotope hydrological studies and for validation of global and regional atmospheric circulation models [VII-5].

ranges and changes in algal, plankton and fish abundance in high latitude oceans and range changes and earlier migrations of fish in rivers.

Looking ahead, WG II estimated the impacts of the range of future climate changes projected by WG I, based on the reference scenario of the OECD-IEA's World Energy Outlook 2004. By mid-century, drought affected areas will likely increase, and heavy precipitation events are very likely to increase in frequency and increase the risk of flooding. Water supplies stored in glaciers and snow cover are projected to decline, reducing water availability in regions supplied by meltwater from major mountain ranges, which is where more than one sixth of the world's population now lives.

Projected climate change related exposures are likely to cause increases in malnutrition and consequent disorders; increased deaths, disease and injury due to heat waves, floods, storms, fires and droughts; more diarrhoeal disease; a greater frequency of cardio-respiratory diseases due to higher concentrations of ground level ozone related to climate change; and changes in the spatial distribution of some infectious disease vectors.

Globally, the potential for food production is projected to increase with increases in local average temperature over a range of 1–3°C, but above this it is projected to decrease. However, in Africa, by 2020, between 75 million and 250 million people are projected to be exposed to increased water stress due to

climate change, and, in some countries, agricultural production, including access to food, is projected to be severely compromised.

Increased insect outbreaks are virtually certain in view of the existing linkages between climate change, changes in pest and disease risks to plants and animals, and the related human health and food security effects. Direct effects of climate change are shifts in the distribution ranges of pests and an increase in the number of generations per year. Distribution shifts can occur as a result of natural expansions, or accidental introductions caused by increased world trade that result in the establishment of pests outside their natural distribution range. Diseases and pests posing particular risks need to be identified, their increased incidence, distribution and potential impact need to be foreseen, and suitable preventive and adaptation strategies and guidance on disease and pest surveillance and control need to be provided.

WG II's report assesses adaptation practices that have already begun as well as possibilities for the future, and it notes that adaptation will be necessary to address impacts resulting from the warming which is already unavoidable due to past emissions. The report also states that adaptation measures are seldom undertaken in response to climate change alone but can be integrated within, for example, water resource management, coastal defence and risk reduction strategies.

#### VII-2.2.1. Nuclear Applications Relevant to Impacts, Adaptation and Vulnerability

In some cases, nuclear applications can be used directly to develop adaptive responses to climate change impacts. But they can also be used to measure and analyse a broader range of impacts, which can also contribute more indirectly to the development of useful adaptations.

The use of isotopes to assess the impact of climate change on agricultural production was reported in greater detail in Annex I of the *Nuclear Technology Review 2007*. For example the Free-Air CO<sub>2</sub> Enrichment (FACE) approach, together with isotopic techniques, is valuable for investigating plant and ecosystem responses to changes in CO<sub>2</sub> concentration as this approach exposes plants to natural conditions with artificially elevated atmospheric CO<sub>2</sub> levels. The added CO<sub>2</sub> has concentrations of <sup>13</sup>C that are below ambient levels, which enables the amount of carbon sequestered and turnover in the soil under elevated CO<sub>2</sub> conditions to be quantified. Climate change also has impacts on crop water use efficiency through changes in plant transpiration and soil evaporation, and isotopic ratios of hydrogen and oxygen, together with carbon isotope discrimination techniques, are increasingly being used to investigate these dynamics.

Soil loss and erosion due to a higher frequency of extreme weather events are further expected impacts of climate change, and these effects can be assessed with a few different nuclear techniques. Erosion, for example, can be measured through the increasing use of environmental nuclide tracers, such as beryllium ( $^7\text{Be}$ ), lead ( $^{210}\text{Pb}$ ) and caesium ( $^{137}\text{Cs}$ ). Sources of soil loss from agricultural catchments can be identified for the purposes of remediation using compound specific stable isotopes (CSSI) of carbon, hydrogen and nitrogen in plants, animal manure and soil samples. Information obtained through combined iso-source (IS) modelling that uses several isotopes and other sources to identify causes of soil loss can be used to assess the effectiveness of different land use practices and soil conservation measures in response to changes in climate [VII-6]. Field studies (e.g. in New Zealand) have demonstrated the successful use of IS and CSSI to identify the contributions of various land uses (e.g. exotic pine forest, grazed pasture and native forest) to soil loss, to estimate their economic and social importance, and thus to facilitate appropriate remedial resource management practices.

Adaptation to the losses of soil and its constituents that are expected due to climate change will become increasingly important elements of land management practices under climate change scenarios. In this context, nitrogen, sulphur and carbon stable isotope ratios will be increasingly used to trace the use of land constituents and external inputs for crop productivity under different climate change scenarios and soil salinity and acidity conditions that are expected to worsen under those scenarios. Another technique, stable isotope probing (SIP), will allow the identification of soil microorganisms that can enhance the acquisition of soil nutrients for crop production, thus improving the conservation and management of land resources. Figure VII-2 shows the role of isotopic techniques in addressing food and biomass production, carbon sequestration in agro-ecosystems, bioenergy production on degraded or marginal soils, and increasing the availability and quality of water resources. A common link is the biogeochemical cycling of carbon and its coupling with the cycles of nitrogen (N), phosphorus (P), sulphur (S) and water. Interactive processes affecting coupled cycling of these elements are strongly influenced by the increasing global energy demand.

Isotope hydrology can be used to evaluate the impact of global change on the hydrological cycle, and isotope tools provide data to assess the effects that an accelerated hydrological cycle due to climate change can have on groundwater quantity and quality, and its interaction with surface water systems. Isotope techniques also can be used to collect the data and build the models needed to develop effective adaptive water management strategies. The WG II report encouraged the integration of climate change adaptations within, among other things, water resource management, which is consistent

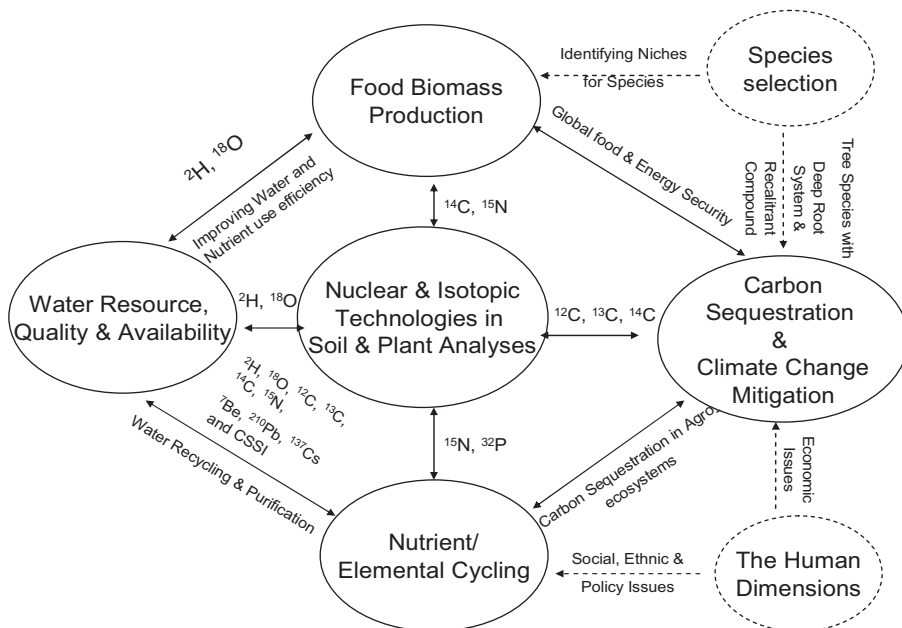


FIG. VII-2. Using isotope techniques to address global issues of concern related to food security and climate change.

with the concept of ‘integrated water resources management’, supported by isotopic techniques, that is promoted by the IAEA. The anticipated disruptive impacts of climate change on the hydrological cycle and precipitation patterns will compound the existing challenges of growing demand and stress, which will make the strategic management of water resources increasingly vital in supporting water security worldwide.

Another way in which nuclear techniques can contribute to adaptation efforts is through mutation techniques for plant breeding to develop crop varieties better suited to a changed climate. Nuclear techniques, e.g. gamma irradiation, can be used to generate varieties with genetically favourable traits, such as increased adaptability to drought and saline conditions, elevated and reduced temperatures, and biotic stresses brought about by climate change. These techniques can be combined with advanced biotechnologies such as high-throughput genomic screening applications, to enhance the efficiency of identifying useful mutants and their use in breeding new varieties.

Isotopic techniques can also be used to evaluate the efficient mobilization of different land constituents to meet the nutrient and water demands of newly developed crop varieties tolerant of harsher weather conditions and soils.

Finally, there are additional nuclear applications that can help countries to adapt to climate change. These include application techniques for the diagnosis and control of transboundary animal diseases, which may spread due to climate change. They include the sterile insect technique (SIT), which may be in greater demand as insect populations expand in geographic range and new pests emerge as a consequence of climate change. As this occurs and international agricultural trade continues to grow, the application of ionizing irradiation (see the Food Irradiation Clearances Database at <http://nucleus.iaea.org/NUCLEUS/nucleus/Content/index.jsp>) to control pests and foodborne microbes as a complement to SIT is likely to increase as well. More detailed information regarding these applications can be found in the main text of this report.

### *VII-2.3. WG III: Mitigation of Climate Change [VII-7]*

As presented in the previous sections, WG I (The Physical Science Basis) of the IPCC AR-4 confirmed the increasing anthropogenic influence on the climate system due to the emission of GHGs, the bulk of which originates in burning fossil fuels. WG II presented discernible impacts of climate change, particularly in sensitive ecological systems, analysed the vulnerability of societies and ecosystems services to changing climatic conditions, identified adaptation options and their limitations and concluded that beyond certain magnitudes of climate change (for most systems and regions more than a 2°C increase in global mean temperature above the pre-industrial level) adaptation possibilities become exceedingly expensive or vanish altogether. Therefore, drastic mitigation action, i.e. a 50% reduction of global GHG emissions by 2050, is required which immensely increases the importance of low-carbon emitting energy technologies including nuclear power.

WG III (Mitigation) analysed GHG mitigation options and costs in large world regions (OECD, economies in transition (EIT) and Non-OECD/EIT), across a range of economic sectors (energy supply, transport, buildings, industry, etc.), and over two time horizons: medium term (up to 2030) and long term (through 2100). Many mitigation technologies and practices that could reduce GHG emissions are already commercially available. Technical solutions and processes could reduce the energy intensity in all economic sectors and provide the same output or service with lower emissions in transport, building and industry. Fuel switching and modal shifts (from road to rail, from private to public) in the transport sector; heat recovery, material recycling and substitution in industry; improved land management and agronomic techniques and energy crop cultivation in agriculture; and fuel switching, efficiency improvements, the increased use of renewables and nuclear power as well as carbon

capture and storage could result in significant GHG reductions in the energy sector. Aggregating the options for each sector, the economic mitigation potential is estimated to be between 0.7 (waste management) and 6 (the buildings sector) gigatonnes of CO<sub>2</sub> equivalent<sup>37</sup> (Gt CO<sub>2</sub>-eq) annually on the basis of carbon prices less than \$100/t CO<sub>2</sub>-eq in 2030.

The assessment confirmed that, compared to other anthropogenic sources, GHG emissions from the energy supply sector have been growing at the fastest rate between 1970 and 2004. Currently, energy-related CO<sub>2</sub> emissions (including feedstocks) comprise by far the largest share (about 60%) of total global GHG emissions and this is likely to remain the case over the coming decades. In the absence of additional policy interventions (relative to those already in place), annual GHG emissions from energy production and use are projected to reach 34–52 Gt CO<sub>2</sub> by 2030 (compared to 28.6 Gt CO<sub>2</sub> in 2000). This implies, as Chapter 4 of the WG III report puts it, that “[T]he world is not on course to achieve a sustainable energy future. To reduce the resultant GHG emissions will require a transition to zero- and low-carbon technologies”. Options and costs of doing so in the electricity sector are summarized below by using data from Chapter 4 of the WG III report.

The IPCC estimates the mitigation potential in terms of GHG emissions that can be avoided by 2030 by adopting various power generation technologies in excess of their shares in the baseline scenario (the reference scenario in the IEA’s World Energy Outlook 2004). The technologies include fuel switching within the fossil portfolio, nuclear, hydro, wind, bioenergy, geothermal, solar photovoltaic (PV) and concentrating solar power (CSP) as well as coal and gas with carbon capture and storage.

The IPCC analysis assumes that each technology will be implemented as much as economically and technically possible taking into account practical constraints (stock turnover, manufacturing capacity, human resource development, public acceptance, etc.). Each technology is assessed in isolation, i.e. possible interactions between deploying various technologies simultaneously are not accounted for. The estimates indicate how much more (relative to the baseline) of each technology could be deployed in major world regions at costs

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<sup>37</sup> The definition of carbon dioxide equivalent (CO<sub>2</sub>-eq) is the amount of CO<sub>2</sub> emission that would cause the same radiative forcing as an emitted amount of a well mixed greenhouse gas (carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O)), perfluorocarbons PFCs, hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF<sub>6</sub>) and ozone depleting substances (ODS: chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons) or a mixture of well mixed greenhouse gases, all multiplied with their respective greenhouse warming potentials to take into account the differing times they remain in the atmosphere.

falling in various ranges. Mitigation costs reflect differences between the cost of the low carbon technology and the cost of the technology it replaces.

Given the overwhelming share of fossil fuels in electricity generation, the first option is to replace existing fuels and technologies by less carbon intensive fossil fuels and more efficient technologies, respectively. For example, replacing a conventional coal power plant with a thermal conversion efficiency of 25% by an advanced plant with 34% efficiency reduces CO<sub>2</sub> emissions by 27% (from 973 to 710 g CO<sub>2</sub>/kW·h). Fuel switching brings even more benefits: replacing the same conventional coal plant by a combined cycle gas turbine (CCGT) burning natural gas at 50% efficiency reduces CO<sub>2</sub> emissions by 58% (to 404 g CO<sub>2</sub>/kW·h).

Another possibility to reduce carbon emissions from fossil fuel combustion is carbon capture and storage (CCS). However, according to the IPCC, its “[P]enetration by 2030 is uncertain as it depends both on the carbon price and the rate of technological advances in cost and performance”. The potential global emissions reductions from CCS used with coal and gas fired power plants are estimated at 0.49 and 0.22 Gt CO<sub>2</sub>-eq, respectively.

Utilizing realistically available potentials for the fuel substitution options would result in total reductions of 1.07 Gt CO<sub>2</sub>-eq (or 1.78 Gt CO<sub>2</sub>-eq together with CCS) in global GHG emissions in 2030. These are considerable yet insufficient reductions with respect to meeting the ultimate objective of the UNFCCC: “avoidance of dangerous anthropogenic interference with the climate system”. Therefore, other energy sources and technologies are needed to supplement or even substitute fossil fuels.

A large number of studies estimated the life cycle GHG emissions from a suite of power generation technologies. Figure VII-3 presents a summary.

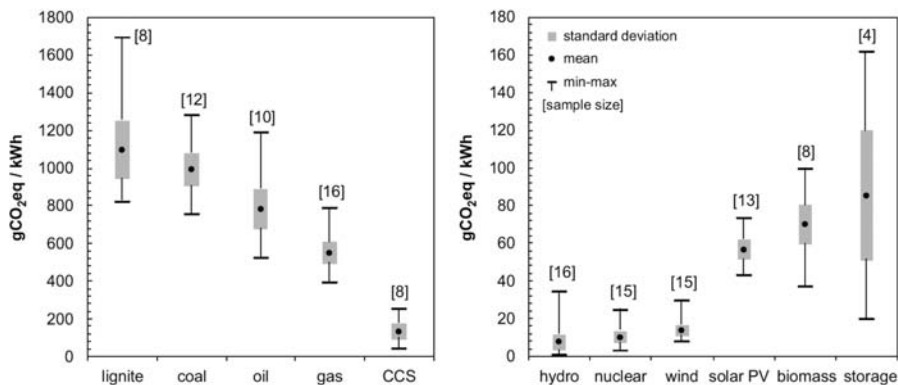


FIG. VII-3. Summary of life cycle GHG emissions for selected power generation technologies [VII-8].



### VII-2.3.1. Nuclear Applications Relevant to Mitigation of Climate Change

The principal nuclear application that can contribute to mitigating climate change is nuclear power. Figure VII-3 shows that nuclear power, together with hydro, wind and CCS technologies, is one of the lowest emitters of GHGs in terms of g CO<sub>2</sub>-eq per unit of electricity generated on a life cycle basis.

Of the low carbon power generation technologies assessed by the IPCC, Fig. VII-4 takes a closer look at those with a mitigation potential of more than 0.5 Gt CO<sub>2</sub>-eq. The figure shows the potential GHG emissions that can be avoided by 2030 by adopting the selected generation technologies. The width of each rectangle is the mitigation potential of that technology for the carbon cost range shown on the vertical axis. Each rectangle's width is shown in the small box directly above it. Thus, nuclear power (the yellow rectangles) has a mitigation potential of 0.94 Gt CO<sub>2</sub>-eq at negative carbon costs<sup>38</sup> plus another 0.94 Gt CO<sub>2</sub>-eq for carbon costs up to \$20/t CO<sub>2</sub>. The total for nuclear power is 1.8 Gt CO<sub>2</sub>-eq, as shown on the horizontal axis.

The figure indicates that nuclear power represents the largest mitigation potential at the lowest average cost in the energy supply sector, essentially electricity generation. Hydropower offers the second cheapest mitigation

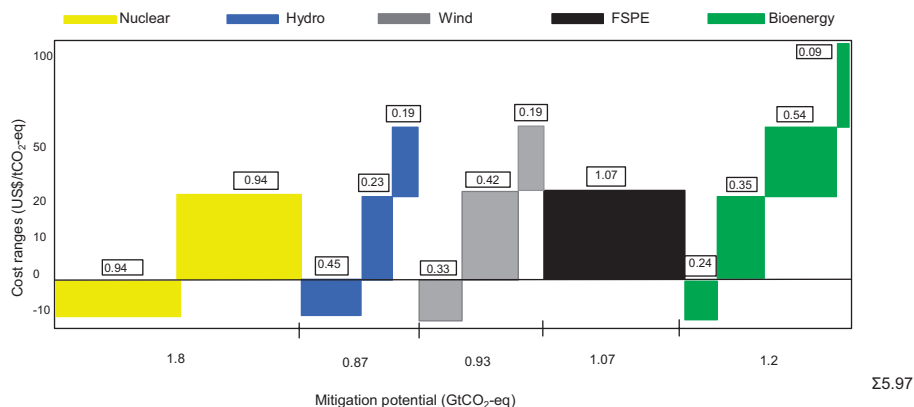


FIG. VII-4. Mitigation potential of selected electricity generation technologies in different cost ranges (source: based on data in Table 4.19 of the WG III report).

<sup>38</sup> In the IPCC report, mitigation options with net negative costs (no regrets opportunities) are defined as those options whose benefits such as reduced energy costs and reduced emissions of local/regional pollutants equal or exceed their costs to society, excluding the benefits of avoided climate change.

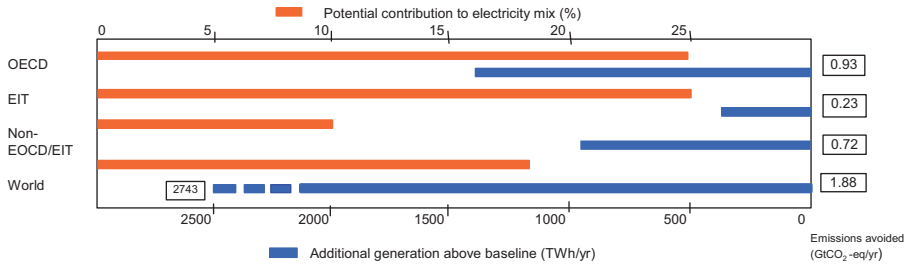


FIG. VII-5. Nuclear power shares, generation volumes and avoided GHG emissions. Source: based on data in Table 4.11 of the AR-4 WG III report.

potential but its size is the lowest among the five options considered here. The mitigation potential offered by wind energy is spread across three cost ranges, yet more than one third of it can be utilized at negative cost. Bioenergy also has a significant total mitigation potential but less than half of it could be harvested at costs below \$20/t CO<sub>2</sub>-eq by 2030.

The mitigation potential of nuclear power is based on the assumption that it displaces fossil based electricity generation. The mitigation volume estimated by the IPCC for nuclear power reflects the contribution it could make to global climate protection by increasing its share of 16% in the global electricity mix in 2005 to 18% by 2030. This figure is consistent with the IAEA’s high projection for that year [VII-9]. The potential nuclear share in the electricity mix and the resulting additional (above baseline) power generation are presented in Fig. VII-5 for the three large global regions and the world. The red bars, for which the scale increases from left to right on the top axis, show the potential percentage of nuclear power in each region’s electricity mix. The blue bars, for which the scale increases from right to left on the bottom axis, show the potential generation from nuclear power in TW·h/a above the baseline scenario. The dashed portion of the bottom bar indicates that its value of 2743 TW·h/a (shown in the box) is off the scale to the left. The boxed numbers on the right show the corresponding carbon emissions avoided in each region and in the world as a whole.

Developments in the world energy markets since 2004 and more recent projections put forward by many national and international organizations suggest that the role of nuclear power over the next two decades is likely to be even more significant than suggested by the IPCC assessment. Beyond climate change concerns, the persistence of drastically higher fossil fuel prices and supply security risks has given additional impetus to (re)considering nuclear policies in many countries. The baseline scenario in the above IPCC estimates assumes a crude oil price of \$25 per barrel on average for the period up to 2030. Even the high oil price scenario averaged \$35 for the same period. Natural gas

prices are projected to follow oil prices in each scenario. Few analysts today expect oil prices to return to the \$20–30 range in the medium term. Hence the cost and supply security advantages for nuclear power are likely to remain for the next two decades.

Non-power nuclear applications also have a role to play in another mitigation technology, carbon capture and storage (CCS), both geological CCS and agricultural CCS.

Carbon capture and storage (CCS) is one means of reducing GHG emissions, and isotope hydrology can facilitate CCS by assessing subsurface aquifers and coal beds that can be used for the storage of CO<sub>2</sub>. Geological storage of CO<sub>2</sub> occurs naturally, with the Earth's subsurface already the largest terrestrial carbon reservoir (through coal and oil deposits, etc.). Deep saline aquifers in sedimentary basins can potentially be used for CCS carried out by injecting CO<sub>2</sub> from stationary sources through a pipeline into the rock formations. Isotopic tools can contribute by mapping and modelling CO<sub>2</sub> distribution, its interactions with groundwater, and possible leakages from formations in order to maintain reservoir reliability.

CCS has potential applications in agriculture as well, as carbon and nitrogen isotopic techniques are being applied to quantify the role of soils in the release of GHGs and to identify soil microorganisms that can effectively use GHGs such as methane (e.g. methane-oxidizing soil bacteria) as a principal source of carbon energy, thus reducing GHG emissions.

Nuclear technologies such as laser-ablation stable isotope ratio mass spectrometry (LA-IRMS), in combination with conventional soil micromorphology, can use <sup>13</sup>C to help develop sustainable land and resource management strategies to maximize the carbon sequestration potential of soils. Analysis of carbon isotopes can reveal carbon distributions in soil to provide a better understanding of short term carbon storage, and also of the quality of soil carbon stocks and their decomposition–storage (sequestration). This information is significant in exploring CCS strategies as these processes are subject to changes in vegetation (e.g. from cropping to biofuel), plant cover intensity, land management practices, and climate variations under both rainfed and irrigated conditions.

In crop production, soil investigations of isotopic ratios of nitrogen and carbon can be used in combination with <sup>18</sup>O and <sup>2</sup>H concentrations to develop management practices such as irrigation scheduling and fertigation for nitrogen fixing crops that harness atmospheric carbon and nitrogen into biomass, and hence ecosystems, for sequestration.<sup>39</sup> Transfer of carbon and nitrogen into

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<sup>39</sup> Detailed information regarding these topics and techniques can be found in Annex I of the Nuclear Technology Review 2007.

productive biomass (e.g. starch, animal feed, biofuel) can also be achieved using a combination of mutation induction and efficiency enhancing biotechnologies for the development of mutant crop varieties capable of absorbing more of these GHGs.

In the production of grain crops, roughly 50% of the above ground biomass, such as straw, either goes unused or increases CO<sub>2</sub> emissions through burning. This potential resource thus has a negative economic and ecological impact. The development of mutant grain crops with enhanced biomass productivity that would increase the digestibility of above ground biomass (e.g. through decreased or modified lignin to increase bioavailability to ruminant animals of lignin harboured carbohydrates), would decrease both CO<sub>2</sub> (from burning and decomposition) and methane production (from husbandry).

### **VII-3. Thirteenth Conference of the Parties (COP-13) to the UNFCCC**

The AR-4 constitutes the IPCC's latest assessment, per its mandate, "on a comprehensive, objective, open and transparent basis [of] the latest scientific, technical and socio-economic literature produced worldwide relevant to the understanding of the risk of human-induced climate change, its observed and projected impacts and options for adaptation and mitigation". The IPCC and its reports are policy relevant without being policy prescriptive.

The Conference of the Parties to the UNFCCC, on the other hand, focuses precisely on the policy issues raised by the IPCC assessments. This section switches from a discussion of the AR-4, as the principal development in 2007 on the assessment of climate change, to a discussion of the Thirteenth Conference of the Parties (COP13) to the UNFCCC, as the principal development in 2007 in terms of climate change policy.

COP-13, held in Bali, Indonesia, in December 2007, marked a step forward in managing the risks related to global climate change. The fundamental issue and the centrepiece of the Conference was the design of an international binding framework to address climate change after 2012 when the Kyoto Protocol's first commitment period expires. The Kyoto Protocol, which entered into force in February 2005, requires most developed countries to limit their GHG emissions in the 'first commitment period', which started on 1 January 2008 and runs through 2012.

'Qualified success' probably is the best characterization of the outcome of COP-13. Many parties had hoped for quantitative GHG emission reduction targets by 2020 based on the findings of the IPCC AR-4, which indicate a need for a 25–40% reduction by the developed countries and peaking of global emission within 15 years as prerequisites for capping the global mean temperature rise at 2°C. This ambitious 'destination' was not agreeable. Indeed

several parties argued that such quantified emission limitations were premature at this stage and that the basic principles of a post-2012 climate policy architecture should be agreed on first before specifying the destination.

Instead, the “Bali Action Plan” (also called “Bali Roadmap”), which charts the way forward, was successfully negotiated at the eleventh hour. The decision frames a two year process to finalize and adopt a post-2012 global climate agreement, including GHG emission reduction arrangements to be completed by COP-15 in 2009. At the core of the Action Plan is the recognition that “deep cuts in global emissions are required to meet the ultimate objective of the Convention”, which is the avoidance of dangerous anthropogenic interference with the climate system. It was decided “to launch a comprehensive process to enable the full, effective and sustained implementation of the Convention through long term cooperative action...” Cooperative action was further delineated to encompass (i) “measurable, reportable and verifiable nationally appropriate mitigation commitments or actions, including quantified emission limitation and reduction objectives, by all developed country Parties, while ensuring the comparability of efforts among them, taking into account differences in their national circumstances”; and (ii) “measurable, reportable and verifiable nationally appropriate mitigation actions by developing country Parties in the context of sustainable development, supported by technology and enabled by financing and capacity-building”.

More specifically, (i) mitigation action and quantified emission reductions are expected for all developed countries and (ii) for the first time developing countries agreed to contribute to climate mitigation reflecting one of the UNFCCC’s basic principles of “common but differentiated responsibilities and respective capabilities”, i.e. taking into account social and economic conditions and other relevant factors.

COP-13 established an Ad Hoc Working Group (AWG) on Long-Term Cooperative Action to instigate the process leading to a post-2012 climate policy architecture. Technological development and transfer are important components of the COP-13 decision but the document does not contain details on specific technological options for mitigation in this context.

In addition, COP-13 adopted and approved numerous decisions encompassing a wide range of issues, including the final design of the Adaptation Fund under the Kyoto Protocol, a decision on reducing emissions from deforestation in developing countries, and outcomes on technology transfer, capacity building, the Kyoto Protocol’s flexible mechanisms, the adverse effects of combating climate change, national communications, financial and administrative matters, and various methodological issues.

Nuclear power was not centre stage at COP-13. The call of one party to eliminate the current exclusion of nuclear power from the flexible mechanisms

(the Clean Development Mechanism (CDM) and Joint Implementation (JI)) under the Kyoto Protocol trailed off without further debate. The architecture, the international flexibility mechanisms and the implementation rules of a yet to be concluded post-Kyoto agreement will determine how important a role nuclear power will play in international climate policies (beyond that at the national level). While the work of the newly established AWG is expected to revolve around the nature of relative magnitudes of developed and developing parties' obligations, discussions on international flexibility mechanisms might surface ideas that could be favourable or unfavourable for the opportunities for nuclear power under a post-Kyoto agreement.

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