Research Reactors

A. General Status

1. For over 50 years, research reactors (RR) have made valuable contributions to the development of nuclear power, basic science, materials development, radioisotope production for medicine and industry, and education and training. As of June 2004, the Agency's Research Reactor Database contains information on 672 RR, of which 274 are operational in 56 countries (85 in 39 developing countries), 214 are shutdown, 168 have been decommissioned and 16 are planned or under construction.

2. It is of concern that many of the shutdown, but not decommissioned, reactors still have fuel, both fresh and spent, at the sites. An extended delay between final shutdown and decommissioning will affect both cost and safety at the time of decommissioning, mainly due to the loss of experienced staff (already ageing at the time of shutdown) necessary to participate in decommissioning activities.

3. The distribution of the number of countries with at least one RR peaked at 60 countries in the mid-eighties, coinciding with the peak at 41 for developing countries. The number of countries with at least one RR remained almost constant for industrialized countries from 1965 and for developing countries from 1985 to the present. Four industrialized countries and three developing countries that once had operational RR no longer have any. Figure 1 indicates that the number of RR in industrialized countries peaked in 1975 and has declined since then. The number in developing countries has gradually increased, but changed little since the mid-eighties.

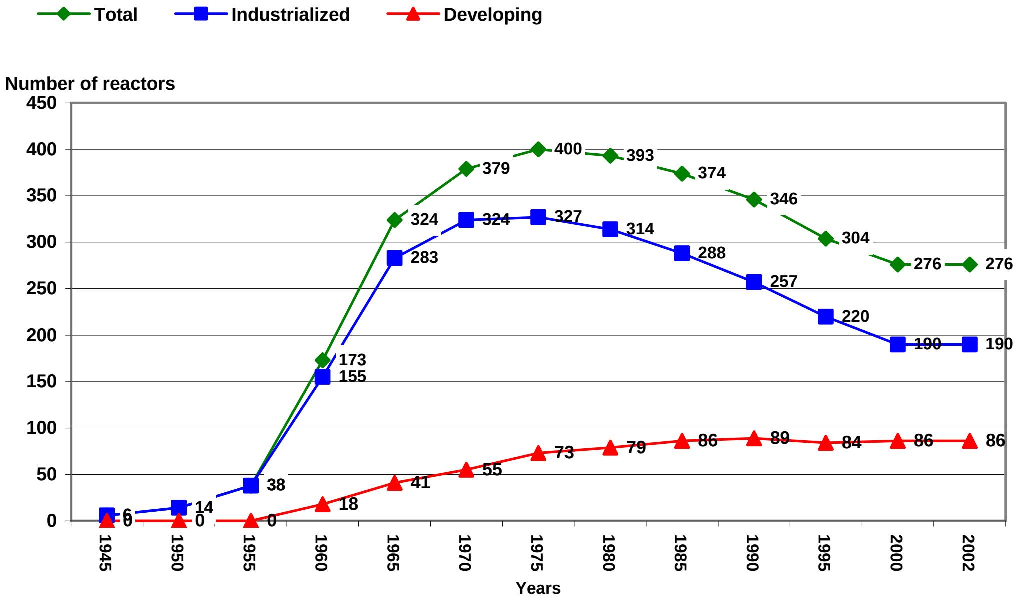

FIG. 1. Number of research reactors in industrialized and developing countries.

4. Figure 2 shows the distribution of operating research reactors among countries. About 70% are in the industrialized countries, with the Russian Federation and USA having the largest numbers.

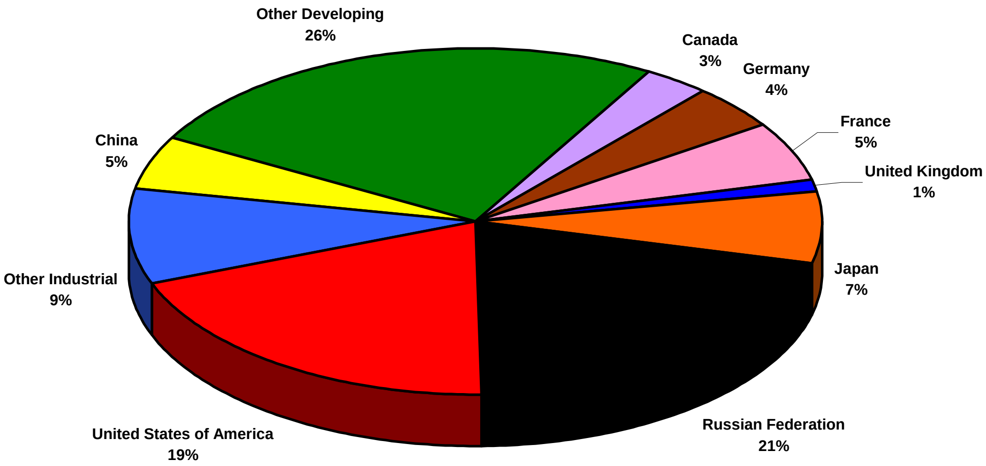

FIG. 2. Operational research reactors in IAEA Member States – 273 reactors.

5. Figure 3 shows the decline in the number of new research reactors being brought into operation in the past four and a half decades, and the increase in the number being shutdown. The pattern reflects the nuclear field’s evolution from a relatively new science into an established technology. It does not mean, however, that new research reactors are unnecessary – eight are currently under construction and eight more are planned. For the most part these are innovative, multipurpose reactors designed to produce high neutron fluxes. Many will meet all the nuclear research and development needs envisioned in the countries in which they are being built, and will offer opportunities for visiting scientists from abroad. In addition, some will provide radioisotopes locally and regionally.

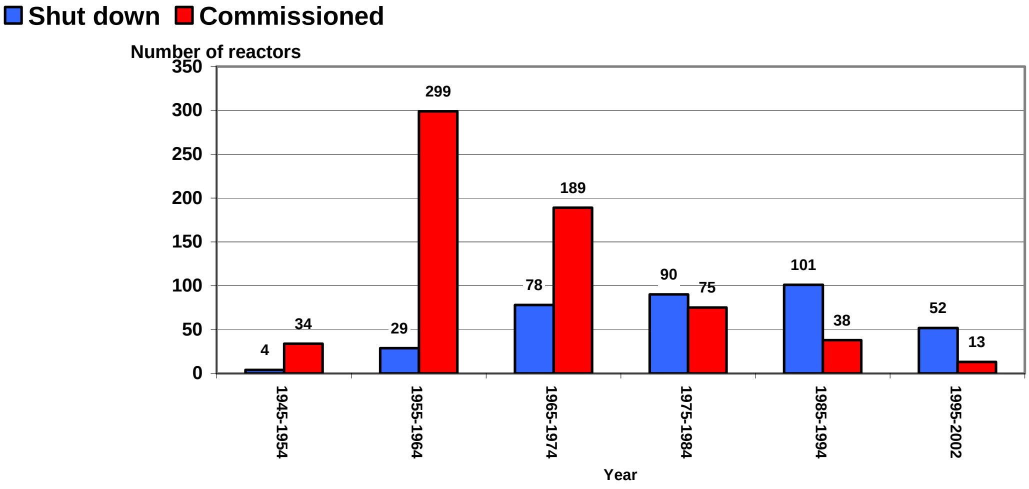

FIG. 3. Number of research reactors commissioned and shutdown.

6. Figure 4 shows the age distribution for operational research reactors. It peaks around 40 years, with almost 65% of operating reactors being more than 30 years old. While a few of these old reactors give cause for safety concerns, the majority have been refurbished at least once so that their key components meet modern safety and technology standards. Figure 5 shows the power distribution of operating research reactors. The thermal power distribution of operating RR indicates that a large fraction of RR, 77%, are less than 5 MW, so that, even in the worst case accidental scenario, there will not be any significant consequences off site. Fifty percent of operational RR are less than 100 kW,

consequently they operate with a lifetime core and so no spent fuel problems will arise until these reactors are shut down permanently. But many of them operate with highly enriched uranium fuel (HEU), i.e., a ^{235}U concentration $\geq 20\%$. HEU programmes are discussed in more detail in Section D of this annex, along with other special fuel cycle challenges associated with research reactors.

7. Research reactors present special challenges in the back end of the fuel cycle because many different designs using a large variety of fuel types have been built, often for special purposes. These include the management of experimental and exotic fuels with no reprocessing route, and significant numbers of fuel assemblies that failed in their reactors or were subsequently corroded in wet storage. Similarly the variety of designs poses special challenges for decommissioning.

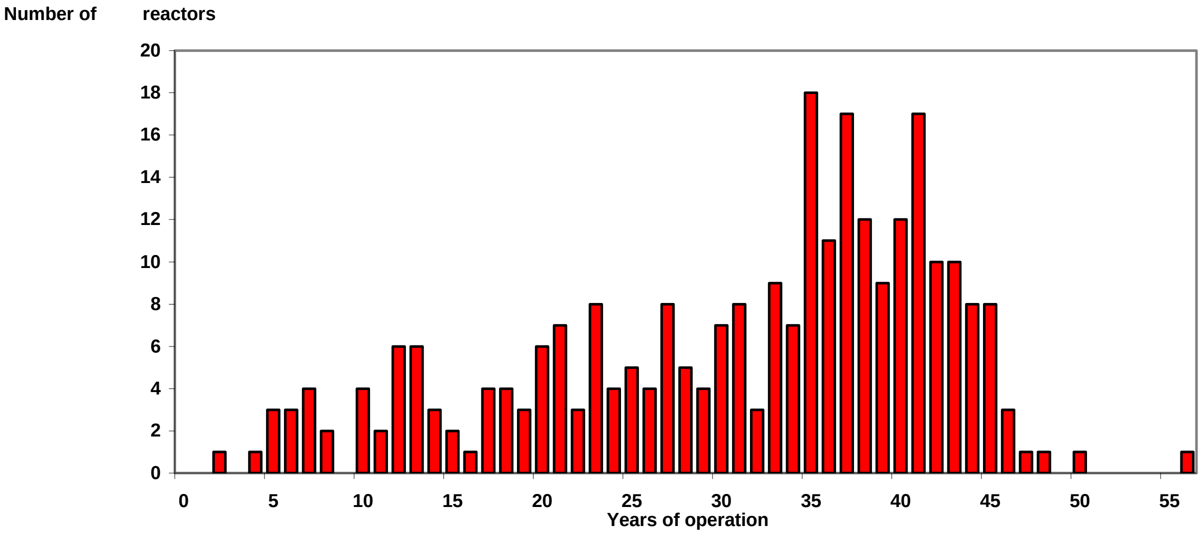

FIG. 4. Age distribution of research reactors in the RRDB: Number of reactors and years in operation.

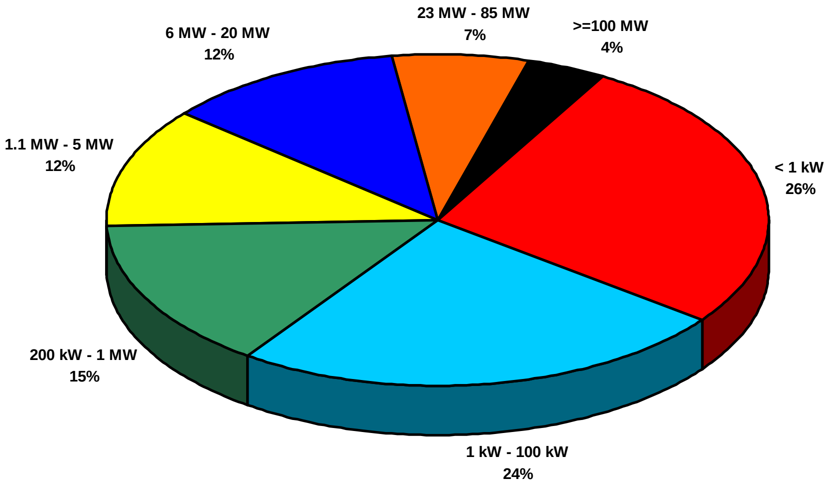

FIG. 5. Pie chart showing distribution of thermal powers of operating reactors.

B. General Trends

8. The worldwide demand for nuclear science research, technology development, reactor services, and education and training no longer requires the large number of research reactors currently in operation. Reactors that prosper are those that have special attributes (e.g., a high neutron flux, a cold source, or in-core loops to simulate power reactor conditions) or have diversified to take advantage of commercial opportunities (e.g., radioisotope production or silicon doping). A much larger number are under-utilized. Older research reactors will therefore continue to be shut down in increasing numbers, and more of those that have already shut down will plan and implement decommissioning.

9. New reactors will be built, but in much smaller numbers than in the past, and will either be multipurpose reactors or dedicated to specific needs, for example, the new research reactor planned for Australia is multipurpose. The high flux multipurpose reactor, FRM II, currently being commissioned in Germany, will be used largely for research using neutron beams. The two Maple reactors being commissioned in Canada are based on a research reactor design but are essentially commercial isotope factories designed to produce ^{99}Mo by fission.

10. Currently, there are eight new research reactors under construction and plans for about eight more. As is usual in the case of research reactors, they vary significantly in power, type and purpose. There is one 30 kW Miniature Neutron Source Reactor (MNSR) that will be used primarily for education and training, plus some neutron activation analysis (NAA) related to national interests in assessing pollution, mineral resources and soil fertility. Two or three facilities will be 1-2 MW multipurpose reactors of the TRIGA type used for a wide gamut of applications including education and training, some limited isotope production, neutron radiography and neutron beam-based materials research. They may also be used for silicon doping and boron neutron capture therapy.

11. There are several 10-100 MW compact core reactors with D_2O reflectors either being planned or under construction. Their primary purpose will be to provide high flux beams for state-of-the-art materials analysis instruments, but they will also be suitable for most of the other standard applications listed above, including significant isotope production. Four or five of the new reactors will be dedicated to single purposes, such as isotope production, testing materials and components for power reactors or desalination. Finally, one or two research reactors under consideration would be intended as prototypes for advanced power reactor designs.

12. Of the research reactors currently operating, many will continue to prosper by finding niches to exploit – such as providing test loops simulating power reactor conditions, neutron activation analysis services, gem colouring, silicon doping, and isotope production – and by being flexible enough to exploit other opportunities as they arise. At the same time these facilities provide important training for the scientists and engineers who are essential for continued progress in nuclear research and development.

13. Many of the higher flux, high utilization research reactors have recently been significantly upgraded, usually to improve the neutron flux, particularly for beam research. In this context, the modifications have involved making the reactor core more compact, increasing the power, and changing reflectors, as well as upgrading or adding cold sources. Whenever beam fluxes are increased, there is naturally a tendency to also add new instruments such as Ultra-Small Angle Neutron Scattering instruments or Spin-Echo spectrometers. Other major modifications have been undertaken recently to enable or enhance boron neutron capture therapy. The pioneering facilities generally add fission converters to obtain a higher epithermal flux, while others modify thermal columns or beam tubes to enable them to perform capture therapy studies, either for research or treatment.

C. Utilization

14. The climate for research reactors has changed in recent years. The original mission of some facilities has been accomplished or become obsolete. In other cases, applications can now be done better or more cheaply using newer technology. Tight budgets and changing priorities have caused some governments to cut back baseline support. The stagnation or decline of nuclear power in many industrialized countries has reduced the demand for nuclear education and training, and simulators have taken over some of the training of nuclear power plant operators previously provided by research reactors.

15. Table 1 provides a good indication of the relative frequency of each major application among research reactors. The table's final category, 'other uses', includes topics ranging from public tours to reactor physics studies, instrument calibration, positron sources, electrical power production and neutron depth profiling.

TABLE 1. FREQUENCY OF APPLICATIONS OF RESEARCH REACTORS

Application	**Number of reactors declaring involvement**
Neutron activation analysis	71
Teaching	68
Training	63
Materials or fuel tests	53
Isotope production	48
Neutron scattering research	34
Neutron radiography	32
Transmutation (Si or gems)	21
Geochronology	14
Neutron capture therapy	9
Other uses	47

D. Nuclear Fuel Cycle

D.1. General Overview

D.1.1. Inventories

16. The Agency has circulated questionnaires for its Research Reactor Spent Fuel Database (RRSFDB), and responses indicate that there are 62 027 spent fuel assemblies in storage and another 24 338 assemblies in the standard cores. Of the 62 027 in storage, 45 108 are in industrialized countries and 16 919 are in developing countries; 21 732 are HEU and 40 295 are LEU (low enriched uranium). The majority use standard types of fuel plus aluminium cladding, although some TRIGA fuel elements have stainless steel cladding. The remaining non-standard fuel types in 59 facilities pose special problems both for their continued safe storage and for their eventual final disposition. Figure 6 compares the numbers of US-origin and Russian-origin HEU and LEU spent fuel assemblies at foreign research reactors that might be involved in take-back programmes. Currently 12 850 spent fuel assemblies of US-origin, and 21 732 of Russian-origin, are located at foreign research reactors.

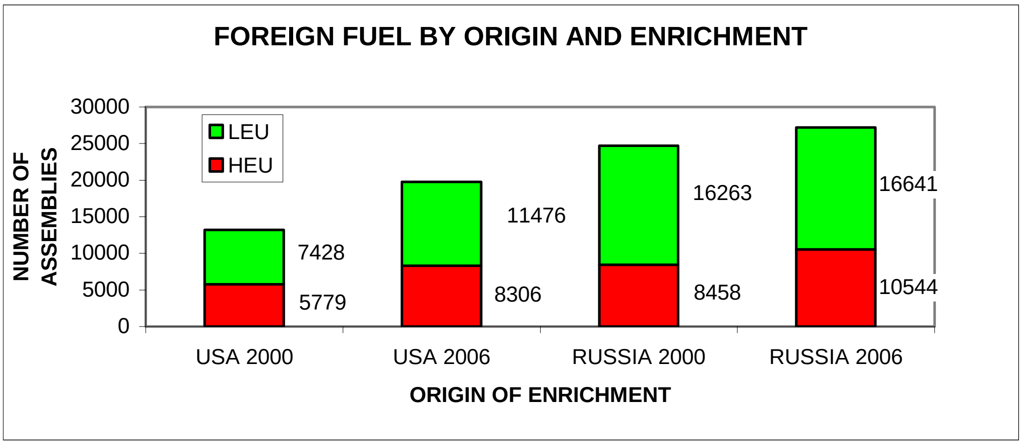

FIG. 6. Present and projected US and Russian origin spent fuel at foreign research reactors potentially involved in take-back programmes.

D.1.2. Storage Conditions

17. Wet storage is the most popular storage technology for storing research reactor spent fuel. However, successful storage of aluminium-clad fuel depends on very strict water quality control. Although aluminium clad research reactor fuel has been successfully stored in water for over 40 years without significant signs of corrosion, penetration of the fuel cladding by pitting corrosion has occurred in as little as 45 days in cases where water quality has been allowed to deteriorate. Aluminium racks, tanks and pool liners used in storing aluminium clad fuel are equally vulnerable to corrosion and thus limit the life time of spent fuel storage facilities.

18. Research reactor fuel has also been successfully stored dry in vaults, concrete canisters and hot cells over long periods. Where problems have arisen, they have invariably been due to a long-term undetected ingress of water or moisture.

D.2. Reduced enrichment for research and test reactors (RERTR) and Fuel Return Programmes

D.2.1. RERTR

19. Section A noted that many research reactors operate on HEU fuel. To reduce and eventually eliminate commerce in HEU for research reactors, the United States set up the reduced enrichment for research and test reactors (RERTR) programme in 1978. A similar programme was initiated in the former Soviet Union, and these programmes have essentially merged with the Russian Federation becoming a full partner in RERTR. Thirty-one reactors to date have been fully converted to low enriched uranium (LEU has a ^{235}U concentration < 20%), and a further seven are in the process of converting with mixed HEU/LEU cores.

20. A major component of RERTR is the development and qualification of new, high-density, LEU fuels based on uranium molybdenum alloys. This effort has two goals: first, enabling further conversions of reactors from HEU to LEU and, second, developing a substitute for LEU silicide fuel that can be more easily disposed of after expiration of the United States Foreign Research Reactor (FRR) Spent Nuclear Fuel Acceptance (SNF) Program in May 2006 (see Section D.2.2).

21. The original schedule was to qualify LEU dispersion fuels based on U-Mo alloys with uranium densities of up to 6 g/cm^3 by the end of 2003, and those based on alloys with uranium densities of

8-9 g/cm^3 by the end of 2005. However, technical difficulties have been encountered that will delay qualification. These occurred during irradiation tests and were observed in the form of pillowing caused by excessive porosity in the (U-Mo)Al$_x$ interaction product between U-Mo particles and the Al matrix under elevated operating conditions (i.e. a high temperature and fission rate). Planned irradiations to qualify full size fuel elements have therefore been postponed until a solution to this problem is developed, which will likely delay qualification until at least the end of 2010.

22. Promising results are being obtained in the effort to develop a fabrication process for monolithic LEU U-Mo fuel. Most existing and foreseen RR could be converted with this fuel, which has a maximum uranium density of between 15.4 and 16.4 g/cm^3. The most promising method produces the fuel meat by cold rolling a small ingot produced by casting. The aluminium clad and the fuel meat are then bonded by friction stir welding and the cladding surface is finished by a light cold-roll. This method has been demonstrated for mini-plates and appears to be possible for full size Materials Testing Reactor (MTR) plates, with the possible inclusion of intermediate anneals.

D.2.2. Fuel Return Programmes

23. The US Foreign Research Reactor (FRR) Spent Nuclear Fuel (SNF) Acceptance Program has made significant progress since its inception in May 1996. Under the programme, 4576 MTR elements have been received at the Savannah River Site and 961 TRIGA elements have been received at the Idaho National Engineering and Environmental Laboratory. These and projected future shipments are expected to greatly reduce the inventories of spent fuel at research reactors worldwide, thereby resolving operational problems at many reactor sites and reducing proliferation concerns.

24. The tripartite US-IAEA-RF Initiative on Russian Research Reactor Fuel Return to examine the feasibility of implementing a programme to return Russian origin research reactor fuel to the Russian Federation for management and disposition made steady progress during 2002. Agreements are in place and preparations are ongoing for the first shipment to take place from Tashkent, Uzbekistan.

25. Also under the auspices of the tripartite Initiative, an international operation involving Romania, the Russian Federation, USA and the Agency removed 14 kg of 80% enriched, and 36% enriched uranium from the Pitesti Institute of Nuclear Science in September 2003. The fresh fuel, originally obtained for the now shutdown WWR-S reactor at the ‘Horia Hulubei’ National Institute for Physics and Engineering in Magurele near Bucharest, was flown to Novosibirsk, Russia, where it is to be re-fabricated into LEU fuels.

26. The Agency assisted Bulgarian authorities with the removal of HEU stored at the small (2 MW) IRT research reactor in Sofia. The HEU, 36% enriched and in the form of fresh fuel, was airlifted in December 2003 from Bulgaria to the Russian Federation, which agreed to take back the fuel which it had originally supplied.

27. Also within the framework of the tripartite US-IAEA-RF Initiative on Russian Research Reactor Fuel Return, the Agency assisted the Libyan authorities with the repatriation of 15 kg of 80%-enriched fresh HEU in March 2004. The fresh HEU fuel was shipped to the Russian Federation, which agreed to its return.

E. Decommissioning

28. A breakdown of the statistical data used for Figure 3 into shutdown and not yet decommissioned (‘shutdown (NYD)’) and decommissioned research reactors for individual regions and Member States yields a more precise picture of the importance of decommissioning issues. At present, close to 60% of the ‘shutdown (NYD)’ research reactors are located in North America with a further 12% in the Russian Federation. About 10% of ‘shutdown (NYD)’ research reactors are in developing Member States and distributed as follows: Asia-Pacific - 10; Eastern Europe - 8; Latin America - 4; and Africa and Middle East - 3.

29. However, as discussed in Section A, many of the operating research reactors in these regions are over 30 years old and a significant number will join the shutdown list in the next few years.

30. With respect to operational research reactors to be shut down and decommissioned in the future, a meaningful breakdown of the numbers is difficult, because future plans remain open for many countries.