Uranium—Fuel for Nuclear Energy 2002

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U.S. Department of the Interior
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By Warren I. Finch

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Conversion Factors

To convert	To	Multiply by	Divide by
pounds U_3O_8	metric tons U (tU)	0.8480	2205
pounds	kilograms	0.4536	
metric tons (t)	short tons		0.9078
percent U_3O_8	percent U	0.8480	
miles (mi)	kilometers (km)	1.609	
feet (ft)	meters (m)	0.3048	
inches (in.)	centimeters (cm)	2.540	

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Executive Summary

Uranium in its various chemical and physical forms plays roles in all parts of the nuclear fuel cycle, from the front end of its source from natural geologic resources, through transformation into fuel elements for the power plant cycle to produce electricity, and finally to the back-end cycle of spent-fuel storage in an underground geologic repository. In 2002, uranium has taken on renewed interest in its role in the energy mix for our national energy policy.

At the beginning of the nuclear era in December 1942, the United States became the most thoroughly explored country for uranium and led the western world in production of uranium into the 1960s. During this period, low-cost, low-grade ores near the land surface were mined, leaving deeper, higher cost ores to be mined in later years. The discovery of extremely high grade, near-surface, low-cost uranium ores in other countries, particularly in Canada and Australia, however, has caused domestic U.S. mining and production of uranium to become noncompetitive in the world market. In 2001, the overall activity of the U.S. uranium industry continued to decline. Mining of uranium in the U.S.A. accounted for less than 5 percent of the total needed to produce the current 20 percent of the Nation's electricity. The free-trade agreement of 1988 with Canada assures the U.S.A. of an adequate supply for any emergencies.

The breakup of the Soviet Union in 1991 brought about the entry of the former Soviet Union states into the world uranium market. In 1993, the decision of Europe and the U.S.A. to limit imports and to penalize the price of uranium from Russia and Commonwealth of Independent States (CIS) was made in order to prevent dumping of their extremely large inventories of low-cost uranium mined during the "Cold War," notably from East Germany. As time went on, various amendments to the agreements with each CIS country changed the situation, and by 2002, Russia was the only country under quota restriction, and the price penalty was eliminated because of market forces.

The conversion of Russian and U.S. weapons-grade, highly enriched uranium (HEU) into low enriched uranium (LEU) was agreed upon by Russia and the U.S.A. in 1993. By October 2002, 150 metric tons of Russian HEU with 94 percent U-235 had been blended down to LEU with 4.4 percent U-235 and was shipped to the U.S.A. for use by U.S. utilities. The agreement requires that a total of 500 metric tons of uranium (tU) be converted by 2013. The U.S.A. plans to start converting its HEU in 2010. Agreement has not been made on how to dispose of some 200 metric tons (t) of weapons-grade plutonium (93 percent Pu-239).

Countries with more than 200,000 tU classified as reasonably assured resources (RAR, essentially equivalent to the category of "reserves") are, in order of decreasing RAR: (1) Australia, (2) Canada, (3) Kazakhstan, (4) U.S.A., and (5) South Africa. Since the breakup of the Soviet Union, Kazakhstan has joined this elite group. Its notably large uranium reserves are amenable to in-situ leach (ISL) mining, and, in the future, it could become one of the dominant world producers.

Of the 438 nuclear power plants producing electricity in the world, the U.S.A. had 104 as of January 2002. The total net 1 million watts of electric power (MWe) for the world plants is 353,298 of which the U.S.A. has a total of 97,800 MWe. The efficiency of existing U.S. plants is at an all-time high, and the present cost of a kilowatt of electricity of many nuclear plants is highly competitive with that of coal- and oil-powered plants. Utilities are presently planning to build the new designs of safer, even more efficient nuclear power plants described in this report.

The licenses of existing nuclear power plants in the U.S.A. expire between 2006 and 2035 as reported December 31, 1998 by the Nuclear Regulatory Commission (NRC). The NRC is in the process of extending licenses for an additional 20 years beyond the original 40-year limit. This relicensing may extend the use of many nuclear plants to the middle of the 21st century.

Reprocessing of spent fuel to obtain plutonium-rich material for the mixed oxide (PuU) (MOX) fuel for use in breeder reactors and modified light-water reactors has been banned in the U.S.A. since 1975. In May 2001, this matter was reopened to consider research on and development of reprocessing in order to reduce intensities and volumes of high-level uranium (HLU) waste as well as to increase resistance to weapons proliferation by terrorists. Breeder reactors in France and other countries have proven not to be economical, and they may not be competitive economically until at least 2030.

Several potential geologic sites for a repository for high-level wastes have been investigated in the U.S.A. by the U.S. Department of Energy (DOE). In 1983, Yucca Mountain in southwestern Nevada near the Nevada Test Site, an area used for underground testing of nuclear weapons, was selected as having favorable geologic characteristics for long-term isolation of highly radioactive nuclear wastes. Intensive technical, scientific, and engineering investigations have been conducted to evaluate the suitability of the Yucca Mountain site to host an underground waste repository. Congressional and presidential approvals were given in early 2002 to proceed with license application for the construction of the facility.

In addition to the studies related to radioactive waste storage, geologic research on uranium ores in the past decade has been generally focused on geochemistry relative to environmental problems. The most significant results of this research are in a 14-chapter volume: "Uranium: Mineralogy, Geochemistry and the Environment" by P.C. Burns and Robert Finch, published by the Mineralogical Society of America in 1999.

In 1995, funding for research on geology and resources of domestic uranium ores in the U.S. Geological Survey (USGS) was terminated. Monitoring of worldwide uranium activities was continued at a reduced rate, and results accumulated from past geologic research were prepared for publication. As part of a new project on alternative energy resources begun in 2001, an archival activity of USGS uranium geology and resource assessment file data was undertaken.

The national uranium resource assessment completed by the DOE in 1980 is significantly out of date. A new Federal assessment, using recent developments in uranium assessment methodology and applying new geologic concepts, would greatly aid future planning for the uranium industry and contribute to the formulation of a national energy policy.

Future uranium mining in the U.S.A. will be mainly by ISL mining of large reserves in Tertiary sandstone formations in Wyoming, Nebraska, and Texas. Mining of equally large reserves of uranium in Mesozoic sandstone formations in the Colorado Plateau region is less amenable to ISL. Borehole hydraulic mining is a potential method for vanadium-uranium ores in western Colorado and eastern Utah. Federal research is recommended for both ISL and borehole hydraulic mining technology to aid the uranium industry.

In late 2001, the International Atomic Energy Agency, Vienna, Austria, released its report, "Analysis of Uranium Supply to 2050," which covered both primary sources, such as uranium mining, and secondary sources, such as downgraded HEU, industry/utility pipeline inventories, and MOX fuel. Analyses were made for cumulative worldwide uranium requirements in three basic worldwide cases: (1) high demand, (2) median demand, and (3) low demand. The current worldwide reserves, as estimated in 2001, would fall short in all three of these cases. The long lead times from exploration to production will require greatly increased exploration by 2010 to discover large high-grade ores that can be brought into production by 2025 and to allow orderly reserve increases to 2050.

Introduction

As a result of the consideration of nuclear energy as part of the new National Energy Policy as outlined in the Report of the National Energy Policy Group in May 2001 (accessed July 2000 at URL http://www.whitehouse.gov/energy, Summary of Recommendations, p. 9), uranium became of greater interest as a fuel supply for nuclear power plants to produce electricity in the U.S.A. The present report covers mainly recent developments (mid-1995 to mid-2002) in uranium's role in the national and global energy mix, as was outlined previously in USGS Circular 1141 (Finch, 1997). Emphasis is placed on (1) uranium exploration and production from natural sources and from downgrading of weapons material; (2) analyses of uranium demand and supply; (3) enrichment of U-235; (4) conversion and fabrication of uranium oxide into fuel elements; (5) upgrading of existing nuclear power plants; (6) relicensing of existing plants; (7) development of new nuclear power reactor designs and plans for new U.S. plant construction; (8) reprocessing of spent fuel to yield MOX fuel; and (9) the status of a repository for spent fuel. Each of these topics represents a part of the nuclear fuel cycle (fig. 1). The report concludes with discussions of a review of recent and recommended future research on uranium geology and resources, the archiving of uranium geology and resource data, the future of uranium mining in the U.S.A., and the future of nuclear power in the world.

New and additional data are found on several web sites, including Energy Information Administration (EIA), DOE, Washington, D.C., U.S.A.; International Atomic Energy Agency (IAEA), United Nations, Vienna, Austria; Uranium Information Center (UIC), Canberra, Australia; Nuclear Energy Institute (NEI), Washington, D.C., U.S.A.; and World Nuclear Association (WNA), London, England (see appended Selected Nuclear Energy Web Sites).

Quantitative data regarding uranium resources, demand, and supply are expressed in two different weight systems: (1) internationally, in metric kilograms U (kgU), and in metric tons U (tU) (NEA/OECD, 2002); and (2) nationally, in pounds U_3O_8 and short tons (2,000 pounds) U_3O_8 (EIA, 2002). In the present report, both systems are used as given originally in the referenced sources. Conversion from pounds U_3O_8 to tU is made by using the following: tU = pounds U_3O_8 times 0.8480 divided by 2,205 pounds. For an easy rough comparison of pounds U_3O_8 and tU, simply divide by 2,000. See Conversion Factors table on page iv.

Demand and Supply of Uranium

The annual uranium requirements for the 438 operating nuclear power plants in the world in 2001 were about 64,000 tU (NEA/OECD, 2002). Furthermore, with a worldwide total of 32 reactors under construction in 2001, the Nuclear Energy Agency/Organization for Economic Cooperation and Development (NEA/OECD) expects the requirements to either

PROCESS	MATERIAL/PRODUCT
FRONT END	
Mining/milling	Yellowcake U_3O_8
Conversion	UF_6 gas 0.71% U-235
Enrichment	0.71% U-235 → 3.3% U-235 in UF_6 liquid (SWU). Depleted UF_6 = 0.20% U-235 (tails assay).
Conversion	UF_6 → UO_2 powder → UO_2 pellets
Fabrication	Fuel rods in Zr alloy
IN PLANT	
Nuclear steam/electric plant	Fuel → Electricity → Spent fuel UO_2 → U + Pu
	Interim surface storage in H_2O
BACK END	
Reprocessing	Spent fuel → Pu-U mixed oxide (MOX) fuel
Waste disposal	High-level radioactive waste (HLW) repository in underground geologic facility.

Figure 1. The nuclear fuel cycle (modified from Finch, 1986; 1997, see fig. 2 for detailed lifetime cycle for a light-water reactor). SWU=separative work units.

rise to about 80,250 tU in the high-case projection or decrease to about 58,000 tU in the low-case projection by year 2020. In January 2002, the 104 nuclear power plants in the U.S.A. generated 20.4 percent of the Nation's electricity (IAEA, 2002), requiring about 18,000 tU annually.

There were no reactors under construction in the U.S.A. in March 2002. The probability of new construction by 2010 (discussed below) would increase the uranium requirements for newly mined uranium ore. The world production in 2001 was about 37,000 tU (NEA/OECD, 2002). In the U.S.A., 2001 production was about 1,000 tU from low-grade (0.03–0.25 percent U) roll-front sandstone ores. The remaining supply of U.S. uranium was imported mostly from Canada and Australia, produced primarily from high-grade (1–12 percent U) unconformity-related vein ores (Vance, 2002; Grubbs, 2002). Increasing production in the U.S.A. is not expected to satisfy demand, because at present U.S. deposits cannot compete economically with high-grade, low-cost foreign sources. For example, the McArthur Lake deposit in eastern Athabasca Basin, Canada, has geological reserves of 416,000,000 pounds of U_3O_8 with an average grade of 15 percent U_3O_8, which includes 189,000,000 pounds of U_3O_8 with an average grade of 19 percent U_3O_8 (McGill, 1999). The deposit is at a depth ranging from 1,500 to 2,000 ft and requires special mining techniques because of its high grade. Mining began in late 1999 and reached its rated annual capacity of 18,000,000 pounds of U_3O_8 in late 2000 (Pool, 2000, 2001).

Reasonably Assured Resources of the World's Uranium

Reasonably assured resources (RAR, internationally used term and essentially equivalent to the term "reserves" used by DOE prior to 1982; see EIA, 2002, Table B1, p. 38, for historical comparison of uranium resource terms) of uranium refers to known uranium ore deposits of delineated size, grade, and configuration that could be recovered in a cost range using current mining and processing technology. RAR at a cost category of less than \$80/kgU/\$40 pound U_3O_8 for various countries in the world are shown in table 1. Countries with more than 200,000 tU RAR in decreasing order of RAR are (1) Australia, (2) Canada, (3) Kazakhstan, (4) U.S.A., and (5) South Africa. Compared with the list in USGS Circular 1141 (Finch, 1997, table 2) for 1993 before the breakup of the Soviet Union, there are several new players, namely Kazakhstan, Russian Republic, Ukraine, Uzbekistan, and Mongolia. Of these, Kazakhstan, with its notably large reserves amenable to ISL mining, could be a dominant world producer in the future. Recently released development plans show that the present annual production of 2,020 tU will be 15,000 tU by 2030 (Rocky Mountain Minerals Scout, 2002).

RAR for various regions and States are as follows: the Colorado Plateau (western Colorado, eastern Utah, northeastern Arizona, and northwestern New Mexico) 120,500 tU, Wyoming basins 112,700 tU, Florida 37,700 tU (byproduct from phosphoric acid fertilizer processing of phosphorite deposits, recovery of uranium not being done at present), western Nebraska 14,700 tU, Colorado Rocky Mountains and High Plains 10,600 tU, Texas Gulf Coast 7,600 tU, Virginia 7,300 tU, and Nevada/Oregon border 7,300 tU (IAEA, 2001b, totals from data in Table LXXXVIII). Deposits in Tertiary host formations in Wyoming, Nebraska, and Texas can be mined by ISL. Uranium deposits in Mesozoic formations are less amendable to ISL. Borehole mining is a possible method of mining Colorado Plateau uranium ores (see below). Conventional open-pit and underground mining is too costly under present economic conditions.

United States Uranium Industry in 2001

The overall activity of the U.S. uranium industry continued to decline in 2001 (EIA, 2002). Exploration for uranium ores continued to be nonexistent, and development drilling of uranium reserves for ISL mining decreased markedly as production decreased. Uranium production in 2001 was 2,600,000 pounds U_3O_8, a decline of nearly 60 percent since 1999. About 93 percent was from ISL mining. Some 55,000,000 pounds U_3O_8 were purchased for civilian nuclear power reactors by the public utility companies, mainly from foreign suppliers, compared to requirements for the reactors of about 53,000,000 pounds. The average price paid was $10.15 per pound U_3O_8. Imports, in pounds U_3O_8, were from Canada 17,120,000, Australia 10,314,000, Russia 5,042,000, Kazakhstan 3,149,000, Uzbekistan 2,643,000, South Africa 2,022,000, and Namibia 568,000, for a total of 42,279,000 (EIA, 2002, table 12, p. 21). The inventory held by utilities at the end of 2001 was nearly 56,000,000 pounds, a 15 percent decrease from the 1998 level. A large inventory level has been maintained by the utilities since the late 1980s for various reasons related to the dynamics of the uranium market and supply cycles (TradeTech, 2001a). Uranium reserves reported to EIA by the mining industry are estimated to be about 268,000,000 pounds U_3O_8.

Uranium Market Prices

The uranium market is complex, for there is a market for the three basic uranium fuel products: (1) U_3O_8, (2) UF_6, and (3) Separative Work Units (SWU, amount of work to separate isotopes U-235 and U-238 expressed in US$/kgU as UF_6, fig. 1). The principal market for U_3O_8 has two prices: (1) the spot-market price for a relatively small quantity of uranium as a single delivery within a given year, and (2) the long-term contract price for substantial quantities of uranium to be delivered over a multiyear period of time. Both prices are

Table 1. Reasonably assured resources (RAR) of metric tons (tU) uranium, at a cost category of less than $80/kgU or $40/pound U_3O_8, for various countries of the world (IAEA, 2001a, summed from data in Table LXXXVIII; sources of data: The Red Book, IAEA, 2001a, and consultants).

Country	Metric tons uranium
Australia	590,400
Canada	535,700
Kazakhstan	431,600
United States	316,600
South Africa	243,700
Niger	193,500
Brazil	154,800
Russian Republic	152,900
Namibia	123,300
Ukraine	95,700
Uzbekistan	80,500
Mongolia	73,000
Other 6 countries	30,000–10,000 each (total 114,100)
Other 16 countries	10,000–1,000 each (total 86,700)
Total 34 countries	3,192,500

mostly for raw, newly mined uranium from the mill, uranium-oxide known as "yellowcake," but in some cases are for material from an inventory. For geologic supply and resource research, these market prices are of primary interest. The relation between spot and long-term prices varies, but generally long-term prices are greater than spot-market prices (TradeTech, 1995). From 1991 to 2001, the spot price for former Soviet Union material was penalized by a lower price (see two-tiered price system below). There are also market prices for UF_6 converted material and for enriched uranium products (EUP) based on enrichment services called Separated Work Units (SWU) (fig. 1).

The spot-market price of uranium is a dominant factor in determining profitable uranium mining, particularly in the U.S.A. Utilities buy uranium based on the relation of spot-market price for small low-cost inventory supply to long-term higher price contracts from new mine production. The spot-market price fell to a low of $7.25/pound of U_3O_8 in October 1991 and rose to $16.50 in May 1996 (Pool, 1996, 1997; TradeTech, 2001b). Since 1996, there was a steady decline to $8.10 by the end of 1998 (Pool, 1998, 1999). In 2002, the spot prices have been increasing, reaching $9.75 by October 3 (Mining Journal, 2002). The U.S.A. has a large uranium mining potential from numerous, relatively small and low-grade ores, but prices of $15–20/pound U_3O_8 would be necessary to markedly increase domestic production (Pool, 2001).

Long-term delivery contract price was about $16.50 per pound U_3O_8 in April 1996 (TradeTech, 1996a), and in September 2001, it was $10.50 per pound (TradeTech, 2001a).

Uranium Production

Historically, world production of uranium, which began in 1948, has been cyclic with peaks in 1959, 1980, and 1988 (fig. 2). The drop from the 1959 peak reflects a large decrease in military demand for uranium. The production increases in the late 1970s reflect growing peaceful use of uranium to produce electricity as the number of nuclear plants being built increased. In the 1980s, uranium production again peaked with the increasing number of nuclear power plants around the world. The largest number of new electric plants was built in the U.S.A. The peak in 1988 was due to the reporting of newly available production data from former Soviet Union states, and did not represent a large overall increase in annual worldwide production (NEA/OECD, 2002). Prior to 1988, the production data shown in figure 2 are only for OECD (Western World) member countries. Prior production from Soviet Union countries was on the order of 100,000 tU from Russia (now Russian Federation), 80,000 tU from Kazakhstan, and 90,000 tU from Uzbekistan (interpretation of data in table 9, NEA/OECD, 2002). Most of this production, as well as

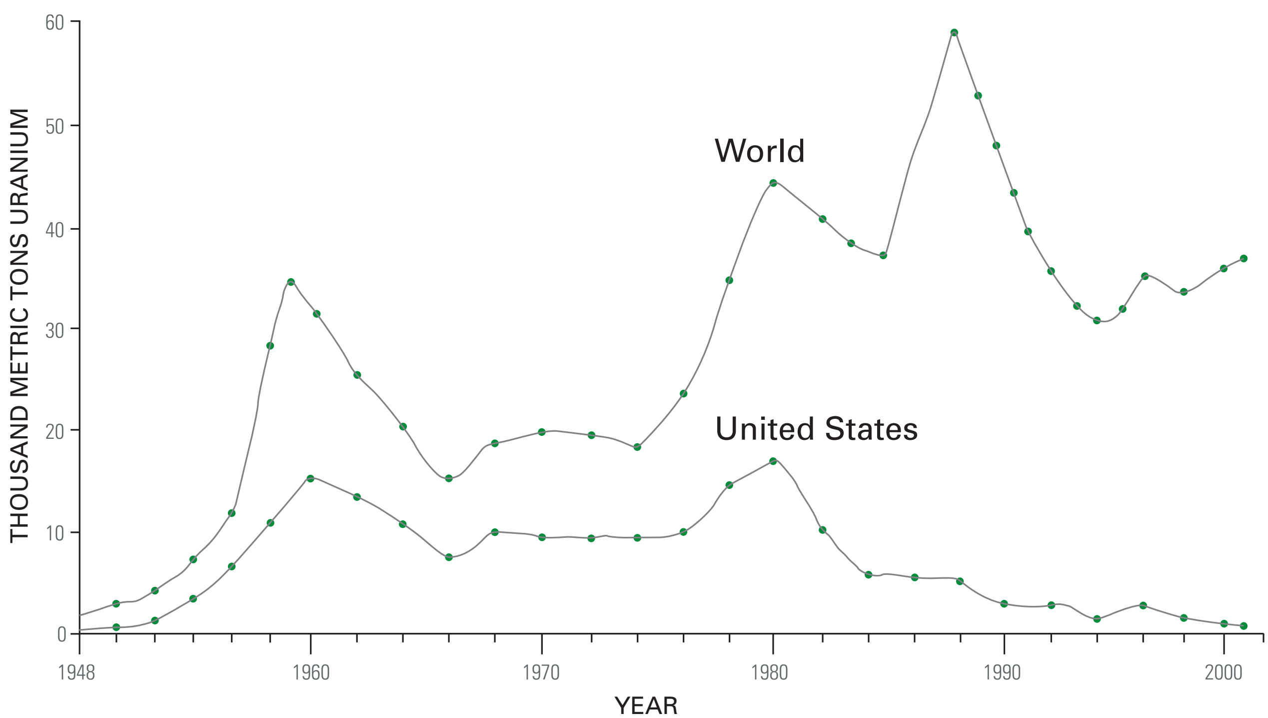

Figure 2. World production of uranium 1948–2001 (NEA/OECD Red Books; EIA Uranium Industry Annuals; EIA, 1998a, 2002).

200,000 tU from GDR (East Germany) went into Soviet Union nuclear weapons during the “Cold War.” This uranium is now entering the world uranium market from the downgrading of HEU weapons material. The steep drop of production, beginning in 1989 and continuing to 1995, was due mainly to the great buildup of consumer and national inventories of uranium during the earlier 1980s that was accompanied by large decreases in the price of uranium (White, 1989; Pool, 1991)—the price of uranium decreased from $16.75 in November 1986 to the $9–10 range in 2001.

World uranium production in 2000 was 36,112 tU, which provided 56 percent of the world requirements of about 64,000 tU, compared to 35,000 tU in 1998, which provided 60 percent of the 60,000 tU requirement (NEA/OECD, 2002). Major producers were Canada 10,687 tU, Australia 7,759, Niger 2,915, Namibia 2,715, Russian Federation 2,760, Uzbekistan 2,028, Kazakhstan 1,870, and U.S.A. 1,522 tU. Total world production from 1948 to 2001 was 1,937,822 tU of which 1,003,099 tU was from OECD countries (NEA/OECD, 2002).

The U.S.A. was the world’s leading producer of uranium from 1950 to 1980 (fig. 2), but since 1980 the proportion has grown smaller. In 1959, the U.S.A. produced about 15,000 tU of the total world production of 34,000 tU; in 1980, about 17,000 tU of the world total of 44,000 tU; in 1988, about 5,000 tU of the peak world total of nearly 60,000 tU; and in 2001, only about 1,000 tU of the total of 37,800 tU (EIA, 1999, 2002). The latter is the lowest level of U.S. production since the earliest years of mining (fig. 2).

During the peak U.S. production, mining was from both underground and open-pit operations; these ores were processed in 25 conventional mills using either acid or alkaline metallurgy. In 2002, there were no mills operating in the U.S.A., but five inactive mills were on standby—two in Utah, one in Washington State, one in New Mexico, and one in Colorado (EIA, 2002). In 2002, all uranium mining was done by the ISL method.

The low price of uranium oxide has caused most uranium mines in the U.S.A. to close, not open as scheduled, or be placed on standby. In December 2001, only three uranium mines were operating, all by ISL mining of low-grade (0.03–0.20 percent U_3O_8) roll-front sandstone ores (Rocky Mountain Minerals Scout, 2002). Two of the mines were in the Powder River Basin in Wyoming—the Rio Algom Smith Ranch (1,200,000 pounds U_3O_8 produced in 2000) and the Power Resources, Inc. Highland (900,000 pounds U_3O_8 produced in 2000)—and the other is to the southeast in Nebraska, where Crow Butte Resources continued to mine and produce at an annual rate of 800,000 pounds of yellowcake. These three properties yielded 2,900,000 pounds U_3O_8 out of the total U.S. production of 4,100,000 pounds in 2000 (Pool, 2001). Milling of stockpiled high-grade Schwartzwalder (mine closed) uranium vein ore at the Cotter Mill in Canon City, Colo., accounted for the rest. The total production in 2001 is expected to be 2,800,000 pounds U_3O_8 (Pool, 2001).

Former Soviet Union States Imports

The breakup of the Soviet Union in 1991 brought about the entry of the former Soviet Union states into the world uranium market. In 1993, the decision was made by the U.S.A. and Europe to limit imports and to penalize the price of uranium from former Soviet Union states because of their extremely large inventories of non-profit-produced, low-cost uranium (EIA, 1998b). The anti-dumping quotas on imports from the Russian Federation, as well as from the other CIS countries to the U.S.A. would be limited to 4,000,000 pounds U_3O_8 each year until year 2003, subject to the same amount being matched by new U.S. production (Pool, 1994, 1998). Imports from Russia and the CIS countries of Ukraine, Kazakhstan, and Uzbekistan were assessed a penalty of about $2.50 per pound of U_3O_8, which lowered the normal unrestricted price to the restricted price of CIS-origin material (TradeTech, 1996b). As time went on, various amendments to agreements with each CIS country changed the original arrangements, and market forces lowered the penalty so that the two-tiered price system was abandoned in 2001. Quota restrictions, which are slated to expire in 2004, remain only on imported uranium from the Russian Federation (Pool, 2001). In 2001, U.S. utilities purchased 5,042,000 pounds U_3O_8 from Russia, 3,149,000 pounds from Kazakhstan, and 2,643,000 pounds from Uzbekistan (EIA 2002, Table 12, p. 21).

Conversion of Highly Enriched Uranium

In 1993, the Russian Federation and the U.S.A. signed a formal agreement for the conversion of 500 t of HEU extracted from Russian weapons into LEU to fuel reactors to produce electricity over a 20-year period (1993–2013) [U.S. Enrichment Corporation (USEC), www.usec.com, Megatons to Megawatts Program]. This conversion begins in Russia with fluorination of HEU oxide with 94 percent U-235 from the warhead to hexafluoride HF_6 and mixing it with a HF_6 of about 1.5 percent U-235 (enriched tails) and blending down this mixture by a gaseous diffusion process to LEU of 4.4 percent U-235. The resulting HF_6 gas is placed into 2.5 ton steel cylinders to be shipped from St. Petersburg to New Orleans and barged up the Mississippi to the Paducah, Ky., USEC plant on the banks of the Ohio River. In the plant, the HF_6 is converted to UO_2 fuel for fabrication into fuel rods. A HEU transparency program is in place to ensure that the LEU from Russia was actually derived from weapons material. As of October 2002, 150 t of weapons-grade material (equal to 6,000 warheads) have been blended to LEU (USEC Press Release, October 3, 2002, accessed July 2001 at www.usec.com). The original agreement as regards to the amount paid Russia for their uranium has been amended several times, but as of January 2003, it will be the U.S.A. market price. The U.S.A. does not plan to convert its HEU until 2010 (Pool, 2001).

Weapons-grade (93 percent Pu-239) plutonium amounts to between 150 and 200 metric tons ("Nuclear Warheads as a Source of Nuclear Fuel," accessed at www.uic.com.au). No firm agreements between Russia and U.S.A. have been concluded as to the use of this plutonium. Most likely, it will be made into (Pu) MOX fuel, but, in the U.S.A., it could be treated as high-level waste and placed in an underground repository.

Nuclear Power Plants

Operating Plants

In April 2001, there were 438 nuclear power plants in the world (IAEA, 2001b), generating a total net MWe of 351,327 (table 2; see Finch, 1997, table 3, for comparison as of April

Table 2. Status of nuclear power plants around the world as of April 2001 (IAEA, 2001a). MWe, 1,000,000 watts of electric power.

	Reactors in operation		Reactors under construction	
Country	**No. of units**	**Total net MWe**	**No. of units**	**Total net MWe**
Argentina	2	935	1	692
Armenia	1	376		
Belgium	7	5,712		
Brazil	2	1,885		
Bulgaria	6	3,538		
Canada	14	9,998		
China	3	2,167	8	6,420
Czech Republic	5	2,569	1	912
Finland	4	2,656		
France	59	63,103		
Germany	19	21,122		
Hungary	4	1,729		
India	14	2,503		
Iran			2	2,111
Japan	53	43,691	3	3,190
Korea, Rep. Of	16	12,990	4	3,820
Lithuania	2	2,370		
Mexico	2	1,308		
Netherlands	1	449		
Pakistan	2	425		
Romania	1	650	1	650
Russia	29	19,843	3	2,825
South Africa	2	1,842		
Slovak Republic	6	2,408	2	776
Slovenia	1	632		
Spain	9	7,470		
Sweden	11	9,432		
Switzerland	5	3,079		
United Kingdom	35	12,968		
Ukraine	13	11,207	4	3,800
United States	104	97,145		
World totals*	438	351,327	31	27,756

*These totals include Taiwan, where six reactors totaling 4,884 MWe are in operation, and two units totaling 2,650 MWe are under construction.

1994). The U.S.A. had 104 plants in operation with a total net MWe of 97,145, about 28 percent of the world capacity. Those countries generating more than 20,000 MWe annually were France with 63,103, Japan with 43,691, and Germany with 21,122. Russia generated 19,843 MWe, and Armenia was the smallest with 376 MWe.

The graph in figure 3 shows the nuclear power plants' share of electrical generation in percent of the national totals as of April 2001 for 30 countries of the world (IAEA, 2001a; see Finch, 1997, fig. 7, for comparison as of December 1993). The four largest shares were 76.4 percent (63,103 MWe) for France, which transmitted some of its electricity to nearby countries; 73.7 percent (2,370 MWe) for Lithuania; 56.8 percent (5,712 MWe) for Belgium; and 53.4 percent (2,408 MWe) for Slovak Republic. The U.S.A. was 19.8 percent (97,145 MWe). Power plants under construction totaled 31 with a total rating of 27,756 MWe.

In recent years, utilities in the U.S.A. have looked more favorably toward nuclear-produced electricity, because of greater efficiency and relatively lower generating costs (fuel costs are a minor proportion of the total generating costs); also, refueling is done on a yearly basis, and the refueling length of time has become much shorter. From an environmental standpoint, nuclear power plants do not emit greenhouse gases; they are environmentally clean with respect to acid rain, global warming, and ozone depletion. If nuclear plants were substituted for coal-fired plants, these environmental problems would be measurably lessened.

The U.S. nuclear power industry achieved record power-generation levels in 1999 and 2000, increasing from 728.1 billion kilowatt hours (kWh) to 753.9 billion kWh (EIA Press Release, March 15, 2001). These records compare to 577.0 billion in 1990 when 111 power plants were in operation as compared to the 103 plants in 2000. Slightly more than 100 billion kWh were recorded in 1974.

The average capacity factor (ratio of electricity actually produced to full-power operation) for the 103 U.S. reactors in 2000 was 87.2 percent compared to 76.41 percent worldwide (TradeTech, 2001b). South Korea had a 90.4 percent capacity for its 16 reactors that generated 789,000 gigawatt hours (GWh) (TradeTech, 2001b).

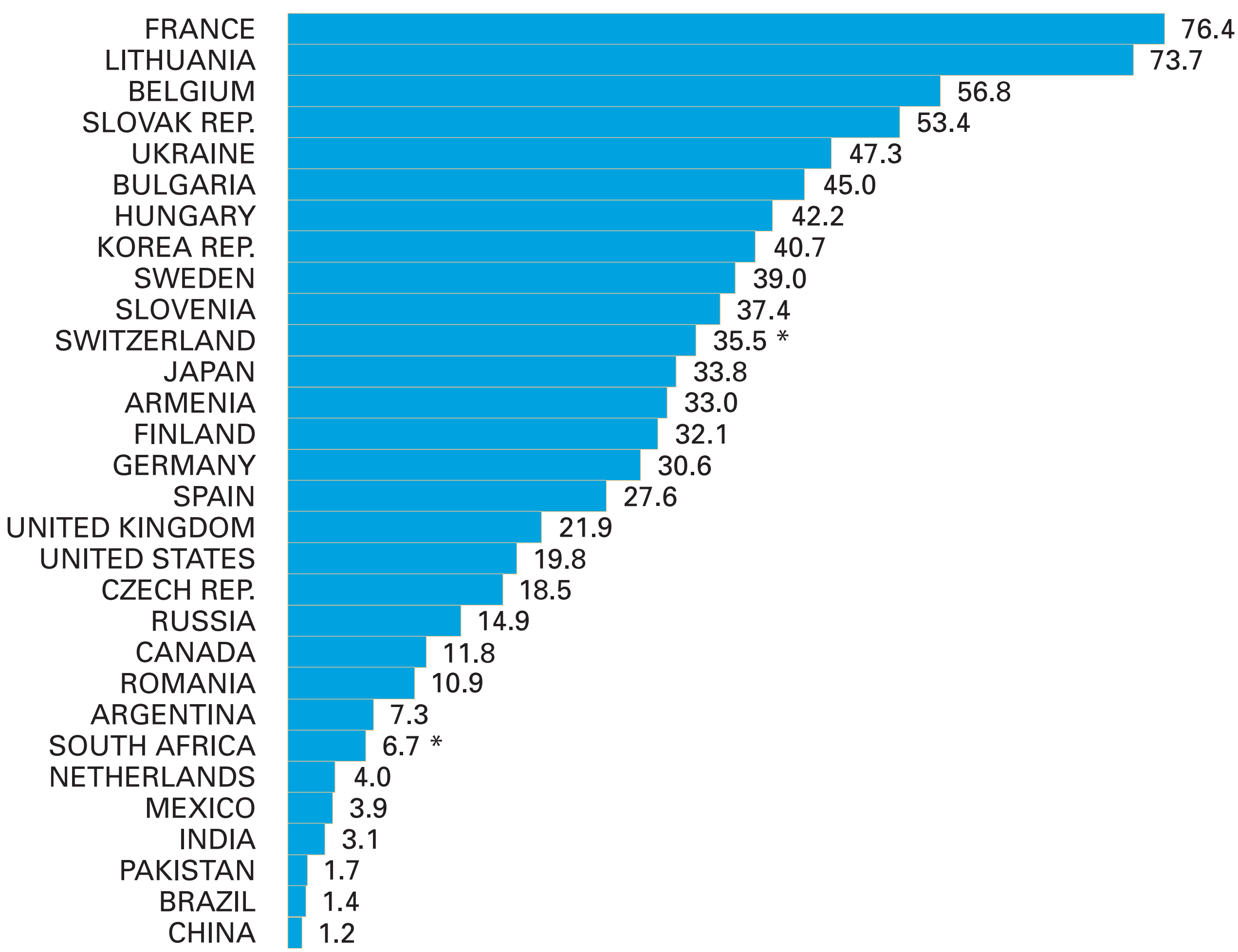

Figure 3. Nuclear power plant share of electrical generation (in percent of national totals) as of April 2001 for countries of the world (IAEA, 2001a). Note that the share for Taiwan was 23.64 percent in 2000. Asterisk (*) indicates estimates.

Refueling times have declined markedly in recent years, which increases power generation. A U.S. national record for the shortest refueling time for boiling water reactors of 15 days, 16 hours, and 45 minutes was set in November 2000 (Exelon Nuclear Press Release, November 6, 2000, www.exelonnuclear.com); the national average in 2000 was 38 days.

The median cost to generate electricity by nuclear reactors in the U.S.A. was 0.521 cents/kWh in 2000 (Mining Journal, 2001). Over a 3-year period ending in 2000, the Duke Power Catawba Nuclear Station established a record of 0.423 cents/kWh (Duke Power Press Release, July 23, 2001, www.duke-energy.com).

Relicensing Extensions

The distribution of the license expiration years for the 104 U.S. nuclear power plants from 2006 through 2035, as reported on December 31, 1998 (EIA, 1998a), is shown in figure 4. From 2012 to 2016, 35 licenses are due to expire and from 2024 to 2027, 27 licenses are due to expire, together well over one-half of the plants. The extension of these plants for 20 years would extend nuclear energy close to the midpoint of the 21st century.

Relicensing or license extensions beyond the original 40-year limit imposed by the Atomic Energy Act of 1954 for an additional 20 years was started in 1998 by the NRC

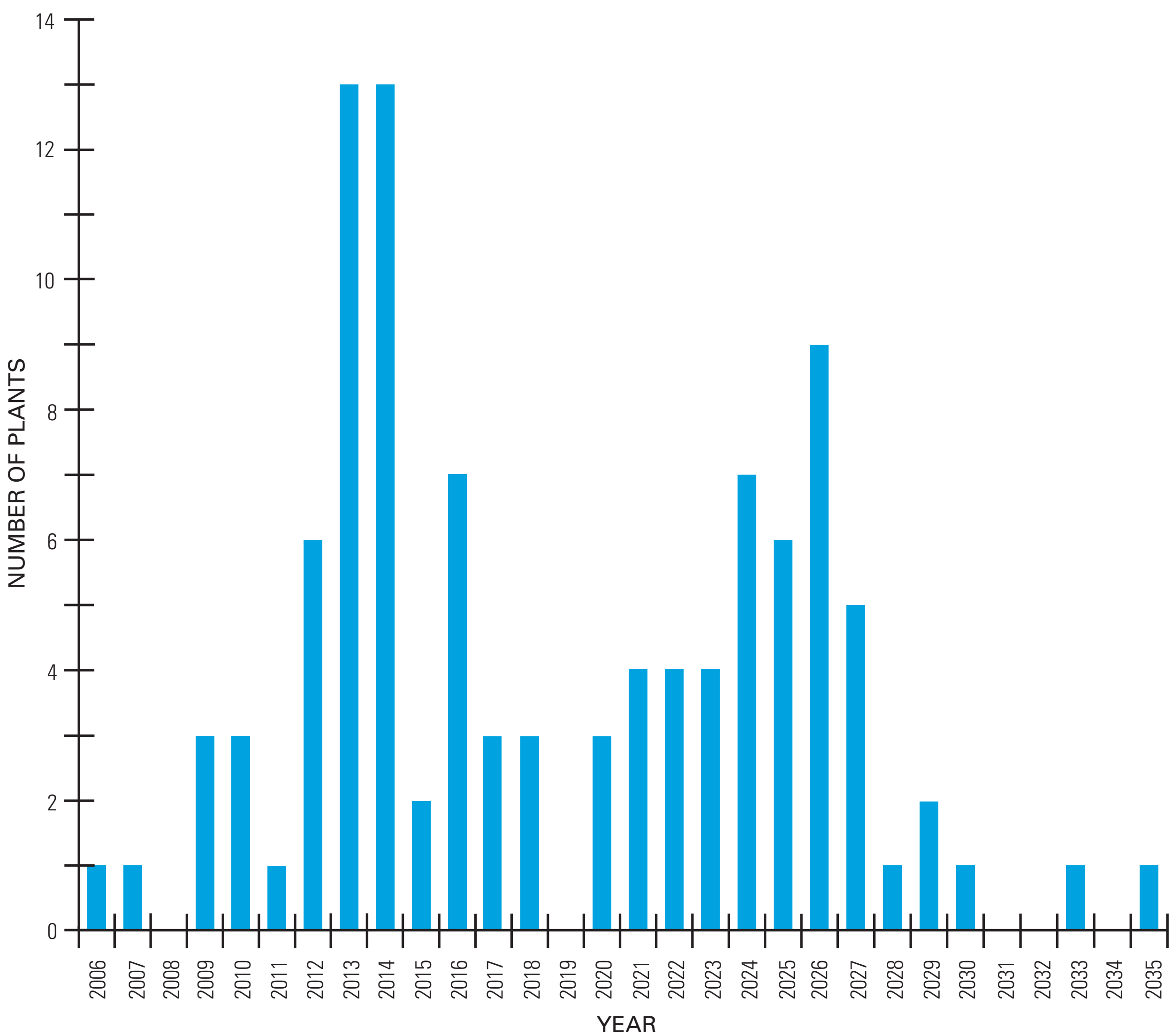

Figure 4. Distribution of license expiration dates for 104 United States nuclear power plants from 2006 to 2035 as of December 31, 1998 (EIA, 1998a).

(TradeTech, 1998; Radsafe, 2001a). These original license time limits were based on economic and antitrust considerations and not on technical limitations of the power plants themselves. The process followed by the NRC to extend licenses consists of environmental and technical reviews. A "Generic Environmental Impact Statement" for license renewal was developed in December 1996 to facilitate timely environmental review (NRC Regulations 10 CFR parts 51 and 54; TradeTech, 1998, 2000; U.S. NRC, 1998). An Aging Management Program was established to monitor the condition of critical equipment and structures in each nuclear plant so repairs and (or) replacement would be done before any license renewal application (NRC Regulations 10 CFR part 54; TradeTech, 1998, 2000). In 2000, NRC approved license renewals of 20 years for six units at each of three plants (two extended to 2033, three to 2034, one to 2038) (NRC Press Release No. 20-004, February 19, 2002, accessed at www.nrc.gov, February 19, 2002). Fourteen additional units at seven plants were under review in 2000. Twenty-eight more license renewal applications are expected by 2004 (EIA Press Release, March 15, 2001). No plants were relicensed in 1998 and 1999.

Advanced Nuclear Reactors

A new generation of light-water nuclear reactors has been developed that received standardized (fuel = 3–4 percent U-235) final generic design certification by the NRC (Uranium Information Center Ltd., 2001). They are simpler and more rugged, of standardized design, and easier to operate and less vulnerable to operational problems, have higher burn-up to reduce fuel costs and waste, and possess longer operating life (as many as 60 years) than the present first-generation reactors. Two second-generation reactors are large evolutionary reactor designs based on prior U.S. experience: (1) the General Electric Advanced Boiling Water Reactor (ABWR, 1,300 MWe) in commercial operation in Japan; and (2) the ABB-Construction advanced pressurized water reactor (PWR, System 80, 1,300 MWe), of which eight are in operation in Korea. A third, smaller advanced reactor is the Westinghouse passive safe AP-600 (600 MWe) that received approval of final design in December 1999. A scaled-up AP-1000 is under development. These reactor designs have fully resolved safety status and are not subject to legal challenge during licensing. A NRC license for construction and operation can be obtained before construction begins. Firm information on construction costs and schedule to build have been developed by DOE. These reactors can be built in 3–4 years. New advanced reactor designs have also been developed in Europe (Uranium Information Center Ltd., 2001).

The breeder reactor (one that both consumes fissionable material and creates new material by a process known as breeding) probably will not be economically competitive in the electricity market until after 2030 (Oi and Wedekind, 1998).

A New Revolutionary Reactor Concept

Designs for a new revolutionary high-temperature (HTR), helium-gas-cooled, pebble-bed nuclear power reactor, a concept under development by various competing groups for decades, were recently completed by a Massachusetts Institute of Technology research team (accessed July 2001 at URL http://www.mit.edu/pebble-bed; Uranium Information Center Ltd., 2001; for best illustrations see Time, 2001). The pebble-bed reactor utilizes heated helium (as much as 950°C) to propel the turbine to generate electricity rather than steam as in the standard light-water reactors. A "pebble" is a ball about 60 mm (about 2.4 in.) in diameter with a kernel or core of uranium oxycarbide grains (enriched to about 8 percent U-235) enclosed by a "containment center" (stable to 2,000°C) and by successive layers of (1) innermost carbon buffer, (2) silicon carbide, (3) pyrolytic carbon, and (4) outermost shell of graphite. Within the reactor vessel, the reactor core contains as many as 450,000 pebbles. The core (bed) is surrounded by helium that is heated by the nuclear reaction within the pebbles and piped to the turbine to generate electricity. Similar to light-water reactors, the helium is cooled by water and returned to the reactor core to be heated again. Test pebble-bed reactors (capacity 110 MWe) are being built near Cape Town, South Africa, by the Exelon Corporation (Uranium Information Center Ltd., 2001; Talbut, 2002).

New Power Plants Planned for Construction in the United States

Three new companies—Entergy Corp., New Orleans, La.; Exelon Corp., Chicago, Ill.; and Dominion Resources, Waterford, Va.—are consolidating nuclear power sites into major blocks to produce nuclear energy (Radsafe, 2001b). They have plans to build additional nuclear power units at existing sites because transmission lines are already established and less regulatory review is needed to start construction (Hartford Courant quoted in Radsafe, 2001b). The new plants would be built using new designs already approved by the NRC that are simpler, safer, and quicker to build. The NRC has an early-siting process that takes about 1 year to complete and allows for a 20-year period in which to complete construction. Construction will take 3 years and full power would be established within 1 year. Permit applications for as many as nine new plants could be made within a year or so. Decisions will be based on existing electricity demand and on political and economic conditions.

Reprocessing of Spent Fuel and Breeder Reactors

Spent fuel from nuclear power reactors can be reprocessed to obtain plutonium-rich material for MOX fuel for use in breeder and modified light-water reactors. In 1974, after much discussion by industry and Federal Government officials (Finch and others, 1975), the U.S.A., by presidential order, decided not to pursue research on the breeder reactor and on reprocessing spent fuel because of fears of proliferation of nuclear weapons by terrorists (Stover, 1995). Thus, plutonium in spent fuel became a high-level waste instead of a potentially useful product. These decisions were continued until May 2001, when research on and development of reprocessing was reopened for examination to reduce high-level waste volumes and intensive radioactivity as well to increase resistance to weapons proliferation by terrorists (Von Hippel, 2001).

Outside the U.S.A., "fast-breeder" reactors, which create more plutonium-rich fuel than consumed, have not proceeded to commercialization as originally expected, even though research in some countries continues (Von Hippel, 2001). Only the French have built two experimental breeders, but their performances have not proven to be commercial so interest in the breeder reactor has waned. Breeder reactors may not be competitive in the electricity market until after 2030 (Oi and Wedekind, 1998).

Status of a Repository for Spent Fuel Waste

Yucca Mountain in southwestern Nevada is the location of the proposed site for the long-term (more than 10,000 years) repository for spent nuclear fuel and other high-level radioactive waste (Bodvarsson and Tsang, 1999; Bodvarsson and others, 1999). It is projected to store 77,100 tons of spent fuel from the existing commercial reactors by 2020 (National Research Council, 1999) and as much as 85,000 tons by 2035 (T.C. Pool, Nuclear Fuels Corp., written commun., *in* Odell, 2002) because of license extensions (see above). The addition of military high-level-waste (HLW) is estimated to be about 3 percent of the amount of commercial spent fuel (National Research Council, 1999).

In 1982, DOE initiated an intensive investigation to determine the viability of Yucca Mountain as a repository facility, based in large part on USGS studies of unsaturated-zone rocks in the adjacent Nevada Test Site for underground testing of nuclear weapons (Hanks and others, 1999). A large number of Federal, State of Nevada, university, and industry scientists and engineers have examined the geology, hydrology, geophysics, and geochemistry of rock formations in the semi-arid Yucca Mountain area.

Yucca Mountain is an uplifted ridge of unsaturated welded and nonwelded silicic volcanic tuff of Miocene age within a region of extensional tectonics, characterized by the presence of numerous normal faults, some of which show movements as young as a few thousand years ago (Stuckless, 2002; Stuckless and Dudley, 2002). The potentiometric surface beneath Yucca Mountain is relatively flat and water movement is extremely slow (8–20 mm/yr; National Research Council, 1999), and geochemical retardation by exchange by zeolite and other minerals in the unsaturated zone provides a natural barrier to contaminant movement in pore water. These two characteristics contribute to long-term isolation of radioactive wastes in the unsaturated zone (Stuckless, 2002). The waste can be placed in robust bimetallic canisters in underground space about 300 m below the ridge surface and about 300 m above the water table (Levich and others, 2002).

Although the Viability of Total Systems Performance Assessments (U.S. Department of Energy, 1998) supports the development of Yucca Mountain as a geologic repository, there are significant concerns that remain to be addressed (Hanks and others, 1999). For example, there are questions about control of heat generation by radioactive waste and the lack of understanding of moisture changes over time, if the walls were concreted, that need to be further addressed. Also, Dyer and others (2002), of the Yucca Mountain Site Characterization Office, discussed the latest developments concerning the likelihood of the occurrence of volcanic activity (also see Smith and others, 2002), transport of radionuclides in water through the unsaturated zone, and potential radionuclide transport in the saturated zone some 1,000 ft below the level of the planned repository; they outlined unfinished experiments to be completed in future years before containment. Additional concerns have been raised by Steve Frishman (2002) and by Don L. Shettel and Maury E. Morgenstein (2002), all from Nevada institutions, about the effectiveness of the engineering barrier system. On the other hand, Levich and others (2002) reported that studies to date indicate that the natural geologic system combined with supporting engineered barriers would provide a safe environment to isolate nuclear wastes.

Despite some as yet unresolved issues, the technical, scientific, and engineering investigations at Yucca Mountain have progressed to the point that congressional and presidential approvals were given in early 2002 (see Pianin, 2002) for DOE to proceed with applying for a license from NRC to construct a waste facility at the site.

Recent and Future Research on Uranium Geology and Resources

Geology

Worldwide geologic research on uranium in the latter part of the 20th century was focused primarily on (1) environmental remediation of mine, mill, and processing sites; and (2) issues related to finding a suitable repository for high-level nuclear waste in geologic settings.

The preparation of a short course on "Uranium: Mineralogy, Geochemistry and the Environment," sponsored by the Mineralogical Society of America in 1999, resulted in an in-depth reference book (Burns and Finch, 1999), with contributions from numerous authors representing U.S. and foreign universities, and in addition the Argonne National Laboratory, Southwest Research Institute (San Antonio, Texas), the British Geological Survey, and The National Museum in the Czech Republic. Funding other than from the institutions of residence for these endeavors came from the DOE, NRC, British Geological Survey, Polish Research Committee, and Czech State Department. A foundation for appreciating recent research is laid in the first chapter—"Radioactivity and the 20th century"—historic research after the discovery of radioactivity in 1896. The book presents research results, mainly since 1990, on (1) uranium crystal chemistry, systematics and paragenesis, isotopic geochemistry, and geomicrobiology of uranium minerals; (2) genesis of uranium ore deposits; (3) geochemical behavior of uranium and other actinides in natural fluids; (4) environmental aspects of ground-water contamination; (5) mineralogy of spent fuel; and (6) disposal of nuclear wastes. Such topics cover the mineralogy of all three parts of the nuclear fuel cycle (fig. 1). The volume concludes with in-depth descriptions of various updated analytical techniques applied to uranium phases of natural and man-made occurrences. Reviews of this volume by Donald Langmuir (2001) and K. Morris (2001) gave good perspectives of the book and are worthy of being consulted.

Future research on the mineralogy and geochemistry of all aspects of the nuclear fuel cycle needs to be continued by both academic and government institutions. Burns and Finch in their preface of the volume stated "***importantly, the reader may develop a sense of the tremendous amount of work that remains to be done, not only concerning uranium in the natural systems, but for low-temperature mineralogy and geochemistry in general***."

Detailed mineralogical studies of roll-front ores in Wyoming and Nebraska by Stewart and Reimann (2002), sponsored by Power Resources, Inc., have provided essential information for increased economic recovery of ISL-mined uranium ore (Stewart and others, 2000). Furthermore, these authors combined mineralogy with water chemistry to provide a predictive model for restoration of post-mine water in the ore-bearing aquifer. This is an example of potential research for future USGS uranium programs to aid the uranium mining industry.

Funding for research on geology and resources of domestic uranium ores in the USGS was terminated in 1995, but the author (as the USGS's Uranium Resource Specialist) continued to monitor worldwide commercial uranium exploration, mining, and market trends; electricity-producing utility actions; and new trends in scientific research. The use of internet sources of information has been invaluable for this purpose (see appended Selected Nuclear Energy Web Sites), and this report, as well as others (Finch, 1996, 1997, in press; Finch and others, 2000), is a direct result of this continued effort. In 2001, a new formal project—Alternative energy resources of the future—was begun to cover these uranium studies as well as similar ones for oil shale and heavy oil.

An essential activity has been the continued USGS participation in the NEA/IAEA Uranium Group, which produces the biannual Red Book: Uranium Resources, Production and Demand (see Appendix A of Finch and McCammon, 1987). The author reviewed the U.S. contributions to the Red Book in 1997, 1999, and 2001 and, as the USGS representative, attended two foreign meetings of the Uranium Group that involved field examinations of uranium districts: (1) in Johannesburg, South Africa, with field trips to the Witwatersrand Gold/Uranium Fields in South Africa, and to the Rossing Uranium Mining District in Namibia in 1996; and (2) at the Industrias Nuclear do Brazil offices in Rio de Janeiro, Brazil, with field trips to the new active Caetite Uranium District west of Salvador and the Pocos de Caldas Mining District north of Sao Paulo in 2000.

In 2001, the author, with R.L. Grubbs (consultant), organized the "Uranium Session: Uranium Energy: Source to Power to Repository" for the 2002 Annual Meeting of the American Association of Petroleum Geologists (AAPG) in Houston, Texas, with 10 abstracts being published to describe results of recent research. These are: R.J. Finch (2002), Grubbs (2002), Levich and others (2002), Maxwell (2002), McLemore (2002), Smith (2002), Stewart and Reimann (2002), Stuckless (2002), Underhill (2002), and Vance (2002).

Uranium Resource Assessment

The first national assessment of uranium resources that was done in 1980 by the DOE's "National Uranium Resource Evaluation (NURE) Program" (U.S. Department of Energy, 1980) is out of date and needs to be updated to incorporate new scientific data and to apply more refined assessment methodology (Finch, 1997, p. 20–21). The new assessment would enhance the national energy policy relative to nuclear energy. The updating should take advantage of an ongoing annual analysis of information on uranium exploration, production, reserves, and resources as well as uranium procurement by utilities reported by the EIA of the DOE (EIA, 2002; see "United States Uranium Industry in 2001" above). The potential uranium resources are updated yearly based on scientific uranium resource data developed prior to 1983 by the NURE program using methodology described by Finch and McCammon (1987).

An independent study of domestic uranium resources and their availability by consultant R.D. Maxwell (Maxwell, 2002) concluded that in 2001 the U.S.A. had no uranium reserves capable of being mined by conventional methods.

In 1997 and early 1998, J.K. Otton (USGS) and the author took part in a review of a contractor's document for EPA's (Environmental Protection Agency) Naturally Occurring Radioactive Materials (NORM) Mine Waste Characteristics Study. For this review, a new database was developed that includes (1) deposits with depleted reserves ("mined out"), (2) inactive mines, (3) producing mines, and (4) occurrences (defined as locations where rock with a grade of 0.03 percent

U_3O_8 occurs in outcrop or drill hole, size not determined). A total of 4,214 uranium deposits and occurrences or properties are listed by name, size (tons U_3O_8), and location in 30 States. Those States with more than 90 uranium properties are Arizona, Colorado, New Mexico, South Dakota, Texas, Utah, and Wyoming.

The USGS has taken part in various international uranium resource missions for the IAEA since 1976. The most recent was an IAEA Technical Cooperative Mission in late 1995 to advise the Argentina Government on their national uranium resource program in the Mendoza District. Earlier ones were in the Cordova and Patagonia uranium districts in 1993 and the Salta uranium district in 1994.

Uranium Geology and Resources Data Archival Project

An extremely large collection of domestic as well as worldwide uranium geology and resources data has been assembled by the USGS, consisting of numerous data sets on uranium deposits, uranium clusters (district areas representing deposits in an area about 5 mi in diameter), uranium provinces, and scattered uranium occurrences outside of defined provinces. A large punch-card uranium-occurrence file created in 1954–1957 was the first comprehensive database. Other key databases include the uranium-cluster database for the Colorado Plateau uranium province (Finch, 1991) and seven other uranium provinces that provided input to show the distribution of large clusters in North America (Finch, 1996). These databases also contributed to the World Atlas of uranium deposits (Finch and others, 1995). In addition, there are many special databases, such as uranium production for various districts, DOE NURE data managed by the USGS, uranium drill-hole logs from various areas, USGS core library data, USGS Field Records material filed from numerous uranium research projects dated 1948 to the present, uranium ore samples from major districts in the U.S.A. and other countries, State Geological Survey databases on file in the USGS, and a comprehensive library of uranium publications.

The USGS is presently preparing a digital archive for these materials; for example, the 1954–1957 punch-card occurrences file is now digitized. The archive will be interactive and open to the public. It will not contain confidential company data. The archivist is Frederick (Nick) Zihlman (zihlman@usgs.gov).

Future Uranium Mining in the United States

Future uranium mining in the U.S.A. will depend upon a higher price for U_3O_8, at least $15 per pound. The principal reserves are in Tertiary and Mesozoic sandstone formations. Tertiary-hosted sandstones in Wyoming, Nebraska, and Texas are highly amenable to ISL mining, but those in Mesozoic rocks of the Colorado Plateau are less so. Possibly, borehole hydraulic mining may be tried in Mesozoic rocks. Conventional underground mining will be practiced only in the few cases where development is completed, such as the deep Nose Rock and Mt. Taylor mines in the San Juan Basin of New Mexico.

In-situ Leach Mining

ISL mining will be the dominant mining method in the U.S.A. for the foreseeable future because costs are lower and environmental issues are less contentious than for conventional mining. The reserves of 135,000 tU in Tertiary formations in Wyoming, Nebraska, and Texas will be mined by ISL. The shallow parts of the reserves of 120,500 tU in Mesozoic sandstone formations in the Colorado Plateau may be mined by ISL. Pilot plant tests by private mining companies have been completed for three large deposits in the Jurassic Morrison Formation in the Grants Mineral Belt in the San Juan Basin of New Mexico (W.L. Chenoweth, consultant, written commun., 2002). Results of these tests have not been released.

In 1982, the U.S. Bureau of Mines (USBM) completed an Improved Solution Mining Production Cost Model for Bendix Field Engineering Corporation, contractor for the DOE (U.S. Bureau of Mines, 1982), of the original cost model (Toth and Annett, 1981). The improved model includes depth and grade of ore, well-flow rates, and chemistry of injection fluids. The model did not consider geologic factors such as porosity, permeability, induration, and chemistry (for example, humate-rich ores in the Grants Mineral Belt, New Mexico) of the host sandstone that would influence recovery by solutions and amounts of uranium recovered from the solutions. Comparison of the costs of ISL mining of Tertiary rock-hosted ores with those of Mesozoic rock-hosted ores would be of interest to the uranium mining industry. Economic parameters for development and rate of return of capital as well as changes in the economy in the past 20 years need to be considered in a new model (T. Pool, Nuclear Fuels Corp., oral commun., 2002). All of these factors would affect the costs of mining. With the closing of the USBM, the USGS, in cooperation with DOE, became the organization to initiate research on and update the ISL cost model; the resulting cost model would benefit the uranium mining industry.

Borehole Hydraulic Mining of Colorado Plateau Vanadium-Uranium Ores

A research and development program was developed by Cotter Corporation to mine Colorado Plateau vanadium-uranium ores in the Salt Wash Member of the Morrison Formation by borehole hydraulic mining (Cotter Corporation, 2002). A proposed testing program consists of (1) drilling a hole using a special bit and high-pressure jet; (2) pumping a slurry of broken rock up out of the hole; and (3) separating the slurry into fine and coarse fractions with a hydroclone. The coarse fraction may then be heap leached or returned back down the hole as back fill in the mined-out cavity. The fine fraction may be heap leached or trucked to the Canon City, Colo., mill to recover the uranium. On-site residue may be returned to the cavity.

The USBM conducted a borehole mining test in the 1970s and found it technically successful but not economic (T. Pool, Nuclear Fuels Corp., oral commun., 2002). Borehole mining of phosphatic fish-scale-hosted uranium ores was done in the Caspian Sea area in Kazakhstan in the 1970s and 1980s (Grigovi Abramov, BHMI, Inc., Denver, Colo., www.boreholemining.com, written commun., 2002; see descriptions of Kazakhstan Uranium Deposits Numbers 224, 235, and 236 in Finch and others, 1995; IAEA, 1996). Research on the potential of borehole mining of sandstone uranium ores is warranted.

Future of Nuclear Power

IAEA Uranium Supply Analysis to 2050

In late 2001, the IAEA released its report "Analysis of Uranium Supply to 2050" (Mining Journal, 2001), which replaces a decade-old report that included the period to the year 2035. A systematic analysis of the long-term uranium supply as the fuel for nuclear power plants is essential for sustainability of the worldwide nuclear power industry (IAEA, 2001b; Underhill, 2002). The life cycle of the nuclear fuel cycle is relatively long; for facilities with a large resource base, it ranges from 30 to 50 years. Sources of uranium supply are of two groups: primary and secondary (fig. 5).

Primary world supply comes from mined and processed reserves of natural uranium ore deposits, and is divided into

PRIMARY SUPPLY

- Market-based production—Cost-competitive sources
- Nonmarket-based production
    - Commonwealth Independent States (CIS)
    - National programs—Argentina, Brazil, India, and others
    - China

SECONDARY SUPPLY

- Highly enriched uranium (HEU)
    - Downgraded—Significant source until 2030
- Pipeline inventories and low enriched uranium (LEU)
- Reprocessed spent fuel to produced mixed-oxide fuel (MOX)
- Re-enrichment of depleted uranium (0.30% U-235 tails)

ANALYSIS 2000–2050

	Accumulative requirement	Reasonably assured resources shortfall
Low demand	3,390,000 tU	800,000 tU
Middle demand	5,394,100 tU	1,500,0000 tU
High demand	7,577,300 tU	3,700,000 tU

Figure 5. Chart showing the International Atomic Energy Agency analysis of uranium supplies (in metric tons U, tU) from 2000 to 2050 (IAEA, 2001b).

(1) market-based production (that is, from cost-competitive sources); (2) nonmarket-based production, including supplies from the CIS countries; (3) various national programs for internal consumption; and (4) Chinese production (fig. 5). The NEA/OECD semiannual Red Book summarized primary 2001 uranium production for 21 countries out of the 45 countries containing uranium resources (NEA/OECD, 2002). Of the CIS countries, the Russian Federation and Ukraine have internal need and use for uranium and, to some degree, they financially support production; however, both Kazakhstan and Uzbekistan have no nuclear power plants and produce uranium with some outside support with an increasing market base. Kazakhstan has the third largest reasonably assured uranium resources (table 1) and could become a major world producer. National-program countries, of which there are about a dozen (most importantly Argentina, Brazil, Spain, and India), dedicate their production, commonly at high cost, for internal need. China's production and resources are uncertain and considered in the IAEA report as being a separate primary supply. China does not release reserve and production data, but little uranium has been exported. In 2001, primary sources provided about 60 percent of world production and came mainly from high-grade uranium ores in Canada and Australia.

Secondary supply comes from (1) downgrading HEU from nuclear weapons and from inventory; (2) inventories of in-pipeline of natural uranium (yellowcake U_3O_8) and LEU used in nuclear power plants; (3) reprocessed spent fuel to produce MOX fuel; and (4) re-enrichment of depleted uranium derived from the tails of original enrichment (figs. 1 and 5). Secondary supplies provided about 40 percent of 1998 world demand but are expected to supply only about 6 percent by 2020.

Analyses of demand were made in three basic worldwide cases: (1) high demand—significant expansion of generating capacity with high economic growth; (2) middle demand—sustained increase in development of nuclear power worldwide with medium economic growth; and (3) low demand—medium growth in new nuclear power but phased out by 2100. Factors influencing demand will be political and subject to environmental restraints and levels of economic growth. The normal growth rate projected for nuclear power is 1–3 percent.

Estimates of cumulative uranium requirements for the 2000–2050 time period for each case are high demand 7,600,000 tU, middle demand 5,400,000 tU, and low demand 3,400,000 tU (fig. 5). The current RAR in 2001 would fall short in all three cases by 3,700,000 tU, 1,500,000 tU, and 800,000 tU, respectively (fig. 5). Current RAR will be depleted by the mid-2030s.

The life cycle from start of exploration to reclamation is on the order of 20–40 years. Long lead times from exploration to mining of 8–10 years will require major increases in exploration by 2010 in order to find new large high-grade ore deposits that can be brought into power-plant production by 2025. This will allow orderly uranium reserve increases in the second 25 years.

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