50 Years of Nuclear Energy[1]

1. “The energy produced by breaking down the atom is a very poor kind of thing. Anyone who expects a source of power from the transformations of these atoms is talking moonshine.” Lord Ernest Rutherford, 1933.

2. “It is not too much to expect that our children will enjoy in their homes [nuclear generated] electrical energy too cheap to meter.” Lewis Strauss, Chairman, US Atomic Energy Commission, 1954.

3. In 2004, half a century after electricity produced by nuclear power was first delivered to an electrical grid at Obninsk in today’s Russian Federation, we know the truth lies somewhere between the extremes.

4. Nuclear fission was discovered in 1939, and the world’s first chain reaction was achieved by the Manhattan Project on 2 December 1942 at the University of Chicago. The Chicago nuclear pile consisted of uranium embedded in bricklike blocks of graphite to serve as the moderator. However, it was not until after the war, on 20 December 1951, that electricity was first generated from nuclear power. The source was EBR-I (Experimental Breeder Reactor-I), a fast breeder reactor at the National Reactor Testing Station in Idaho, USA. EBR-I initially produced about 100 kW(e), enough to power the equipment in the small reactor building.

A. International developments

5. In the 1950s nuclear power research and development focused mainly on technologies for civilian electricity generation and naval propulsion, particularly submarines. The emphasis in the USA was on light water reactor (LWR) designs fueled with enriched uranium, both the pressurized water reactor (PWR) associated principally with Westinghouse and the boiling water reactor (BWR) associated with General Electric (GE). Development in the USSR covered both graphite moderated, light water cooled, enriched uranium designs and WWER designs (water cooled water moderated power reactor) similar to PWRs. British and French efforts focused on natural uranium fueled, graphite moderated, gas cooled reactors (GCR).[2] Canada focused on natural uranium fueled, heavy water moderated designs.

6. Initial success, both for civilian power generation and submarine propulsion, came in 1954. On 9 May 1954 the 5 MW(e) graphite moderated, light water cooled, enriched uranium reactor at Obninsk, USSR reached criticality, and at 5:30 pm on 26 June 1954 it was connected to the Mosenergo grid. In December 1954, the first nuclear submarine, the Nautilus in the USA, began operation under nuclear power.

7. In 1956 Calder Hall-1, a 50 MW(e) GCR, came on line in the UK (and operated until March 2003). Shippingport in the USA was next, a 60 MW(e) PWR connected to the grid in 1957, followed in 1959 by G-2 (Marcoule) a 38 MW(e) GCR in France. Also in 1959, the world’s first non-military nuclear powered ship, the icebreaker Lenin, was launched in the USSR. Figure 1 presents a

[1] This summary borrows heavily, frequently verbatim, from David Fischer’s *History of the International Atomic Energy Agency: the first forty years*, IAEA, Vienna, Austria, 1997.

[2] World Nuclear Association (http://www.world-nuclear.org/info/inf54.htm).

timeline showing these dates, the dates when nuclear power first came on line in other countries around the world, and, in the middle of the bar, the dates when total installed nuclear capacity worldwide reached 100 GW(e), 200 GW(e), and 300 GW(e). At the end of 2003, it stood at 361 GW(e).

8. An important contributor to the initial spread of nuclear power was a new post-war international openness and exchange, triggered most substantially by a United Nations conference in 1955 that came to be known as "The First Geneva Conference". It proved to be the world's largest gathering of scientists and engineers up to that time, and both confirmed for a broad audience that numerous uses of nuclear energy were now feasible, and lifted the blanket of secrecy that had covered nuclear research during the war.

9. European co-operation was also spurred by the Suez crisis in the Fall of 1956. At the height of the crisis, foreign ministers of the European Coal and Steel Community countries – France, the Federal Republic of Germany, Italy and the three Benelux countries – decided to appoint "three wise men" to set targets for nuclear electricity. The target was 15 GW(e) of installed nuclear power by 1967, and in March 1957 the Rome treaties establishing both EURATOM and the European Economic Community were signed.

B. The "turnkey" plants

10. By the early 1960s, demonstration power reactors were in operation in all leading industrial countries, and expectations were high. In December 1963, the idea of "turnkey" plants was introduced in the USA, with a bid for the construction of a plant at Oyster Creek, New Jersey, at a guaranteed fixed price that was clearly competitive with coal and oil fired alternatives. By 1967, US utilities alone had ordered more than 50 power reactors, with an aggregate capacity larger than that of all orders in the USA for coal and oil fired plants, and from 1967-1974 they placed an additional 196 orders. The US Atomic Energy Commission foresaw 1000 nuclear plants on line in the USA by the year 2000.[3] Globally the nuclear industry started to surge up the early slope of the S-shaped curve of global installed nuclear capacity shown in the left panel of Figure 2.

11. The turnkey plants in the USA successfully attracted utilities to nuclear power and gained their manufacturers a strong domestic foundation from which they then expanded internationally. But every turnkey plant lost its manufacturer money.[4] The losses were due only partly to aggressively competitive low bidding. They also reflected a rapidly changing licensing environment that increased costs. In this sense the timing of the turnkey plants could hardly have been worse.

[3] Cohn (1997) p. 127

[4] Simpson (1995) pp. 192-194

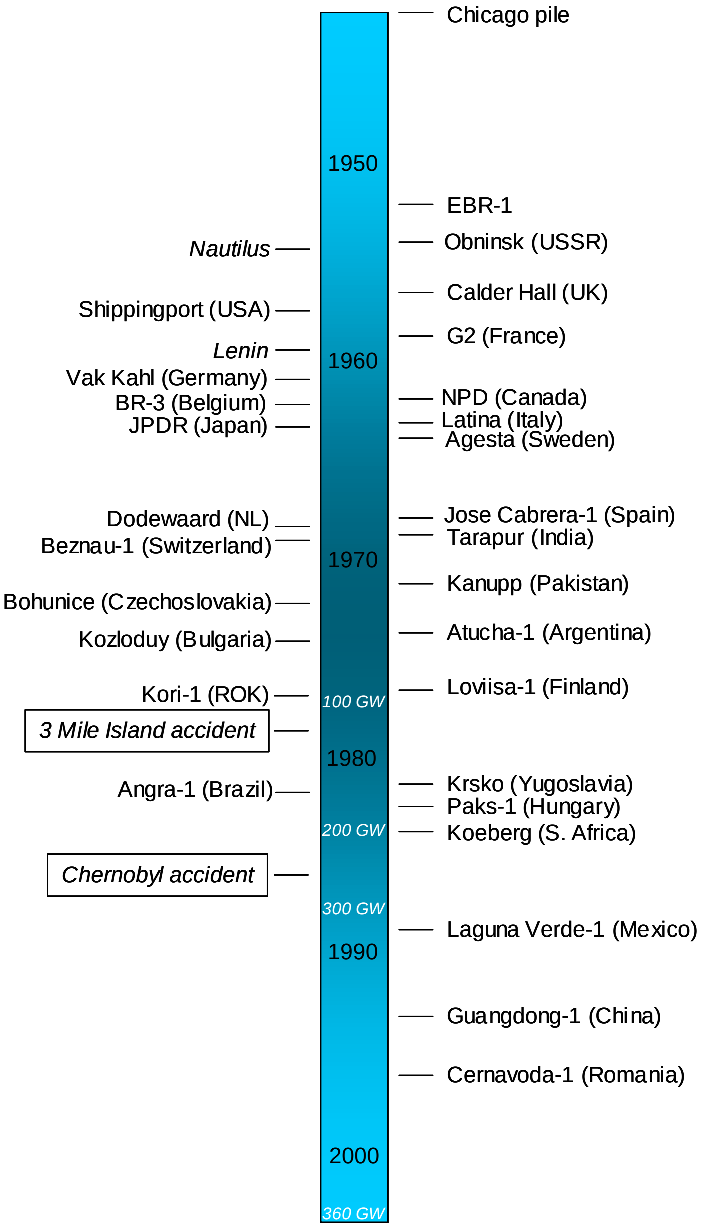

FIG. 1[5]. Timeline of first industrial scale NPPs around the world. The white numbers in the middle of the bar show when total installed nuclear capacity worldwide first passed 100 GW(e), 200 GW(e) and 300 GW(e).

C. Environmentalism, slower growth and bad management

12. Oyster Creek was completed in 1969, and subsequent turnkey plants stretched into the 1970s. Increasing challenges by a growing number of mainly environmentalist nuclear opponents began to stretch out licensing times and sometimes necessitate design changes, thereby delaying cost recovery, increasing costs, and complicating financing. The first Earth Day in the USA took place in 1970, and the National Environmental Policy Act was passed in 1969. It created new requirements (notably an

[5] Taiwan, China commissioned Chin Shan-1 in 1977.

"environmental impact statement") and new institutions (the Environmental Protection Agency and Council on Environmental Quality). All the trends of the time in the USA conspired to increase the numbers, opportunities, and credibility of nuclear opponents.

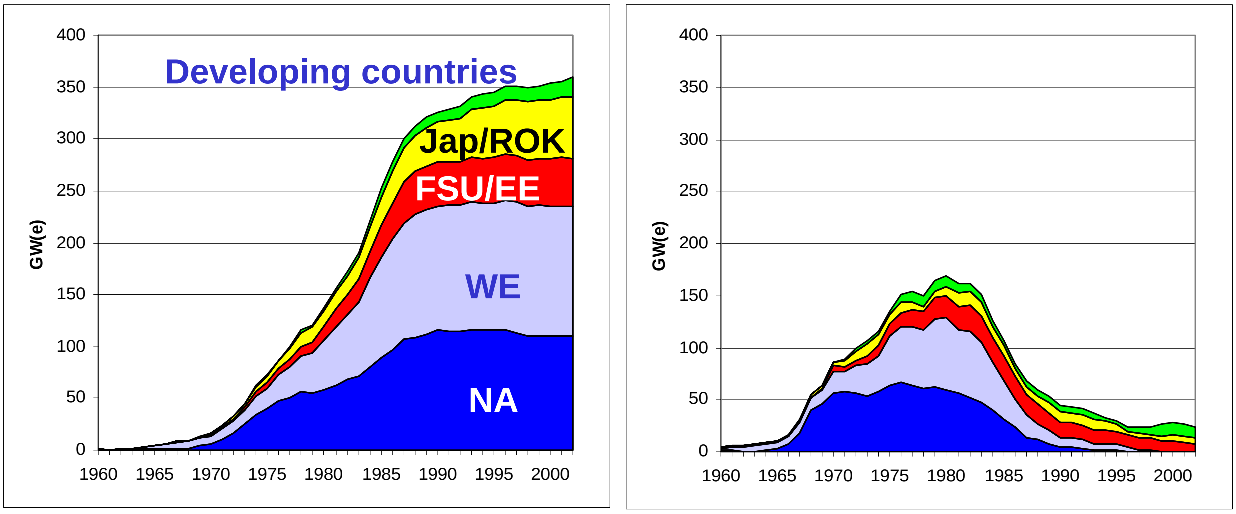

FIG. 2. The left panel shows growth in global installed nuclear capacity in GW(e). The right panel shows the capacity under construction worldwide, also in GW(e). FSU: Former Soviet Union; EE: Eastern Europe; NA: North America; Jap: Japan; ROK: Republic of Korea; WE: Western Europe.

13. The environment was changing in Europe as well. The 1970s saw a surge in environmentalism, resulting in new environmental legislation, environmental ministries and, in several countries, the founding of formal Green political parties, all anti-nuclear.

14. In the USSR the main environmental challenge to nuclear expansion would come later, after the 1986 Chernobyl accident. Throughout the 1970s and early 1980s expectations still remained high, with a target of 100 GW(e) to be installed by 1993.

15. Even in the West, the changed licensing environment took a while to affect the flow of new orders. At the beginning of the 1970s orders rose steadily. But by 1975, the curve of orders had already passed its peak. From 1974 to 1975 orders dropped abruptly from 75 GW(e) to 28 GW(e). Moreover, all 41 reactors ordered after 1973 were subsequently cancelled, and, indeed, more than two-thirds of all nuclear plants ordered after January 1970 were eventually cancelled.[6] The IAEA's *Annual Report for 1975* called the decline temporary, attributing it to economic recession, rising capital and fuel costs and environmental concerns. The combination of inflation and rising energy costs, in particular, both depressed growth in electricity demand (and thus utility revenues) at the same time that they increased utility costs. A more lasting, but less immediately apparent effect, was the slow and continuing decoupling of economic growth from energy and electricity growth. As the ratio of electricity consumption to GDP decreased, growth forecasts and orders that had assumed the ratio would never change became untenable.

16. Towards the end of the 1970s the shrinking flow of nuclear power orders in the USA dried up completely, and it has not revived. The most obvious cause was the Three Mile Island accident on 28 March 1979, the first major accident at a civilian nuclear power station. The psychological effect on the population in the neighbourhood, and eventually throughout the Western world, was immense. So was the damage to the plant itself and to the reputation of the nuclear power industry. In 1979, the

[6] Cohn (1997) p. 127

total capacity of nuclear power plants on order worldwide actually decreased by about 8000 MW(e); eight new plants were ordered but 14 previous orders were cancelled, and in subsequent years, US utilities continued to cancel orders they had already placed.

17. Not all of nuclear's diminishing popularity in the 1970s and 1980s could be laid at the feet of external forces. A big contributor to high costs was the inability in many cases of utilities, equipment suppliers, contractors and regulators to rise to the management challenges of the new technology.

18. The downturn in orders in the 1970s slowed the build-up of global nuclear capacity and eventually led to a flattening after 1985 of the capacity curve shown in the left panel of Figure 2. As growth slowed, calculations about the long term evolution of nuclear energy and the relative near term economic attractiveness of particularly breeder reactors and the closed fuel cycle began to change. The initial rapid expansion of nuclear capacity – at an average rate of 30% annually in the first half of the 1970s – and a very conservative understanding of the long-term availability of uranium resources, had made breeders and reprocessing appear almost essential. The argument for breeders and reprocessing was especially strong in countries with limited uranium resources, such as France, Japan, the UK and India.

19. Breeders were hardly exotic. The first nuclear electricity had been produced by a fast breeder reactor EBR-I in 1951, and in 1959 the Russian BR-5 fast neutron reactor reached its design capacity of 5 MW(e) at Obninsk. The UK completed the 14 MW(e) Dounreay fast breeder reactor in 1962, and in 1963 the USA completed the 61 MW(e) Fermi fast breeder reactor. In 1973 France connected the 250 MW(e) Phénix to the grid and the USSR did the same for the 350 MW(e) BN-350, at Shevchenko (now Aktau in Kazakhstan). BN-350 went on to provide both electricity and desalinated water for Aktau city and neighbouring industries for 26 years before being shut down only in 1999. In 1975 the UK completed the 250 MW(e) Dounreay prototype fast reactor. In 1980 the commercial sized BN-600 (600 MW(e)) was connected to the grid in the USSR, and in 1986 the Superphénix at Creys-Malville, rated at 1242 MW(e), was connected to the French grid. India's 13 MW(e) fast breeder test reactor went critical in 1985, and, finally, in 1994 Japan commissioned the 280 MW(e) Monju fast breeder reactor, although a sodium leak in December of the following year has kept it out of operation ever since.

20. Economic incentives for breeders and reprocessing have diminished with the slow down in capacity growth since the 1970s. But they have also diminished because estimates of uranium resources have continually risen – a rise both driven by, and reflected in, the evolution of uranium prices shown in Figure 3. Rapid capacity growth in the early 1970s pushed up prices, which in turned encouraged exploration. Greater exploration increased resource estimates, which, along with the slowdown in growth, gradually depressed prices.

21. The changed economic incentives for closing the fuel cycle have limited the introduction of breeder reactors to the units listed above and to continuing research and development programmes in France, Japan, Russia, India, the Republic of Korea and China. They have also limited the need for fuel reprocessing. France has two large facilities at La Hague, and the UK and Russian Federation each have one. Smaller facilities operate in India (three) and Japan (one).

22. About one third of the spent fuel discharged from power reactors is reprocessed; the rest is in interim storage. By the end of 2000, reprocessing had separated 200 tonnes of plutonium from civilian spent fuel – about 20% of the total amount of plutonium discharged from civilian reactors. Some of the recovered plutonium and uranium has been mixed with fresh uranium to create MOX fuel for LWRs.

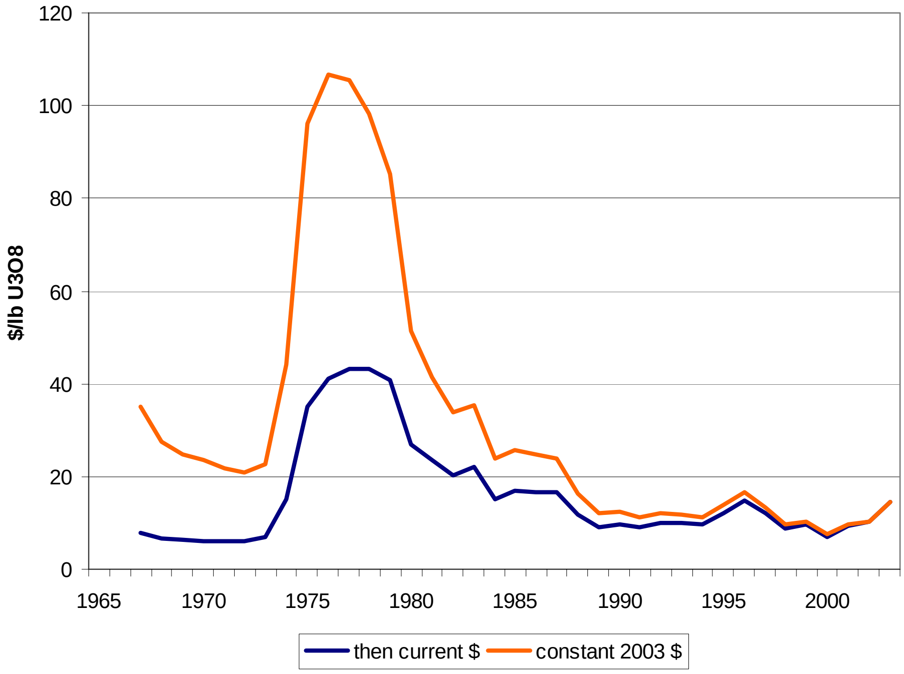

FIG 3. Uranium Prices, 1967-2003.

23. Out of the diversity of initial designs, LWRs have gradually come to dominate the market. In the late 1960s the French authorities abandoned the gas graphite cycle and turned to LWRs. In the late 1980s, the UK followed suit with its first order for an LWR. In the meantime the UK had built a number of advanced gas cooled reactors and had experimented with other designs. As noted above the USSR built two types of power reactors, both using enriched uranium fuel. These were LWRs in its WWER series and the graphite moderated, pressurized water cooled RBMK (reactor bolshoi moshchnosty kanalny – high power channel reactor). The first industrial scale WWER reactor, Novovoronezh-1, came on-line in 1964, as did the first industrial scale water cooled, graphite moderated reactor, Beloyarsky-1. The USSR also exported WWER light water power reactors.

D. The 1990s

24. As shown in Figure 2, trends since 1990 are characterized by slow but continuing capacity growth, new construction dropping to zero in North America and Western Europe, and modest continuing construction elsewhere. Growth in nuclear electricity *generation* has been somewhat greater than Figure 2's growth in nuclear *capacity*, as management efficiencies in the 1990s have steadily increased the average availability factors of the world's nuclear plants (see Figure 4).

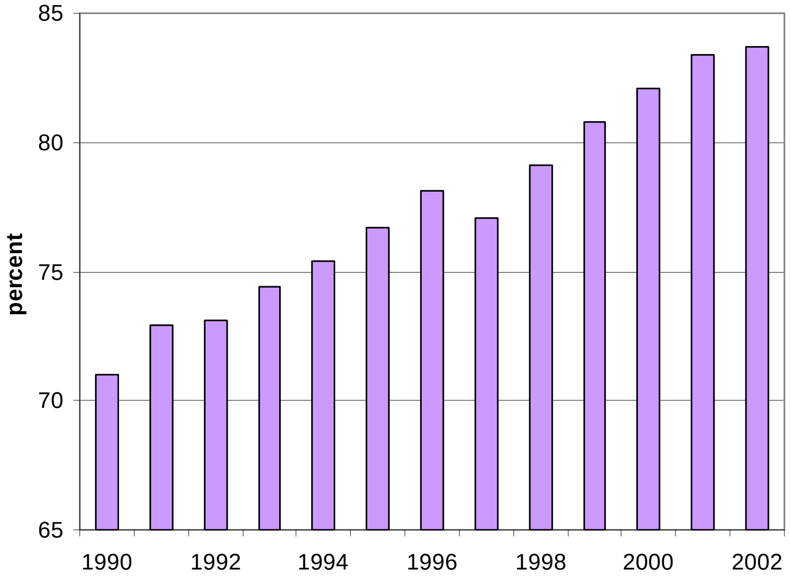

FIG. 4. Increases in the average energy availability factor of nuclear power plants worldwide since 1990.

25. In the left panel of Figure 2, the capacity curves for North America, Western Europe and Russia and Eastern Europe are essentially flat. Two reasons are the 1986 Chernobyl accident and electricity market deregulation in many countries. Ironically, both these reasons, plus consolidation in the nuclear industry, also help explain the rising availability factors shown in Figure 4.

26. As noted above, there had already been a decade of significant opposition to nuclear power in Europe. Austria in 1978 had rejected nuclear power in a general referendum, opposition had stopped Ireland's attempt at nuclear development in the late 1970s, and in 1980 Swedish voters approved a referendum to phase out the country's twelve (now eleven) operating nuclear power plants. But Chernobyl broadened the opposition to nuclear power. Italy, for example, voted in 1987 to shut down all four of its NPPs. Russia's nuclear expansion was also stalled.

27. Another factor was electricity market deregulation in particularly OECD countries. In the USA deregulation began in 1978 with the requirement that utilities buy electricity from qualified independent producers, but open access to transmission networks, competition at the wholesale level, and competition at the retail level were only introduced in the 1990s. Today about half of US states have full competition at the retail level. In Europe, deregulation began in the early 1990s with the Scandinavian countries first liberalizing and then privatizing the energy industry. In the UK the full process took a decade, beginning with the UK Electricity Act in 1989 and reaching full deregulation in 1999. The European Union directive to establish common rules for an internal electricity market was adopted in 1996, with an implementation deadline of February 1999. Proposed next steps would open the electricity market for all non-household customers by July 2004, and for all customers by July 2007. In Japan, initial steps were taken in 1995 with an amendment to the electric utilities law to allow independent power producers (IPPs) into the wholesale market.

28. Deregulation "exposed" excess capacity that had accumulated in regulated markets, pushed electricity prices (and thus utility revenues) lower and made power plant investments more risky. No longer could regulators guarantee rates that would assure cost recovery and profitability. Excess capacity reduced demand for new capacity – of any sort – and the emphasis on rapid reliable returns made nuclear power's "front-loaded" cost structure, with high initial capital costs and low operating costs, an important disadvantage. Because nuclear plants are offered in large units (to benefit from economies of scale), have longer construction times than alternatives, and have organized opposition

to regulatory approval, they present more of an investment risk than particularly new natural gas fired capacity. These differences, coupled with low gas prices through most of the 1990s and natural gas' image as a clean burning fuel, steered new investments away from nuclear and most often in the direction of natural gas.

29. But the 1990s were also characterized by the rising availability factors in Figure 4. The Chernobyl accident was one motivation. It fostered information exchange, comparison, emulation of best practice and communication among operators and regulators facilitated by IAEA, OECD/NEA, World Association of Nuclear Operators and others. The comprehensive exchange of information on operational safety experience in particular has become a major factor in nuclear safety improvements worldwide, and a safer power plant is generally a more available, and more profitable, power plant. At the same time deregulating markets meant that increased availability translated increasingly directly into increased profits. Selected companies moved to define themselves largely by the size and expertise of their nuclear operations, leading to consolidation in the industry and more nuclear plants being operated by those who did it best.

30. The final characteristic of the 1990s is the shift towards Asia and developing countries. As discussed in the 'Global Nuclear Power Picture', current expansion is centred in Asia. One reason is that new nuclear power plants are most attractive where energy demand growth is rapid, alternative resources are scarce, energy supply security is a priority or nuclear power is important for reducing air pollution and greenhouse gas (GHG) emissions. One or more of these features characterize China, India, Japan and the Republic of Korea, where most current construction is taking place.

31. Of the developing countries, India has the longest history while China has the greatest nuclear capacity. Because India has poor uranium resources but substantial thorium, its strategy since the beginning (an Atomic Energy Commission was established as early as 1948) has been aimed at the eventual use of thorium. The sequence was to start with natural uranium reactors to produce electricity and plutonium, use the plutonium in fast breeders to breed more plutonium and uranium-233 from thorium, and then use uranium-233 to sustain breeders converting thorium to uranium-233.

32. Nonetheless, India's first two nuclear units to be connected to the grid, at Tarapur in 1969, were GE BWRs, offered as turnkey plants. But all twelve units since have been PHWRs, as are six of eight units under construction. The other two are WWERs.

33. China is the most recent developing country to adopt nuclear power, with its first industrial sized nuclear power plant at Guangdong-1 being connected to the grid in 1993. Since then it has built an additional six units with four more under construction. As noted in the NTR-2004, the future of nuclear power may be largely determined by its future in countries like India and China – countries with large populations, large prospective increases in GDP and energy demand, established and expanding nuclear expertise, but a still only minor share of nuclear power in the electricity supply.

REFERENCES

[1] Steven Mark Cohn, *Too Cheap to Meter: An Economic and Philosophical Analysis of the Nuclear Dream*, State University of New York Press, Albany, NY, 1997.

[2] David Fischer, History of the International Atomic Energy Agency: the first forty years, IAEA, Vienna, Austria, 1997.

[3] David Hart, Nuclear Power in India: A Comparative Analysis, George Allan & Unwin, London, 1983.

[4] Harry Henderson, Nuclear Power, ABC-CLIO, Inc., 2000.

[5] International Atomic Energy Agency (IAEA), Department of Nuclear Energy, Division of Nuclear Power, “Time-line of Nuclear Power in The World”, unpublished, 2002.

[6] Paul R. Josephson, Red Atom, W.H. Freeman and Company, New York, 2000.

[7] Colin Keay, “A perspective on Nuclear Energy,” referenced in http://www.world-nuclear.org/opinion/razorfeb02.htm, World Nuclear Association, London, February 2002.

[8] Rick Michal (2000), “Richard Rhodes on nuclear technology,” *Nuclear News*, July 2000.

[9] Rick Michal (2001), “Fifty years ago in December: Atomic reactor EBR-I produced first electricity,” *Nuclear News*, November 2001.

[10] Judith Perera, *Nuclear Power in the Former Soviet Union, Volume 2: Nuclear Fuel Cycle Facilities*, The McCloskey Group Ltd, Petersfield, Hampshire, UK, 2002.

[11] Richard Rhodes, *Nuclear Renewal*, Viking Penguin, New York, 1993

[12] Richard Rhodes, “Changing perspectives on nuclear energy,” *Nuclear News*, July 2000.

[13] John W. Simpson, *Nuclear Power from Underseas to Outerspace*, American Nuclear Society, La Grange Park, Illinois, USA, 1995.

[14] Peter Stoler, *Decline and Fail*, Dodd, Mead & Company, NY, 1985.

[15] Joseph P. Tomain, *Nuclear Power Transformation*, Indiana University Press, Bloomington, Indiana, USA, 1987.

[16] Karl Winnacker and Karl Wirtz, *Nuclear Energy in Germany*, American Nuclear Society, La Grange Park, Illinois, 1979.

[17] World Nuclear Association (WNA), “Outline History of Nuclear Energy,” http://www.world-nuclear.org/info/inf54.htm, WNA, London, February 2002.