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Uranium, Its Impact on the National and Global Energy Mix—

And Its History, Distribution, Production, Nuclear Fuel-Cycle, Future, and Relation to the Environment

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Uranium, Its Impact on the National and Global Energy Mix—

And Its History, Distribution, Production, Nuclear Fuel-Cycle, Future, and Relation to the Environment

By Warren I. Finch

U.S. GEOLOGICAL SURVEY CIRCULAR 1141

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1997

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

Free on application to U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Finch, Warren Irvin, 1924–
Uranium, its impact on the national and global energy mix—and its history, distribution, production, nuclear fuel-cycle, future, and relation to the environment / by Warren I. Finch.
p. cm. — (U.S. Geological Survey circular ; 1141)
Includes bibliographical references.
Supt. of Docs. no.: I 19.4/3:1141
1. Uranium as fuel. 2. Uranium—Environmental aspects. 3. Uranium industry.
I. Title. II. Series. III. Series.
TK9363.F55 1998
338.2'74932—dc21 97-26513
CIP

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Pounds U_3O_8 to metric tons[1] U: ÷ by 2205, then × 0.8480
Pounds to kilograms: × 0.4536
Metric tons to short tons: divide by 0.9078
US$ per kg U to US$ per pound U_3O_8: ÷ 2.6 and round to nearest US$10. Example: US$80 kgU = US$30 pound U_3O_8 (the common units to categorize reserves and resources)
Percent U_3O_8 to percent U: × 0.8480

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[1] One metric ton (also known as a "tonne") is equal to 1,000 kg (2,210 pounds).

Uranium, Its Impact on the National and Global Energy Mix—

And Its History, Distribution, Production, Nuclear Fuel-Cycle, Future, and Relation to the Environment

By Warren I. Finch

EXECUTIVE SUMMARY

Uranium, which was discovered and named in 1789, occurs in nearly every natural material. It is very soluble in water containing free oxygen and, under special geologic conditions, is concentrated into minable deposits in many types of rocks. In the United States, economic uranium deposits occur most commonly in sandstone formations in Arizona, Colorado, New Mexico, Utah, Wyoming, and Texas.

The discovery of how to produce energy from uranium by the process of fission of the uranium atom was demonstrated in 1942. Shortly thereafter, the atomic bomb was developed that ended World War II. Production of uranium for weapons continued for decades in the "cold war" that ended in 1992. Development of peaceful uses of uranium was slower, and uranium first became a fuel for commercial generation of electricity in 1953, and, by 1993, it provided about 21 percent of the Nation's electricity supply.

To get uranium from its geologic occurrence in the ground into a nuclear power reactor to produce electricity requires many steps, mainly mining and milling of the ore, conversion of "yellowcake" from the mill to the compound UF_6, enrichment of the isotope U-235 from its 0.7 percent in natural uranium to about 3 percent, and fabrication of fuel elements for the reactor. This is called the front end of the fuel-cycle. The nuclear power plant is the middle part of the cycle, and the handling and reprocessing of spent fuel and handling of the waste is the back end of the cycle.

Uranium was discovered in the United States in the Central City district, Colorado, in 1871. The discovery of radium in 1898 led to the wide search for uranium minerals containing radium. Deposits of carnotite, a uraniferous vanadium mineral, on the Colorado Plateau were the world's major source for radium from 1912 to 1922 and for vanadium from 1924 to 1945. Uranium was discarded for the most part in vanadium tailings, and much of the uranium needed for atomic bombs came from these tailings. Mining of uranium ores for military use started in late 1947 and continued until 1970. Use of uranium for nuclear power plants to produce electricity began in the early 1950's. The commercial uranium industry began with the passage of the Private Ownership of Special Nuclear Materials Act in 1964. Mining of uranium was intense not only in the Colorado Plateau region but also in Wyoming Basins and the South Texas Gulf Coast regions in three periods: 1957–1962, 1968–1973, and 1976–1980. Since then, production has dwindled, and, in 1984, the United States lost its role as the world's leading producer to Canada. The annual consumption of uranium in 1993 was more than ten times the domestic production; therefore, supplies came from inventory and imports, mainly from our Free Trade Partner, Canada.

Government and politics have influenced the nuclear fuel-cycle more than that of any other energy commodity, mainly because of fear of its military use and the special environmental problems associated with radioactivity. In the United States from 1947 to 1964, the only market for uranium was the Government; private ownership of refined uranium became possible in 1964. In many countries, uranium supply is still strictly controlled by the government.

The 1994 energy mix in the United States shows that the share of nuclear-generated electricity was about 45 percent in the Atlantic Coast and Appalachians, 34 percent in the Midcontinent region, 11 percent in the Gulf Coast region, and about 5 percent each in the Pacific Coast and adjacent Basin and Range regions. The main sources of uranium occur in the Colorado Plateau region, Wyoming Basins region, and South Texas Gulf Coast region; these are all outside the main usage areas.

The role of uranium in the global energy mix varies widely geographically, with the greatest use of nuclear electrical power in Europe and NAFTA (North American Free-Trade Agreement region, mainly the United States and Canada) and most of the remaining use in the New Independent States (NIS, which includes most of former Soviet Union) and the Far East (largely Japan). France gets nearly 78 percent of its electrical power from nuclear plants; the United States and Japan get 21 and 31 percent, respectively. The small nation of Lithuania gets 87 percent of its electrical power from nuclear plants! In 1994, there were 430 nuclear power plants in the world distributed in more than 30 countries; the United States had 109 nuclear power plants and

produced about 30 percent of the world's nuclear electrical energy. Australia and New Zealand have no nuclear power plants. South America, Africa, the Middle East, and Indian subcontinent have a limited number of nuclear electrical power plants.

Uranium resources are concentrated in a few places in the world. The bulk of uranium production from 1946 to 1992 came mainly from Canada, Czechoslovakia (mostly the present Czech Republic), German Democratic Republic, South Africa, and the United States; leading producers during the time period prior to knowledge of Soviet Union and allied countries production were the United States, Canada, and South Africa. The presently reasonably assured uranium (economic) resources are mainly in Australia, Canada, Namibia, Niger, South Africa, Kazakhstan, Uzbekistan, and United States. World consumption in 1993 was about 150,000,000 pounds of U_3O_8 compared to world production of about 88,000,000 pounds; the shortfall was made up from inventory. Prices of uranium in 1992 were at new lows in constant-dollar terms. The end of the "cold war" has freed huge supplies of uranium from the dismantling of nuclear weapons; the 80–95 percent U-235 in weapons fuel can be reduced to about 3 percent U-235, thereby creating a very large amount of new material available for sale. In particular, Russia has agreed to place large amounts of this kind of uranium on the market, whereas the United States has not decided on how to handle its supply from weapons.

The environmental problems related to nuclear energy are considered by some to be serious and have affected its use and acceptance as a viable energy source. The military use of nuclear energy and two accidents at power plants, a relatively minor one in the United States in 1979 and a very serious one in the Ukraine in 1986, have increased the visibility of the problem. Technology to safely meet environmental needs and to store spent nuclear fuel has been developed, but the "not-in-my-backyard" syndrome delays the application of the technology, as it does for all types of waste material.

Plutonium is of the greatest concern because of its use in weapons—a very small quantity is needed to make a bomb. It is also part of the spent fuel from power plants. In many countries outside the United States, spent fuel is reprocessed and plutonium is used in breeder reactors. This reduces the amount of plutonium waste. Plutonium was produced in 1940 in early nuclear experiments, and before then it was not known to occur in nature. Now Pu-239, the most abundant and hazardous plutonium isotope, is measurable in most soils and water throughout the world, especially near nuclear test sites, former plutonium facilities, and power plants.

Enormous amounts of tailings from uranium mills and waste from uranium mines have a lower level of radioactivity than reactor wastes and still are perceived to be environmental problems. Many of the large tailings piles have been reclaimed to safe agricultural, range, and recreational land uses. Reclamation activities are underway for all mill sites and most of the larger mines in this country.

Nuclear power plants are environmentally clean with respect to acid rain, global warming, and ozone depletion. If nuclear power were substituted for coal to generate base-load electricity, these global changes would be measurably lessened.

The supply of fuel for a nuclear plant comes from a mixed stock of enriched uranium products that have lost their geographic and geologic identities. Thus, uranium does not travel directly from mine to power plant; and because of its chemical purity after milling, conversion, and enrichment, its origin is not important, except nationally, relative to export and import

The future of nuclear energy in the energy mix in this country will be determined by policies of the U.S. Government relative to waste management and the decisions of utilities to build the new, simplified, "passively safe" reactors presently available. Moreover, a decision to build breeder reactors in the United States to consume plutonium would reduce the amount of high-level nuclear waste.

Energy and mineral resource assessments are dynamic exercises that result in improved estimates with the considerations of data on deposit depletions, new discoveries of deposits and districts, new resource assessment methodologies and recovery technologies, and new geoscience research results. Experience in the 1995 National Assessment of Oil and Gas Resources has shown that utilization of similar factors resulted in rigorous and more credible estimates than the previous assessment done only 6 years earlier. A new assessment of uranium resources, to replace the one done in1980, would aid in resource and land-use planning and aid the U.S. uranium industry in preparing for a potential upswing in uranium mining, which would decrease our dependence on foreign supply.

The need for new geologic studies of uranium deposits in the next decade will remain low, except as they relate to solving environmental problems.

INTRODUCTION

The term "energy mix" is used to describe the range of various energy sources that are produced and consumed. A discussion of the energy mix of a nation or region requires consideration of the importation and exportation of energy resources as well as the production and consumption of domestic resources. During the past 40 years, uranium, the fuel used in nuclear power generation, has played an increasing role within the energy mix of the United States and many countries of the world. This paper discusses this evolving role of uranium and nuclear power in the energy mix, generally based on data available at the end of 1994. This paper will discuss how energy is harnessed from the metal uranium, how the use of uranium as a fuel has evolved to its current status and how nuclear power is currently used in the United States, and briefly review nuclear power generation throughout the rest of the world. The paper concludes with a discussion of the environmental concerns related to the extraction and utilization of uranium and discusses the future use of uranium for energy generation. It is hoped that the paper will provide a useful review of uranium's role in the production of energy and will serve as a readable introduction to the topic for those not familiar with the uranium industry. The paper is written from the perspective of a geologist and discusses how geology has influenced the current pattern of uranium use in our energy mix and what sort of geologic studies of uranium may be needed within the foreseeable future.

In the future, the dynamic role of uranium in the energy mix may result in new statistical data available after 1994 that may change the conclusions drawn from the data in this paper. The reader is encouraged to update statistical data and make his own conclusions by consulting the following annual and periodic publications: Energy Information Administration's (EIA) *Uranium Industry Annual, Commercial Nuclear Power, Electric Power Annual, Annual Energy Review, and World Energy Outlook;* Nuclear Energy Agency/Organization for Economic Cooperation and Development (NEA/OECD) "Red Book": *Resources, Production and Demand*, published every 2 years; monthly TradeTech's *Nuclear Review*; and McGraw Hill's *Engineering and Mining Journal* annual overview of metal commodities, which is available in March or April each year.

English, metric, U.S., and international units of measurements for uranium resources, production, costs, and other related items are used in this report as they were originally reported and, where useful, converted to equivalent units (shown in parentheses). Definitions of terms and units are given in the Glossary section of this report.

ACKNOWLEDGMENTS

This paper was greatly improved by unpublished information provided by W.L. Chenoweth, consulting geologist, Grand Junction, Colo.; Scott Peters, Nuclear Research Institute, Washington, D.C.; T.C. Pool, International Nuclear, Inc., Golden, Colo.; and Bertram Wolfe, Consultant, Monte Sereno, Calif. These men and J.K. Otton, Peter McCabe, and K.L. Varnes, USGS; and Taesin Chung, Energy Information Administration, Washington, D.C., made many helpful suggestions in their reviews of the manuscript.

HOW WE HARNESS ENERGY FROM URANIUM

A detectable amount of uranium is present in nearly all natural materials, including our bodies, especially our bones and teeth. Uranium, along with thorium and potassium, imparts background radioactivity to rocks. Uranium is very soluble in surface and ground waters that contain free oxygen and travels easily with the water through and on the surface of the Earth. Under special geologic conditions, concentrations of uranium minerals with oxygen are formed in deposits rich enough to be economically recoverable. Uranium occurs in many types of deposits and in many kinds of rocks. In the United States, economic uranium deposits occur most commonly in sandstone formations in Arizona, Colorado, New Mexico, Utah, Wyoming, and Texas (fig. 1). These sandstone uranium deposits have yielded about 97 percent of our domestic supply. Important collapse-breccia pipe uranium deposits occur in Paleozoic sandstone formations in the Grand Canyon region of Arizona. Uranium also occurs in fractured hard rocks as veins and related disseminations in metamorphic, igneous, and limestone host rocks, notably in Colorado, Nevada, Oregon, Washington, Alaska, and Virginia. Uranium also occurs in lesser amounts in other kinds of rocks and can be recovered as a by-product. Important in the United States are deposits of uranium-bearing phosphorous minerals in Florida, where uranium has been recovered since 1975 as a by-product of the manufacture of phosphoric acid fertilizer. In recent years, this source has provided a large percentage of U.S. uranium production.

Natural uranium is a silvery white metal that consists of three semistable radioactive isotopes U-238, U-235, and U-234. It is an important energy source because fission of U-235 releases large amounts of energy in the form of heat to drive steam generators to produce electricity. This readily fissionable nuclide constitutes only about 0.7 percent of natural uranium; most of the remaining 99.3 percent is U-238 and about 0.005 percent is U-234. The isotope U-238 is not readily fissionable, but it is a fertile material that under neutron bombardment converts to fissionable plutonium, Pu-239, constantly in a nuclear reactor (Frost, 1986).

The splitting or fission of uranium, first demonstrated in 1942 (Olson and others, 1978), takes place when a tiny particle called a neutron enters the nucleus of a uranium atom by either induction or spontaneously and causes the nucleus to split into two parts.[1] Some of the energy binding the nucleus together is released as heat. Fission also releases at least two neutrons from the nucleus to move through space. When they encounter the nuclei of other uranium

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[1] Although this process is usually induced artificially by human actions, it apparently has occurred spontaneously in nature. In 1972, isotopic evidence (depleted U-235) for natural nuclear fission reactors was discovered in 2-billion-year-old, Precambrian, high-grade (20–60 percent U_3O_8) uranium ores at Oklo, Gabon (International Atomic Energy Agency, 1975; Gauthier-LaFaye and others, 1989). These natural reactors produced energy (heat) and waste in 14 zones in three different uranium deposits just like modern man-made reactors. Plutonium was produced but has completely decayed.

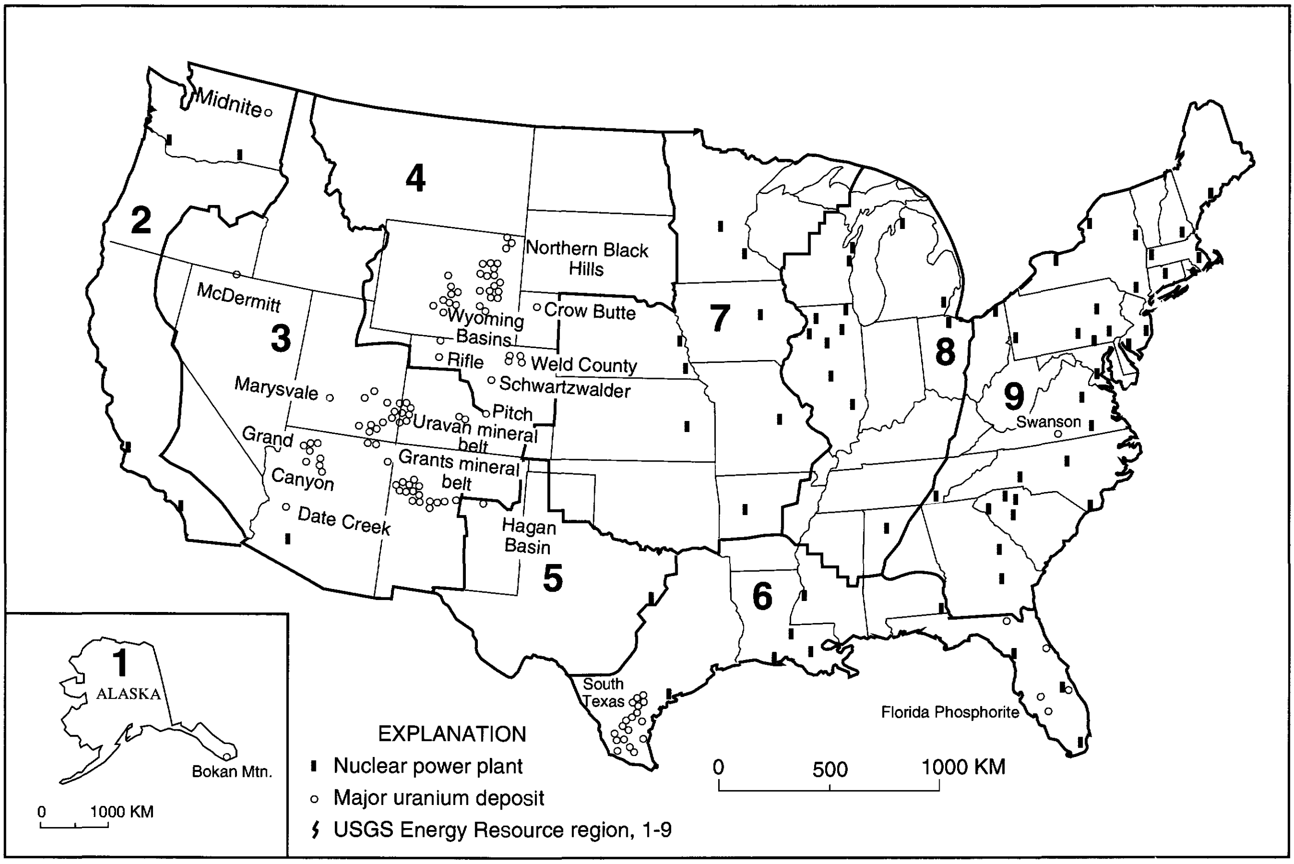

Figure 1. Map showing the distribution of major uranium deposits and nuclear power plants in the USGS Energy Resource regions in the conterminous United States. Region 1, Alaska, Hawaii; 2, Pacific Coast; 3, Colorado Plateau, Basin and Range; 4, Rocky Mountains, Northern Great Plains; 5, Permian Basin; 6, Gulf Coast; 7, Western Midcontinent; 8, Eastern Midcontinent; and 9, Atlantic Coast, Appalachian Basin. Power plant locations from EIA (1991).

atoms, the free neutrons cause further fission, which, if continued, becomes a chain reaction.

To get uranium from its geologic occurrence in the ground into nuclear power reactors requires the following steps: exploration, development, mining, milling, conversion, enrichment, and fuel fabrication. This is termed the "front end" of the fuel-cycle (fig. 2); the "back end" consists of handling and reprocessing of spent fuel and disposal of waste; the nuclear power plant is the "middle" energy-producing cycle (Nero, 1979).

Exploration can be carried out in several stages: geologic evaluation of potentially favorable terrains to select exploration areas, airborne radiometric surveys, ground check of airborne anomalies and (or) surface radiometric prospecting without an airborne survey, and drilling of favorable geologic ground. Drilling commonly begins with widely spaced drill holes that are logged geologically and radiometrically to identify uranium-bearing hosts. More closely spaced holes are then drilled to discover and define orebodies. Depths of drilling are generally less than 2,000 ft and no more than 5,000 ft.

Uranium ore is mined by several methods: conventional open-pit and underground mines and by in situ leach (ISL) mining. The choice of mining method depends upon the geologic character and size of the deposit, nearness to the ground surface, and economic and environmental considerations. Flat-lying sandstone ores and vertical vein ores require different methods. Shallow, flat-lying ores and veins at the surface are generally mined by open-pit methods, but deeper ores are mined underground. In recent years, ISL mining has been chosen for ores in permeable sandstone because of its lower overall recovery costs and environmental advantage over conventional mining. In the United States, ISL mining is done by injecting an alkaline (bicarbonate) solution as the lixiviant and oxygen gas as the oxidant; both are relatively benign chemicals (Szymanski, 1994). ISL production of "yellowcake" is done in the plant using an ion-exchange process by which solutions from injection wells are recirculated until the uranium content of the solutions is too low to be economically recoverable.

Uranium ore from conventional mining is milled by dissolving it in either acid or alkaline solutions and precipitating uranium by either ion exchange or solvent extraction; in either case, the product (commonly ammonium diuranate) is similar and is called "yellowcake" because of its color (Cooper, 1986). Its composition is a form of uranium oxide

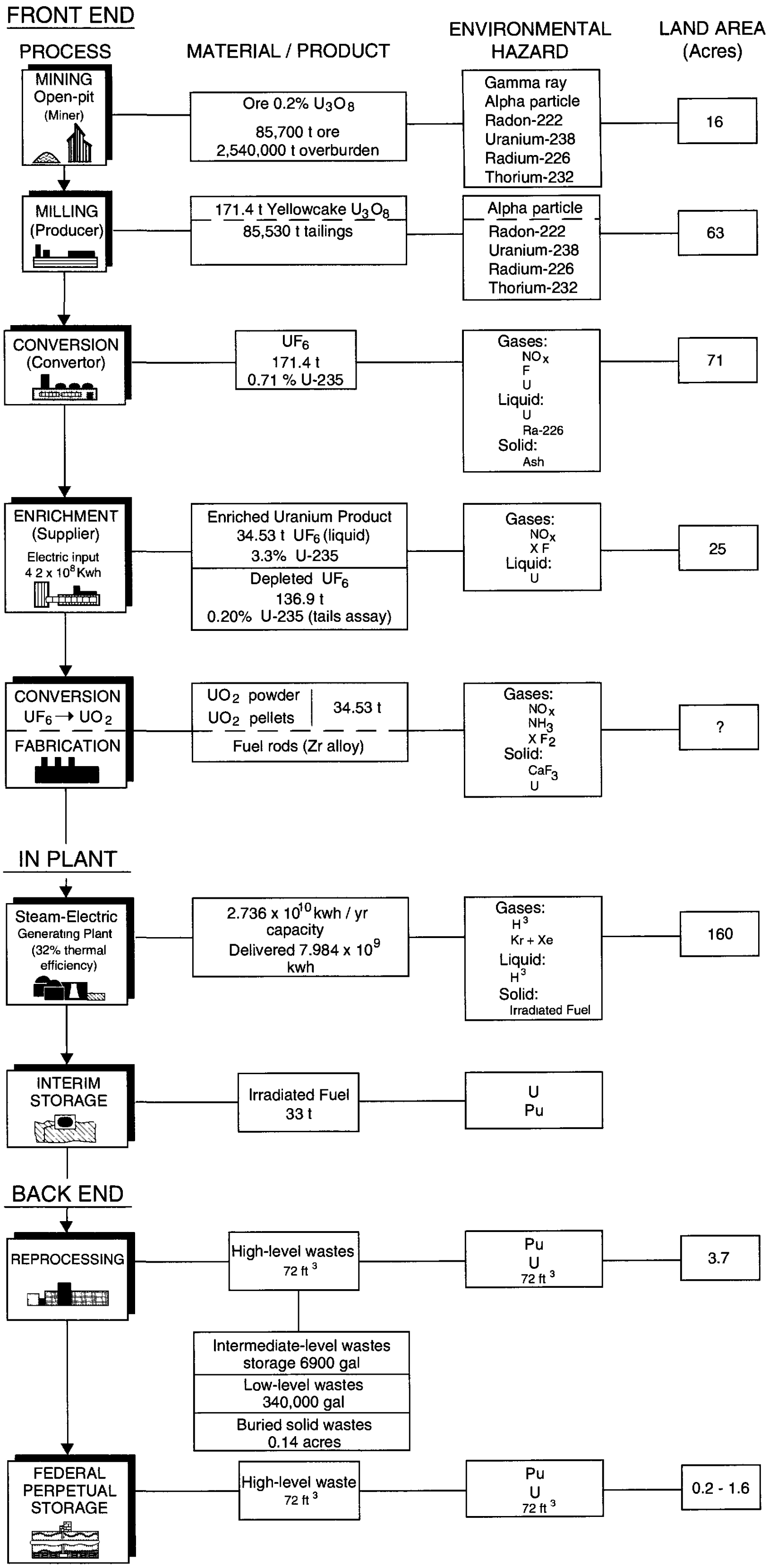

Figure 2. The life-time (~30 years) nuclear fuel-cycle for a 1,000-MWe light-water reactor plant (based on information in figure F1-1 of Nero, 1979; icons adapted from various U.S. Department of Energy publications). t, metric tons.

(U_3O_8), which is the principal unit in which uranium is bought and sold on the U.S. market. Newly formed yellowcake is not very radioactive because most of the highly radioactive decay products in the original ore have been removed and insufficient time has elapsed for new decay products to form. Yellowcake is stored in 55-gallon drums and shipped to conversion plants. Mills are generally located near the largest mine within a mining district. In the late 1940's, four old vanadium mills, three private and one Government-owned, were converted to recover uranium. In the early 1950's, the U.S. Government established widespread ore-buying stations to promote a ready market. As private companies developed sufficient reserves to receive Government contracts, many conventional mills were built. By 1957, there were 25 mills located in Arizona, Colorado, New Mexico, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming. By 1992, all of them were closed as ISL mining and processing became more feasible. The first commercial ISL operation began in 1974, and, by the end of 1993, 11 uranium ISL plants were licensed in Nebraska, Texas, and Wyoming (Szymanski, 1994). In 1995, only five were in operation.

All yellowcake is sent to conversion plants where U_3O_8 is converted into UF_6, a gas, by a solvent-extraction-fluorination process (Cooper, 1986). The gaseous UF_6 is condensed into a liquid and solidified; the solid is then shipped to the enrichment plant. In 1994, the only conversion plant in the United States was operated under contract to the U.S. Government at Metropolis, Ill. A plant at Gore, Okla., closed recently. Although the process of conversion was developed at the Oak Ridge National Laboratory, Tennessee, commercial conversion is no longer carried out there.

Converted UF_6 contains natural proportions of uranium isotopes, and, for most nuclear power reactors, the U-235 must be enriched. The enrichment of U-235 in UF_6 is carried out by gaseous diffusion through a porous membrane. The isotope molecules U-235 and U-238 have different masses and speeds, and successive passes through the membrane results in a gradual physical separation and enrichment of U-235 in the UF_6 (Nero, 1979). The resulting "enriched uranium product" (EUP) generally contains about 3 percent U-235 in material still containing some U-238; EUP is the fuel for most nuclear power reactors in the United States. The tails from the enrichment of UF_6 have an assay of about 0.20 percent U-235 and are called depleted uranium. Some of the depleted uranium is converted into uranium metal that has important uses in ballistics and as ballast in close-fitting counter-balance situations, such as aileron controls in airplane wings. Enrichment plants are operated under contract to the Government at Paducah, Ky., and Portsmouth, Ohio. The measurement of the effort to separate the isotopes to a desired U-235 content is called "separative work units" (SWU); the cost of a SWU is expressed in US$ per kgU (kilogram of uranium) as enriched UF_6. Utilities can buy and trade SWU on the open market where supply and demand control the price, similar to that in the U_3O_8 market. Traditional long-term contracts are between the utility and the primary enrichment supplier (domestic or foreign; these contracts are made as book transfers, sales, loans, and exchanges); short-term supplies are from spot-market sources for small amounts of U_3O_8.

The enriched UF_6 is sent to fabrication plants (fig. 2) where it is converted into ceramic-grade UO_2 by pyrohydrolysis in steam followed by reduction (Ainscough, 1986). Reduction is commonly done using hydrogen in a rotary kiln to produce pure UO_2 powder (Klepfer, 1986). Fabrication of fuel elements for use in light-water reactors (LWR) is done by mechanically pressing UO_2 powder into pellets, typically 8–10 mm in diameter and 10–13 mm in height that are stabilized by firing them in either a hydrogen or hydrogen-nitrogen atmosphere (Klepfer, 1986). The pellets are assembled in columns in zirconium-alloy tubes or fuel rods about 12 mm in diameter and 350 mm in length under precise quality-controlled specifications. Domestic fabrication plants are at Hematite, Mo.; Columbia, S.C.; Wilmington, N.C.; Richland, Wash.; and Lynchburg, Va. (Energy Information Administration, 1994a).

There are a number of different designs of nuclear power reactors. A reactor that yields less fissionable material than consumed is called a converter reactor, and one that yields more is a breeder reactor. Pu-239 is the fuel in breeder reactors in France and other countries, but, in the United States, it is treated as a waste because we have no plans to develop breeder reactors (Finch and others, 1975). The most common reactor in the United States is the light-water reactor (LWR) in which fission is moderated with ordinary water. In Canada, heavy water (see Glossary) is used as the moderator of the fission of uranium in fuel with the natural isotope ratios in the CANDU (PHWR) reactor (see Glossary).

Bundles of fuel rods are the fuel elements loaded into light-water reactors (LWR). Using a 1,000-MWe LWR as a standard and a 30-year life, about 35 metric tons of EUP at 3.3 percent U-235 is required (fig. 2; Pigford and others, 1975). The initial fuel load lasts about 3 years; some is replaced about once a year. Thus, a continuous daily or hourly supply of uranium is not needed. Furthermore, transportation of uranium fuel is a negligible cost factor and is not controlled by weather or other temporal factors. Spent fuel rods are stored in a building at the reactor site in water for radiation shielding and cooling until a national storage facility becomes available. The commercial industry currently stores ~30,000 metric tons (t) of spent fuel at more than 100 nuclear power reactor sites; additionally, weapons account for about 2,700 metric tons of spent fuel at 30 sites (U.S. Department of Energy, Office of Environmental Management, 1995). The volume of spent fuel rods is relatively small so that a waste-storage facility for spent fuel rods from all reactors in the United States would be on the order of 1 million cubic meters, or about the size of an average department store.

Spent fuel can be reprocessed to obtain plutonium, a possible fuel in breeder power reactors. The only reprocessing plant in the United States is at Barnwell, S.C. In 1977, after much discussion by industry and Government officials (Finch and others, 1975), the United States by Presidential order, decided not to reprocess fuel (Stover, 1995) or to develop the breeder reactor. Plutonium thus became a high-level waste instead of a useful product. France and other countries, on the other hand, have developed the breeder reactor and use plutonium as a fuel.

THE GROWTH OF URANIUM USE FOR POWER GENERATION IN THE UNITED STATES

PRE-1900

Uranium was discovered and named in 1789, but not until 1871 was the first pitchblende of potential economic interest in the United States discovered on the dump of the Wood mine in the Central City district in Colorado (Sims and others, 1963). The discovery of radium by the Curies in 1898 led to a wide search for uranium minerals containing radium. Uranium was not used for energy generation at this time.

PERIOD 1900–1950

Deposits of carnotite, a mineral containing both uranium and vanadium, on the Colorado Plateau were the world's major source of radium from 1912 to 1922 and of vanadium from 1924 to 1945. Uranium, recovered as a byproduct from these mining operations, had limited use for coloring glass and ceramic glazes, so most of it went into mill tailings. In 1942, controlled nuclear fission demonstrated two new and vastly more important uses for uranium: as a military explosive and as a peaceful source of heat to produce steam for generating electricity. In order to acquire the uranium needed for the atomic weapons in World War II, the Army's Corps of Engineers, Manhattan Engineer District was established in August 1942 (Chenoweth, 1997). About 2,700,000 pounds of U_3O_8 was acquired from the vanadium tailings from 1943–1945, which constituted about 14 percent of the uranium required for the three atomic bombs used in World War II. The rest of it came from the Belgian Congo (now Zaire) and Canada (Chenoweth, 1997). Production of uranium ores primarily for military use was begun in 1947, and, by 1960, a surplus of uranium was evident for that use. Production of 38,000 short tons of ore in 1948 rose to 5,200,000 short tons in 1958 (U.S. Department of Energy, Office of Environmental Management, 1995). Uranium was still not present in the energy mix at this time (see fig. 4).

PERIOD 1951–1965

The first use of uranium in a nuclear reactor to produce electricity was in 1951 at the National Reactor Test Site in Idaho (Frost, 1986). The first commercial nuclear generating reactor ordered in the United States was for the power plant at Shippingport, Me., in 1953. It had a design capacity of 60 MWe (1 million watts of electric capacity) and was retired in 1982 (EIA, 1991). By the end of 1965, a total of 20 units with a total design capacity of nearly 9,000 MWe had been ordered.

Mining of uranium in the United States can be divided into three periods of intensity, the first was from 1957 until 1962, the second 1968–1973, and third 1976–1980 (U.S. Department of Energy, 1981). Initial uranium mining began in the Colorado Plateau region in 1947. As prospecting and exploration expanded in the mid-1950's, uranium ores were discovered and mining began in Wyoming, Texas, and regions adjacent to the Colorado Plateau. There was a large increase in reserves of uranium from 1948 to 1957.

The commercial industry for uranium began with the passage of the Private Ownership of Special Nuclear Materials Act of 1964, but mining and milling companies did not start "outside sales" until 1966. The buying of uranium by the Government started to decrease in 1962 and ended entirely in 1970 (U.S. Department of Energy, 1984).

PERIOD 1966–1980

By mid-1976, nuclear-powered electricity plants reached a capacity of about 41,000 MWe, about 8.1 percent of total U.S. electrical capacity; plants totaling another 97,400 MWe were being built; and plants totaling 70,000 MWe had been ordered (Olson and others, 1978). Concern over the Three Mile Island nuclear plant accident in 1979 was followed by numerous cancellations of reactors under construction.

Annual production of uranium declined from the peak of 36,000,000 pounds of U_3O_8 in 1960 to a low of 20,000,000 pounds in 1965 (U.S. Department of Energy, 1984). A mild upswing in production occurred from 1968 to 1973. Activity began to increase in 1977 and reached an all-time high of 43,700,000 pounds of U_3O_8 in 1980 (EIA, 1995b).

PERIOD 1981–1994

In December 1982, there were 42 nuclear power plants operating in the United States (Anonymous, 1984). By the end of 1993, 109 nuclear plants were operating at a capacity of 99,041 MWe (EIA, 1994c). The Chernobyl accident of April 26, 1986 (much more serious than the Three Mile Island event in 1979), augmented the concerns over the safety of nuclear power plants and resulted in the cancellation of orders and reactor construction for 40 units in the United States.

The annual consumption by domestic electric utilities in 1993 was about 44,000,000 pounds U_3O_8 (Pool, 1994b) compared to about 17,000,000 in 1980 and 8,000,000 in 1970 (NUEXCO, 1993).

Underground mining ceased in the United States in 1992 when in situ leach (ISL) mining became predominant in Wyoming and Texas; ISL mining began in the new Nebraska district in 1991. Production of uranium decreased from the high of 43,700,000 pounds of U_3O_8 in 1980 to 3,100,000 pounds in 1993 (EIA, 1995b). In 1984, the United States relinquished its role as the principal world producer of uranium to Canada, and Canada has led ever since. The spot-market price of uranium of $43 per pound in 1978 dropped to $7.25 a pound in October 1991 (Pool, 1992; NUEXCO, 1993); late in 1994, it began to rise, and, in early 1995, it rose to $11.75 (see update under "Future U.S. Uranium Production" section below).

The agreement between the United States and Russia to destroy nuclear weapons in 1993 resulted in a supply of uranium large enough to potentially flood the market. Russia proceeded to convert its weapons material into fuel for nuclear reactors for producing electricity, whereas the United States had not decided on the schedule of conversion and placing its uranium on the market. In 1994, an agreement to limit the Russian import to 4,000,000 pounds U_3O_8 per year into the United States and to require matching new U.S. production resulted in price increases and in new domestic production, particularly from breccia pipes in Arizona and ISL mines in Texas and Wyoming.

The U.S.–Canada Free Trade Agreement of 1988 had an adverse affect on the U.S. uranium industry because Canada's shallow, high-grade, low-cost supplies were able to drive out many domestic U.S. suppliers. The formation of NAFTA (North American Free-Trade Agreement, mainly Canada and United States) in 1993 has had little further effect on the domestic market and supply because Mexico produced no uranium.

Monitoring the viability of the U.S. domestic uranium industry by the Department of Energy was ordered by Public Law No. 97-415 in 1983 (EIA, 1985). Yearly assessments by DOE deemed the industry nonviable from 1984–1992.

PRESENT URANIUM USE IN THE UNITED STATES

The role of uranium in the energy mix in the United States is significant for electricity generation (fig. 3). Its role in energy for transportation, household/commercial, and industrial sectors is negligible, but it has critical use in specific military transportation, namely submarine power.

In 1950, uranium had no part in the energy mix (fig. 4). By 1991, uranium fuel supplied about seven percent of all energy used in the United States (fig. 3), and 21 percent (increased to 23 percent in 1995; EIA, 1996) of all electricity, principally as a base-load or minimum required component (fig. 4). Coal and nuclear power provide the largest share of base-load electricity. Compared to coal, oil, and gas, so little uranium is required to fuel a nuclear electrical plant that the location of the natural source of uranium in relation to power plants is irrelevant (figs. 1 and 2). Similarly, the conversion facilities that produce the uranium fuel from "yellowcake" are neither near uranium mines, mills, nor nuclear plants. Peak load of electrical energy comes mainly from oil- and gas-powered plants, which have relatively lower initial construction costs but higher fuel costs than either coal or uranium. Nuclear fuel is generally loaded at yearly intervals whereas coal, oil, and gas require a continuous hourly feed. Thus, uranium fuel supplies are not interrupted by severe weather, labor strikes, international embargoes, and other calamities.

Uranium and its use in generating electrical energy is and has been controlled by political and governmental entities, both national and international, throughout its history beginning in the 1940's when it was the sole property of various governments. In the United States, the only market for uranium was the Government from 1947 to 1964, and ownership of uranium became private in 1964. Every part of the nuclear fuel-cycle is controlled by the U.S. Government through laws, licensing, and regulations—this also applies to imports and exports of uranium.

URANIUM RESOURCES AND NUCLEAR POWER GENERATION BY REGIONS

The Energy Resource regions shown in figure 1 are based largely on the distribution of petroleum and coal resources. Although uranium resources are distributed quite differently, those regions are used here to be consistent with comparisons with petroleum and coal energy information. The discussion presented here begins with the highly populated Eastern United States—an area poor in uranium resources but with high nuclear power usage—and proceeds to more sparsely populated areas in the Western United States—an area rich in uranium resources but with low nuclear power usage. In 1993, there were 109 nuclear power generators with a capacity of about 100,000 MWe (EIA, 1994c).

ATLANTIC COAST AND APPALACHIAN BASIN

In 1993, the Atlantic Coast and Appalachian Basin (region 9, fig. 1) had 49 nuclear generators with a capacity of about 44,000 MWe, 44 percent of the Nation's total nuclear

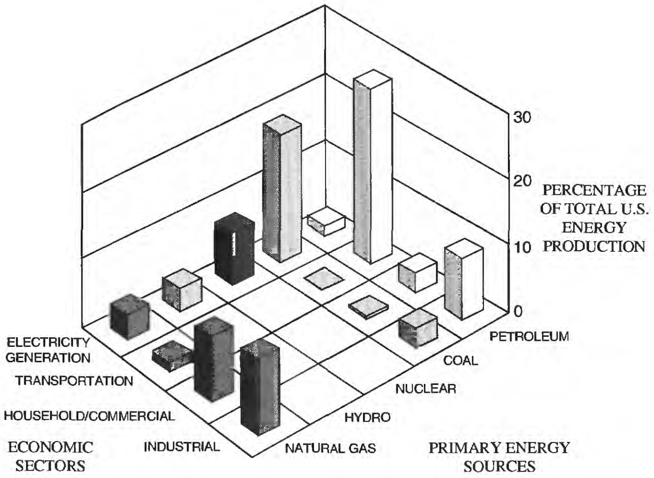

Figure 3. Graph showing percentages of the total U.S. energy production in 1991 related to primary energy sources and various economic sectors in 1991 (McCabe and others, 1993).

electrical capacity (EIA, 1994c). This region yielded a minuscule amount of uranium from small mines in Pennsylvania and New Jersey in the 1950's. A large uranium deposit, Swanson, occurs in igneous rocks in Virginia (fig. 1), but the State bans uranium mining so it is not an available reserve.

MIDCONTINENT REGION

In 1993, the Midcontinent region (regions 7 and 8, fig. 1) had 37 nuclear reactors with a generating capacity of about 33,600 MWe, 34 percent of the Nation's total nuclear electrical capacity (EIA, 1994c). A very small amount of uranium production (about 750 pounds U_3O_8) is recorded from two small prospects in Oklahoma (W.L. Chenoweth, consulting geologist, written commun., 1995). There are no viable uranium reserves.

GULF COAST REGION

In 1993, the Gulf Coast region (region 6, fig. 1) had 11 nuclear plants with a generating capacity of about 10,600 MWe scattered throughout the region from south Texas to Florida, amounting to 11 percent of the Nation's nuclear electrical capacity (EIA, 1994c). There are major uranium resources in the Gulf Coast region. The roll-front deposits in Tertiary sandstone formations in south Texas have been major producers since the late 1960's, and major ISL mining has contributed a large proportion of U.S. production in the 1990's. Total production from South Texas is about 70,000,000 pounds U_3O_8 through 1994 (compiled by W.L. Chenoweth from various sources). By-product production of uranium from manufacture of phosphoric acid fertilizer (from phosphorite mined in Florida and processed in Louisiana) has been important since 1991 and totals about 46,000,000 pounds U_3O_8 through 1994 (W.L. Chenoweth, consulting geologist, written commun., 1995).

PERMIAN BASIN

In 1993, the Permian Basin (region 5, fig. 1) had one reactor with a generating capacity of about 1,000 MWe that contributes 1 percent of the Nation's nuclear capacity (EIA, 1994c). Minor production (about 3,300 pounds U_3O_8) in the early part of the uranium era is recorded from uranium deposits in Triassic sandstones in west Texas and in Tertiary rocks in Hagan Basin.

COLORADO PLATEAU AND BASIN AND RANGE REGIONS

The Colorado Plateau (region 3, fig. 1) has no nuclear power plants, but it has provided about 94 percent of the uranium to the Nation, a total of nearly a billion pounds of U_3O_8. The Jurassic Morrison Formation in the Uravan and Grants mineral belts was the main source. Deposits in collapsed breccia pipes in Paleozoic rocks have in recent years yielded significant production.

In 1993, the Basin and Range region (region 3, fig. 1) had 3 nuclear power plants with a total capacity of about 3,600 MWe that contribute about 4 percent of the Nation's nuclear electrical generating capacity (EIA, 1994c). A small amount of uranium production is recorded from deposits in volcanic rock environments at McDermitt, Marysvale, and Date Creek in Oregon, Nevada, Utah, and Arizona.

ROCKY MOUNTAINS AND NORTHERN GREAT PLAINS REGIONS

The Rocky Mountains region (region 4, fig. 1) had no nuclear power plants operating in 1993, but did have one plant, a unique high-temperature gas-cooled reactor (HTGR) in Colorado, that operated intermittently from January 1974 to August 1989; it has been decommissioned. The Wyoming Basins region has been a major source of uranium; production totals about 210,000,000 pounds U_3O_8 through 1994 (compiled by W.L. Chenoweth, consulting geologist, written commun., 1995) A significant contribution has come from the Schwartzwalder high-grade vein deposit in Precambrian rocks in the Front Range of Colorado (Finch, 1996).

The Northern Great Plains (region 4, fig. 1) has no nuclear power plants. It has yielded about 6,300,000 pounds of U_3O_8 (compiled by W.L. Chenoweth, consulting geologist, written commun., 1995) from Cretaceous sandstone formations in the Black Hills region, mainly the Northern Black Hills district of Wyoming and Tertiary low-grade uraniferous lignite deposits (not shown in fig. 1) in North and South Dakota.

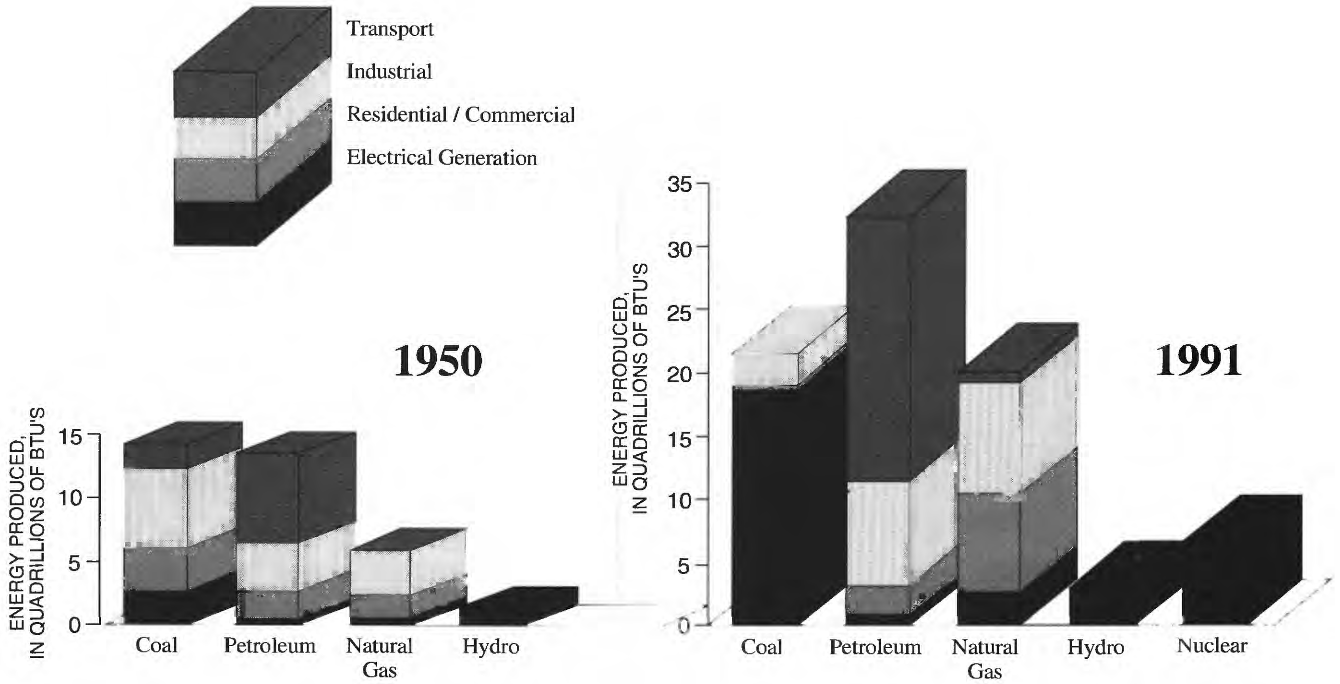

Figure 4. Distribution of primary energy sources for transport, industrial, residential/commercial, and electrical generation in the United States 1950 vs. 1991. Figure constructed by Peter McCabe in 1995, based on data in EIA (1994b).

PACIFIC COAST REGION

In 1993, the Pacific Coast region (region 2, fig. 1) had 5 nuclear power plants with a capacity of about 5,400 MWe, nearly 5.5 percent of the Nation's total capacity. Uranium production was about 12,000,000 pounds U_3O_8 (compiled by W.L. Chenoweth, consulting geologist, written commun., 1995) from mines in Cretaceous igneous rocks near Spokane in the State of Washington.

ALASKA AND HAWAII

There are no nuclear power plants in either Alaska or Hawaii (region 1, fig. 1). The only production from Alaska was from the Cub mine (670,000 pounds U_3O_8) on Bokan Mountain in Southeast Alaska. The uranium resources in Alaska are poorly known but are judged to be small; Hawaii has none.

GLOBAL USE OF NUCLEAR POWER

A GLOBAL OVERVIEW

Uranium resources are concentrated in a few places in the world, and the use of nuclear-generated electricity is concentrated mainly in developed countries. The bulk of historical production from 1946 to 1992 came mainly from Canada, Czechoslovakia, German Democratic Republic, South Africa, and the United States (table 1); in 1993 economic reasonably assured resources (RAR) of uranium were mainly in Australia, Canada, Namibia, Niger, South Africa, Kazakhstan, Uzbekistan, and the United States (table 2, footnote 3).

In 1992, uranium production worldwide was about 36,250 tU (metric tons of uranium) compared to 50,130 tU in 1990 (NEA/OECD, 1994). The world-wide distribution of more than 600 major uranium deposits shown by geologic type, size, and production status is illustrated on a digitized geologic map of the world by the International Atomic Energy Agency and Geological Survey of Canada (Finch and others, 1995).

In many countries of the world, such as Argentina, India, China, Mexico, and Russia, uranium is still the sole property of the government. Many utilities are owned and operated by national and local governments.

The greatest use of nuclear electrical power is in Europe and NAFTA (mainly United States and Canada), a total of 1,429 GWh generation vs. 1,896 GWh for the whole world (fig. 5). Most of the remainder is in the New Independent States (NIS) countries, 250 GWh, and in the Far East, 199 GWh, mostly Japan. Developing countries make up the remaining small amounts. World nuclear electrical generating capacity was 356.9 GWe in 1993, and its distribution reflects closely the net generation data (fig. 5) (NEA/OECD, 1994). World consumption in 1993 was about 149,000,000 pounds U_3O_8 compared to world production of 87,500,000 pounds (33,650 tU) (Pool, 1994a). The shortfall was made up from inventory, and production is expected to fall until

Table 1. Historic world uranium production in metric tons U, 1946–1992

[NEA/OECD, 1994, table 9. tU, metric tons of uranium]

Country	tU
Argentina	2,183
Australia	54,143
Belgium	490*
Brazil	960
Canada	257,692
CSFR**	102,245
Finland	30
France	68,174
Gabon	22,226
Germany	5,110
German Democratic Republic	213,380
Hungary	16,718
India	5,920
Japan	87
Kazakhstan	72,000
Mexico	49
Mongolia	549
Namibia	56,682
Niger	56,575
Pakistan	660
Portugal	3,568
Romania	16,850
Russian Federation	2,900
Solvenia	2
South Africa	143,302
Spain	3,774
Sweden	200
Ukraine	1,000
USSR	57,000
United States	339,290
Uzbekistan	2,700
Yugoslavia	380
Zaire	25,600
TOTAL	1,532,439

*Produced as a byproduct from imported phosphate.

**Czech and Slovac Federal Republics; most production from the Czech Republic.

inventory stocks are substantially reduced (NEA/OECD, 1994).

The world population has doubled in the past three decades and is expected to double again by the year 2020, mostly in developing countries (IAEA, Public Information Communication, June 1995). The need for electricity for the fundamentals for higher standards of living (such as food, clothing, and housing) in these countries will be enormous; nuclear power for generating electricity will be a major part of their energy policies as noted below (for example those for China, Indonesia, and India). This is brought out in the small number of planned nuclear power plants in developed countries, versus the large number in developing countries (NEA/OECD, 1996).

Table 2. Reasonably assured resources[1] (RAR) in the cost category $80/kg U or less in metric tons U as of January 1993 for selected countries.

[NEA/OECD, 1994, table 1. tU, metric tons of uranium]

Country[2]	RAR (tU)
Algeria	26,000
Argentina	4,600
Australia	462,000
Brazil[3]	162,000
Canada	277,000
Central African Republic	8,000
Czech Republic	15,850
France	19,850
Gabon	9,780
Greece	300
Hungary	620
Italy	4,800
Namibia	80,620
Niger	159,170
Peru	1,790
Portugal	7,300
South Africa	144,400
Spain	17,850
Sweden	2,000
Turkey	9,130
United States	114,000
Zaire	1,800
Zimbabwe	1,800
TOTAL	1,531,000

[1] RAR refers to known uranium deposits of delineated size, grade, and configuration that could be recovered in the cost range using current mining and processing technology.

[2] Denmark, Finland, Germany, Indonesia, Japan, Republic of Korea, Mexico, Slovenia, Somalia, Thailand, and United Kingdom report no resources in this cost category.

[3] Current 1995 market price of uranium is below $40/kg U, but some countries cannot report the category $40/kg U and less due to confidentiality of data; hence, compilation of the category $40/kg U or less was not published. Therefore, data in this table should not be taken as economic reserves. The large RAR for Brazil is an example of a small amount below the $40 kg U category so that the number is not comparable to other large RAR.

NORTH AMERICA FREE-TRADE AGREEMENT (NAFTA) REGION

The NAFTA region consists of Canada, United States, and Mexico (fig. 5). The United States led Canada in reserves and production in the early years, 1950–1970's, but Canada became the leader in the mid-1980's as the United States exhausted its low-cost, near-surface, relatively low grade (0.1–0.25 percent U_3O_8) sandstone ores, and Canada discovered and developed large, high-grade (1–12 percent U_3O_8), near-surface, unconformity-related ores in the 1980's (fig. 6). In 1993, Canada produced about 25,000,000

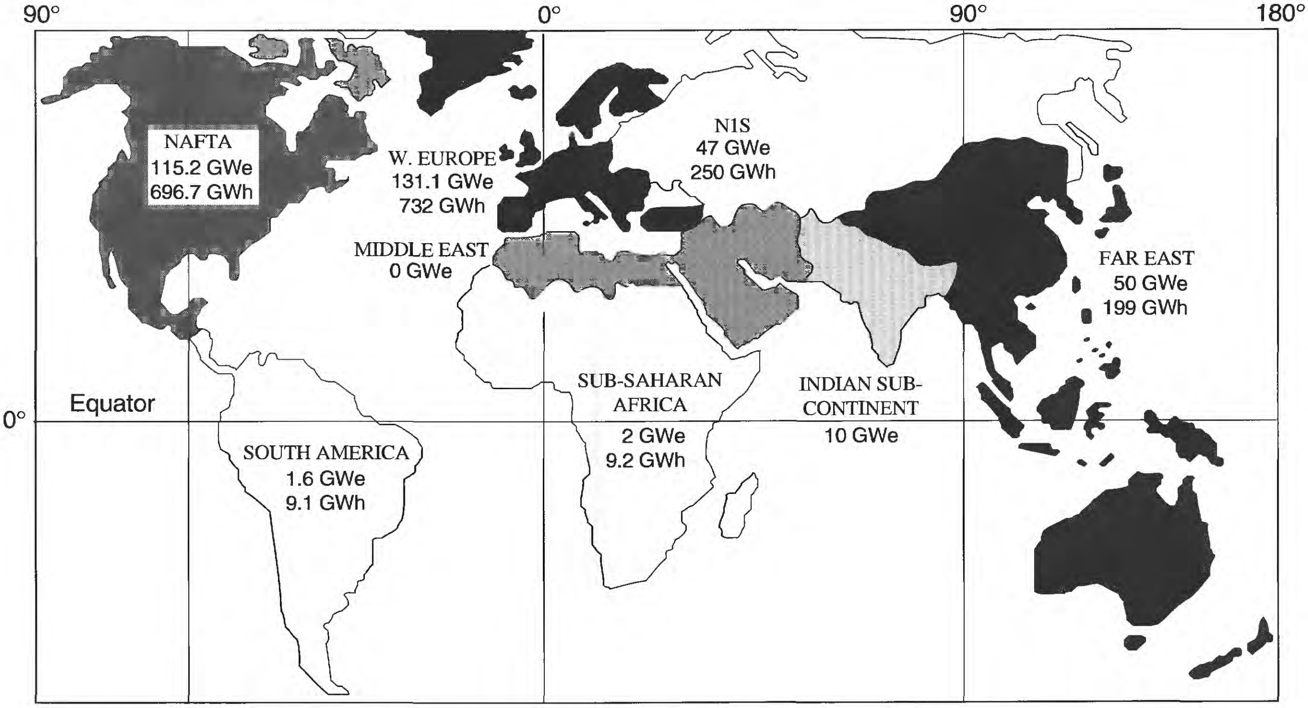

Figure 5. Map showing distribution of world nuclear electricity by generating capacity in GWe/net generation in GWh (world total = 356.8 GWe/1,896 GWh) for 1991 (NEA/OECD, 1994; EIA, 1994b).

pounds U_3O_8 (TradeTech, 1995) compared to 3,500,000 pounds by the United States; whereas in 1981, United States production was about 17,000,000 pounds and Canada's was about 7,000,000 pounds. The United States led world production (excluding Soviet Union and associated countries) from the beginning in 1947 and through 1981 (fig. 6). Mexico's reserves and production are relatively very small.

Canada's requirements for its 22 CANDU reactors, capacity 15,755 MWe, which provide about 17 percent of its electricity, are fully supplied by domestic 1,900 tU production (fig. 7, table 3) (NEA/OECD, 1994). The remaining Canadian production is exported, mainly to the United States under the 1992 North America Free-Trade Agreement (NAFTA). The export policy of Canada has been that uranium should be upgraded to a maximum, commonly as UF_6, before export, but the United States was exempt from this policy because of NAFTA, and in 1995 this policy requirement was to have been phased out worldwide. Canada imports only small amounts of enriched uranium for research and depleted uranium for castings.

The U.S. requirements for its 109 reactors, which in 1993 generated about 630,000 GWh and equaled one-third of world's nuclear electricity (TradeTech. 1995), are about 17,000 tU (44,000,000 pounds U_3O_8)—this was met by the domestic production, inventory, and imports. Imports totaled 21,000,000 pounds purchased under contract mainly from Canada, China, Australia, Russia, and Namibia (EIA, 1994d). Exports in 1993 totaled 3,000,000 pounds. Reasonably assured resources (RAR) recoverable at US$80/kgU in 1993 were 114,000 tU (table 2).

Mexico has one reactor with a capacity of 654 MWe and obtains its annual supply of 116 tU as fabricated fuel from U.S. Department of Energy, who maintains one reactor reload of 150 tU as UF_6 for Mexico (NEA/OECD, 1994). All uranium in Mexico is owned by the government; it produced 49 tU from 1969–71 mainly from volcanic ores at Peña Blanca, Chihuahua. Although in-place reserves total about 23,000,000 pounds U_3O_8 (Salas and Nieto, 1991), no production is anticipated in the near future.

SOUTH AMERICA

There are three nuclear power plants in South America, which have a combined capacity of 1.6 GWe (fig. 5).

Argentina has two power plants with a total capacity of 935 MWe that require 150 tU/yr. A third plant of 692 MWe capacity is expected to start in 1996 (NEA/OECD, 1994). All uranium is owned by the State, and production in 1992 was 123 tU from the San Rafael district, Mendoza Province. A total of 2,183 tU have been produced since 1953. In 1993, the reasonably assured resources (RAR) recoverable at US$80/kgU were about 4,600 tU (table 2).

Brazil has one power plant of 626 MWe capacity that requires 110 tU/yr, which is met from domestic production and enrichment. A second plant is under construction and others are planned. Uranium is State owned, but privatization is being planned. Production through 1990 was 960 tU; Pocos de Caldas, the major producing mining district where uranium occurs in collapse-breccia pipes, has been on

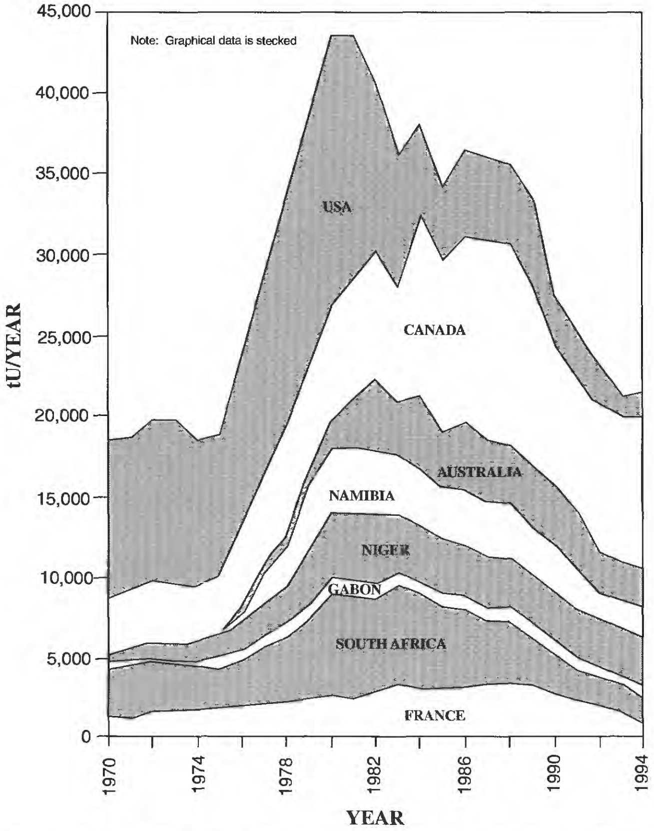

Figure 6. Production from selected major uranium-producing countries (Soviet Union and associated countries not selected), 1970-1994. Production for a specific country in a specific year can be calculated by subtracting the lower intercept from the upper intercept (NEA/OECD, 1996).

standby since 1988. RAR in the US$80/kgU or less category were 162,000 tU in 1993 (NEA/OECD, 1994).

WESTERN EUROPE

Mining of uranium in Western Europe (fig. 5), considered here as European countries outside the New Independent States (NIS), has decreased markedly from the peak years of 1970 to the mid-1980's to new lows in 1992 when many reserves neared exhaustion (see table 9 in NEA/OECD, 1994). The main producers were France (table 1, fig. 6) and the German Democratic Republic (GDR), Czechoslovakia (now Czech and Slovac Federal Republics, CSFR). Other producers were Portugal, Spain, Bulgaria, Hungary, and Romania. The Western European countries produced a total of about 5,500,000 pounds U_3O_8 in 1994, including uranium recovered during clean-up from closed mine sites in GDR, but this total is expected to decrease markedly in the near future (TradeTech, 1995). The chief ores in France were granite and high-grade vein types; in the other countries, they were mainly rich vein and low-grade sandstone ores. Production from GDR and other countries under Soviet influence went to the Soviet Union for military use prior to 1992. Now, this highly enriched uranium (HEU) is being downgraded by reprocessing for sale on the world market. Historic production from the GDR of 213,380 tU through 1992 ranks it third in the world behind Canada with 257,692 tU and the United States with 339,290 tU through 1992 . The legacy of the mining in GDR and other Soviet influenced countries is the multi-billion dollar cleanup up of mines and tailings with essentially zero dollars with which to do it.

In 1994, the 168 nuclear power plants in Western Europe generated a total of about 800,000 GWh, excluding the Czech and Slovak Republics, Lithuania, and Romania, which had 10 plants with a combined 6,6024 GWe capacity, and Ukraine (included below with CIS), which had 15 plants that generated 64,000 GWh (table 3) (TradeTech, 1995). France, United Kingdom (UK), and Germany, with 57, 35, and 21 plants, respectively, generated 78, 26, and 30 percent of their electricity (fig. 7). France and Germany had aggressive exploration programs outside their borders during the past 25 years that now provide a large share of their fuel needs. France obtains its major supply from Niger and Gabon. UK has no domestic uranium resources, and its strategy to obtain uranium supplies has been to diversify sources from major producing countries and from supplies generated by foreign exploration programs of the British Civil Uranium Procurement Organization. Bulgaria had six plants in 1994 with a capacity of 3,538 GWe (table 3) that generated 12,160 GWh, which is about 37 percent of its electricity. Extensive uranium mining of Bulgarian deposits began in 1946 and yielded an undisclosed large amount from 35 mines; mining was to have closed down in 1996 by government decree (NEA/OECD, 1994). Belgium, which gets nearly 60 percent of electricity from seven nuclear power plants (capacity 5,527 GWe), obtains its uranium fuel as a by-product of processing imported phosphate. Sweden, Switzerland, Finland, and Netherlands produce 42, 38, 32, and 5 percent, respectively, of their electricity from 23 nuclear plants with a total capacity of 15,801 GWe (table 3, fig. 7); they produce no uranium.

NEW INDEPENDENT STATES (NIS)

Uranium mine production from the New Independent States (NIS, fig. 5) of Russia, Kazakhstan, Ukraine, and Uzbekistan totaled about 15,500,000 pounds U_3O_8 in 1994 (TradeTech, 1995). Russia produced about 6,500,000 pounds from its only mine, which is in veins in volcanic rocks in southeastern Siberia east of Lake Baikal (NEA/OECD, 1994, p. 220). It is estimated that this mine produced more than 600,000,000 pounds since its start in 1946 (TradeTech, 1995). Most of Kazakhstan mining was by in situ leach (ISL) from sandstone ores, and it was third in 1994 world production behind Canada and Niger (TradeTech, 1995, p. 51). Kazakhstan's single nuclear power plant was shut down in 1994. Ukraine fulfills its domestic requirements for its 15

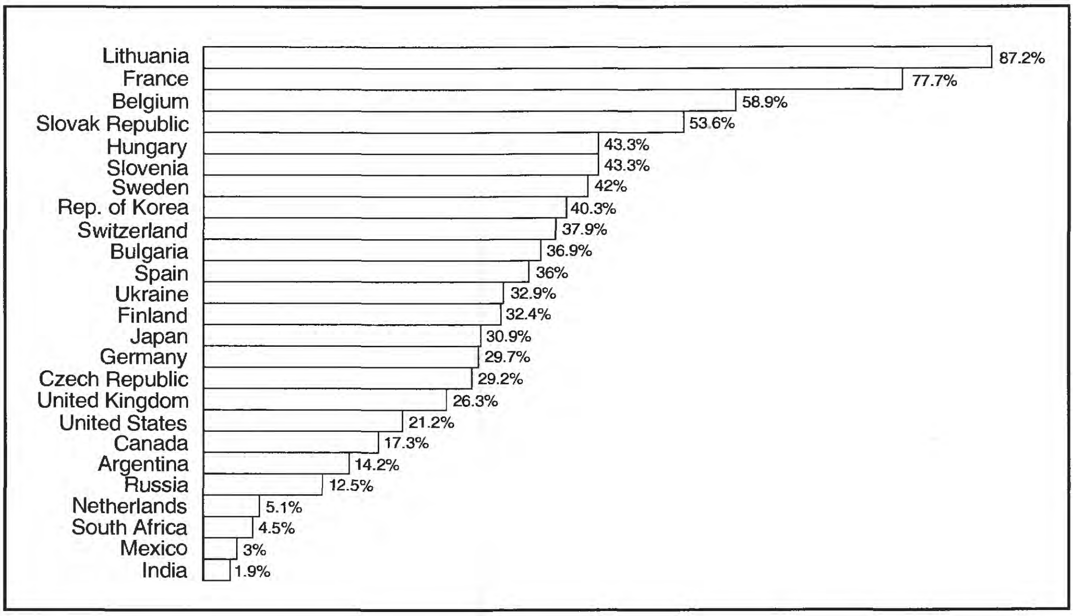

Figure 7. Nuclear power plant share of electricity generation as of December 1993 in selected countries (IAEA, 1995). Other countries include Pakistan (0.9% estimated); Kazakhstan (0.5%); China (0.3%); Taiwan, China (33.5%); and Brazil (0.2%).

nuclear plants, capacity of 12,095 MWe, mainly from mining metasomatic ores in the famous Zholtye Vody iron-ore district (TradeTech, 1995). Uzbekistan produced 5,900,000 pounds from ISL operations in sandstone ores; it has very large uranium reserves. Moderate reduction of uranium mining in NIS is expected in the near future.

With the U.S. Department of Commerce Suspension Agreement signed in 1994, Russia planned in 1995 to export enriched uranium to the United States obtained from downgrading of HEU weapons material. Both Kazakhstan and Uzbekistan have vast uranium reserves that they plan to mine and export, mainly to the United States under the same agreement.

Russia has 29 nuclear power plants that generate about 91,000 GWh (NEA/OECD, 1994), which is 12.5 percent of its electrical energy (fig. 7). Russia has complete nuclear fuel-cycle facilities and not only supplies its fuel needs but also those of the other NIS countries; although steps are underway for some to seek lower cost supplies outside of Russia. Since the Chernobyl accident on April 26, 1986, measures have been taken to upgrade the safety of existing plants and to redesign new plants under construction in Russia.

SUB-SAHARAN AFRICA

Uranium production from Sub-Saharan Africa (fig. 5) totals about 280,000 tU through 1992 from the four countries of South Africa, Namibia, Niger, and Gabon, which have been major world sources of uranium (NEA/OECD, 1994). South Africa has been the largest producer of uranium (143,000 tU) as a by-product from gold operations in the Witwatersrand quartz-pebble conglomerate basin. It produced 4,300,000 pounds in 1994. Namibia and Niger each have total production of nearly equal amounts of about 56,000 tU through 1992 (Namibia from the Rössing granite deposit and Niger from sandstone ores). They produced about 5,000,000 and 7,600,000 pounds U_3O_8, respectively, in 1994 (TradeTech, 1995). Niger ranked second in world production in 1992 (fig. 6). Production from Gabon was about 22,000 tU through 1992 and 1,500,000 pounds in 1994 from the Oklo district, famous for its natural nuclear reactors. The major proportion of uranium from Gabon and Niger goes to France through long-term contracts with COGEMA. Large deposits of uraniferous phosphate occur in Western Sahara, but by-product recovery of uranium has not been reported.

The only nuclear power reactors in Africa are the two in South Africa that generated 9.9 GWh through 1991 (Energy Information Administration, 1994a). By 1992, South Africa had produced 143,302 tU mainly as a by-product of gold mining in its famous Witwatersrand gold fields (table 1). South Africa has its own front-end nuclear fuel-cycle (fig. 2) capabilities to provide fuel for its power reactors. No records of exporting uranium have been found.

MIDDLE EAST

The Middle East countries (fig. 5) have not recorded any uranium production, and only few minable uranium deposits have been found. However, extensive deposits of uraniferous (average 0.009 percent U_3O_8) phosphate

Table 3. Status of nuclear power plants around the world as of April 1994 (IAEA, 1995).

[MWe = one million watts of electric power]

Country	In operation		Under construction	
	No. of units	Total net MWe	No. of units	Total net MWe
Argentina	2	935	1	692
Belgium	7	5,527		
Brazil	1	626	1	1,245
Bulgaria	6	3,538		
Canada	22	15,755	1	881
China	2	1,194	1	906
Cuba			2	816
Czech Republic	4	1,648	2	1,824
Finland	4	2,310		
France	57	59,033	4	5,815
Germany	21	22,559		
Hungary	4	1,729		
India	9	1,593	5	1,010
Iran			2	2,392
Japan	48	38,029	6	5,645
Kazakhstan	1	70		
Korea, Rep. of	9	7,220	7	5,770
Lithuania	2	2,370		
Mexico	1	654	1	654
Netherlands	2	504		
Pakistan	1	125	1	300
Romania			5	3,155
Russian Federation	29	19,843	4	3,375
South Africa	2	1,842		
Slovak Republic	4	1,632	4	1,552
Slovenia	1	632		
Spain	9	7,101		
Sweden	12	10,002		
Switzerland	5	2,985		
United Kingdom	35	11,909	1	1,188
Ukraine	15	12,679	6	5,700
United States	109	98,784	2	2,300
WORLD TOTAL*	430	337,870	55	44,369

*The total includes Taiwan, China, where six reactors totalling 4,890 MWe were in operation.

occur throughout Late Cretaceous to Eocene rocks of the paleo-Tethys Sea that stretched from Iraq, Syria, Jordan, and northern Saudi Arabia to Morocco and Western Sahara (de Voto and Stevens, 1979). The latter two have extracted by-product uranium during the manufacture of acid phosphate fertilizer (de Voto and Stevens, 1979).

There are no nuclear power plants in the Middle East countries.

INDIAN SUBCONTINENT

This region has uranium resources only in India and Pakistan (fig. 5). They are relatively small and production in 1994 was less than 1,000 tU.

India has a large national exploration and resource evaluation program that is independent of any international assistance. Success has been moderate, but identified resources and fuel-cycle processing operations are adequate for its domestic fuel requirements. India has nine nuclear power plants, two BWR and seven pressurized heavy-water-moderated and cooled reactors (PHWR), with a 1,834-MWe capacity, and, in 1994, 4,434 GWh were produced, which provided about 1.9 percent of the electricity supply (TradeTech, 1995). Nearly 20 new plants are either under construction or planned, with a combined capacity of 7,440 MWe (TradeTech, 1995).

Pakistan has one nuclear power plant, a CANDU, with a capacity of 125 MWe (TradeTech, 1995). Pakistan's acute shortage of electrical power and other forms of energy make nuclear power attractive.

Neighboring India and Pakistan have both refused to sign the International Treaty for the Non-Proliferation of Nuclear Weapons; this has forced both to develop their own complete fuel-cycles (fig. 2). Pakistan is banned from importing uranium in any form and may not import hardware for reactors and fuel-cycle facilities, including material for heavy-water plants. Its enrichment plant apparently has not been able to produce weapons-grade U-235 (TradeTech, 1995).

FAR EAST

The Far East, including Southeastern Asian countries, equatorial island countries, and Australia, is characterized by extremes of one country with very large uranium resources, low-density population, and no nuclear plants to generate electricity to many countries with high-density populations, rapidly expanding needs for electricity, options to increase nuclear power plants, and either relatively small or no uranium resources.

Japan, with few indigenous energy resources, has "the world's most progressive and comprehensive long-term nuclear power program" (TradeTech, 1995). It had 48 nuclear plants with a capacity of 38,029 MWe in operation in 1994 that generated more than 243,000 GWh of electricity, which is about 31 percent of its requirements and makes Japan the third largest user of nuclear electricity (table 3, fig. 7). Growth in demand for electricity has prompted Japan to begin construction of seven nuclear power plants with a combined capacity of 5,770 GWe and to order 16 new plants with a combined capacity of 16,766 GWe to meet growth in demand. Uranium production since 1969 totals only 45 tU, and none of its identified uranium resources of 6,600 tU are economic (NEA/OECD, 1994). All of Japan's uranium requirements are fulfilled by imports mainly through long-term contracts with major world suppliers. Japan plans to reprocess spent fuel, recycle plutonium and uranium, and use breeder reactors in the future to conserve on imports of uranium and to reduce the amount of high-level waste (Trade Tech, 1995). A prototype liquid metal fast breeder reactor went on line in 1995, but plans for more are delayed (TradeTech, 1995). Japan has a commercial enrichment plant. Japan is the world leader in technology for recovering uranium from seawater.

China had three nuclear plants with a capacity of 2,080 MWe in operation since 1993 that contributed less than one percent of its electrical needs, so it has low domestic requirements for uranium fuel to generate electricity (TradeTech, 1995). However, it has one plant under construction with a capacity of 906 MWe and plans for 11 new reactors with a combined capacity of 8,800 MWe. China has an official policy of not allowing publication of uranium reserve and production data. However, production in 1994 was estimated to be about 1,500,000 pounds U_3O_8 mainly from granite deposits in southeast China; from 1963 through 1993 China produced about 45,000,000 pounds (TradeTech, 1995). About 30,000,000 pounds of this was probably exported, and the present inventory is about 14,000,000 pounds (TradeTech, 1995). New important discoveries in sandstone formations have been reported in remote basins in northwest China (NEA/OECD, 1994). China has its own fuel-cycle facilities, including reprocessing.

Taiwan, China, has six nuclear power reactors with a capacity of 4,890 GWe that generate about 33,000 MWh of electricity, which yields 33.5 percent of its electricity. It has no uranium reserves.

Mongolia has no nuclear power plants. Uranium production began in 1989 from several volcanic deposits and totaled about 450 tU by 1992, which was processed in Siberia, Russia (NEA/OECD, 1994). Landlocked Mongolia has a large uranium resource potential.

The Republic of Korea has nine reactors with a capacity of 7,220 MWe that generated more than 55,000 GWh in 1994, which is 40 percent of its electricity (TradeTech, 1995). Seven plants with a total capacity of 5,770 MWe are under construction (table 3). It has no economic deposits of uranium. Korea has joint ventures with foreign countries, such as the United States, for supply and has no domestic fuel-cycle services. Imports have been from stable suppliers, such as United States, Canada, Australia, and Russia.

North Korea has no nuclear plants to generate electricity but apparently has a uranium mine and mill complex at Pyongsam in the south and some fuel fabrication and reprocessing capabilities (Nelan, 1994).

Malaysia, Philippines, Thailand, and Vietnam have no operating nuclear plants and few uranium reserves. A plant in the Philippines was not running in 1993.

Indonesia has a great need for electrical energy but has no nuclear plants operating. One was under construction and scheduled to start in 1996 (TradeTech, 1995). Indonesia has a pilot fuel fabrication plant. It has fairly high grade uranium vein ores in West Kalimantan (Borneo), but their remote location makes them non-economic.

Australia, which is in the Southern Hemisphere and generally considered outside the Far East region, has large, high-grade, low-cost uranium resources and no nuclear power reactors. In 1994, Australian production was 5,700,000 pounds of U_3O_8, which was 10 percent of Western World production; it has 30 percent of world reserves (Trade Tech, 1995). All of its production is exported. Mining of its reserves in 1994 was constricted by the government's "three-mine policy" that limits only three active mines in operation at one time. Reasonably assured resources (RAR) at low cost totaled 462,000 tU (NEA/OECD, 1994). Australia's southern neighbor, New Zealand, is a nuclear-free country with a few very small uranium deposits.

URANIUM USE AND THE ENVIRONMENT

Environmental effects are a part of the entire fuel-cycle: front-end, in-plant, and back-end, as shown graphically on figure 2 for the lifetime of a typical light-water reactor (LWR) plant. The front-end and in-plant wastes consist of gamma rays, alpha particles, various radionuclides, and non-radioactive chemicals in gaseous, liquid, and solid forms. Plutonium is a major environmental hazard in the in-plant and back-end cycles. The radionuclide wastes may be contained within the cycle (fig. 2) or transmitted directly to the atmosphere, ground surface, and surface and ground waters. The radionuclides may affect the health of the workers and, in some cases, that of the general population. Radioactive materials produced by nuclear power plant reactors (fig. 1) are those of the nuclear chain reaction and are well controlled under normal operating conditions. Radioactivity contributed to individuals in the plant are well below those received from natural radiation sources (Nero, 1979). Detailed discussion of radionuclide wastes for the LWR and other types of reactors are found in the works of Nero (1979) and Eisenbud (1987).

RADIONUCLIDES

A radionuclide is a radioactive species of an atom. A radioactive element changes its structure by releasing protons, neutrons, electrons, or energy to become a new element or isotope, known as a daughter product—a process known as radioactive decay. Radioactivity from decay takes the form of gamma rays, alpha particles, and beta particles; gamma rays are the most dangerous form of radioactivity; they, like the other forms of radioactivity, are undetectable by our senses. The time it takes for one-half of an element to decay is a half-life. The main radionuclides in the natural environment are uranium-238 (half-life 4.4 billion years), uranium-234 (half-life 250,000 years), radium-226 (half-life 1,620 years), and radon-222 (half-life 3.82 days) (Wirt, 1994). The shorter the half-life, the more hazardous a radionuclide is to human health. Radon from natural occurrences and tailings created by uranium mining, and from other activities in the front end of the fuel-cycle, is a national problem (fig. 2). The U.S. Geological Survey has had an extensive research program studying radon hazards from natural causes (Otton, 1992; Gunderson and Szabo, 1995). In 1994, a concerted research effort was begun to study the effects of radon and other radionuclides related to operating, inactive, and abandoned uranium mines.

PRE-NUCLEAR AGE

Before the discovery of fission of uranium in 1942, radioactivity in the Earth's environment was due to natural sources, namely uranium, thorium, radioactive potassium, and radium, and to decay products of these elements, such as radon from radium. All underground water contains a natural radioactivity due chiefly to uranium, radium, and radon (Zapecza and Szabo, 1986). The natural radioactive elements are distributed unevenly in all rocks and soils; in places, deposits of uranium and thorium have formed and crop out at and near the land surface. Radium was recovered from uranium/vanadium mines in Colorado in the early 1900's. Many small mines and 10 mills to extract vanadium from the uranium deposits in the Colorado Plateau region were developed before 1942. Uranium was not generally recovered and went into tailings piles, which increased the environmental radionuclide impacts.

WEAPONS USE

The initial use of the fission products was for weapons in 1943, and the extensive, extreme environmental concerns of activities related to production of bombs are addressed by the U.S. Department of Energy, Office of Environmental Management (1995). Tritium and about 100 metric tons of plutonium for warheads were produced from 14 nuclear reactors between 1944 and 1988 that yielded about 2,700 metric tons of spent fuel stored in nearly 30 indoor pools of water, one-tenth of that stored by electric utilities, mainly at Hanford, Wash.; Savannah River, S.C.; West Valley, N.Y.; and the Idaho National Engineering Laboratory. The storage of highly enriched uranium (HEU) is in deep rock-salt formations at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, N. Mex.

Plutonium, a man-made radioactive element discovered in 1940 and later produced extensively by fission of uranium, was nonexistent in nature. Since the advent of aboveground nuclear testing and peaceful applications of nuclear energy, plutonium has become measurable in most soils and water throughout the world. Pu-239, one of several hazardous isotopes of plutonium, has a half-life of 24,000 years and is most abundant near nuclear facilities and test sites.

PEACEFUL NUCLEAR USE

Although the earliest use of uranium was in weapons programs, peaceful uses of nuclear power began in the early 1950's. Since then most uranium mined in the United States has been used for electrical power generation.

MINING AND MILLING HAZARDS

In early mining of uranium, little attention was paid to hazards of radon gas emitted from uranium ores within mines so that few underground mines were properly ventilated. Modern mining requires adequate ventilation, and dosages of radiation for each miner are now monitored. The higher the uranium grade of the ore the greater is the radon emission. At Cigar Lake in Saskatchewan, Canada, the ores average more than 10 percent U_3O_8 so that the ore is mined remotely without human contact.

Mining and milling of uranium ores for both weapons and peaceful uses in the United States have produced more than 35,000,000 cubic meters of radioactive mill tailings that contain radium, emit radon, and contain toxic heavy metals such as lead, molybdenum, and vanadium (U.S. Department of Energy, Office of Environmental Management, 1995). Although sulfur in the form of iron-sulfide (pyrite) is present in nearly all domestic uranium ores, it rarely is rich enough (>10 percent S) to cause acid drainage problems from mines and mills (Finch, 1993). The only significant example of sulfide-bearing ores are in quartz-pebble conglomerate deposits in the Elliot Lake area, Canada, where acidic tailings are a serious problem (Chung, 1995). These kinds of ores do not occur in the United States. The elements selenium and arsenic associated with sulfur in sandstone ores in the United States, however, are a problem.

LAND-USE CONCERNS RELATED TO NUCLEAR ENERGY GENERATION

Each part of the nuclear fuel-cycle impacts land use, but the total land area required for the 30-year cycle of one 1,000-MWe plant is small—only 350 acres distributed in many separate places in the United States (fig. 2). Reclamation of mines is regulated by the Environmental Protection Agency and individual State government agencies, mainly in Arizona, Colorado, Nebraska, New Mexico, Texas, Utah, and Wyoming. Reclamation of many open-pit mine areas has returned land surfaces to safe agricultural, range, and recreational uses. The Uranium Mill Tailings Radiation Act of 1978 (UMTRCA) governs environmental restoration of uranium mill sites (Chung, 1995). Mill site remedial actions, including the dismantling of surface structures, tailings reclamation, and ground-water restoration, are being carried out by the U.S. Department of Energy for mills operated by the U.S. Atomic Energy Commission, the predecessor agency of the U.S. Department of Energy (DOE) (EIA, 1995a).

Contamination of ground water by uranium mining activities appears to be insignificant (Wirt, 1994, p. 20). A detailed study of 20 years of extensive uranium mining in the San Juan Basin, New Mexico, and a very large single accidental release of uranium mill tailings and contaminated water in 1979 in the Puerco River basin in New Mexico revealed insignificant contamination of ground water in the basin (Wirt, 1994). However, the impact of unanticipated ground-water problems can be costly for individual mines (T. Chung, written comm., 1995).

Mining of deposits of radioactive minerals can be as safe for miners as mining any metal deposit but requires additional safety measures, mainly proper ventilation and the monitoring of radiation exposure. Uranium mining is certainly safer than coal mining, which involves dangerous explosive gases (Finch, 1993).

STORAGE OF SPENT FUEL FROM POWER PLANTS

Nearly all spent fuel is stored at the nuclear power plant site in a building with a steel-lined water pool that holds and cools the fuel rods and shields the surroundings from radioactivity. The Nuclear Waste Policy Act of 1982 required that the U.S. Department of Energy provide a national disposal site by January 31, 1998. It also required that utilities charge their customers one cent per KWh for a nuclear waste fund to develop the site. Many potential sites were investigated, and the Yucca Mountain, Nev., site has been selected. It is not expected to be ready without further large costs until well after the year 2000. The facility would house utility waste of more than 30,000 metric tons (U.S. Department of Energy, Office of Environmental Management, 1995).

GLOBAL CHANGES

Nuclear power plants are environmentally clean with respect to acid rain, global warming, and ozone depletion.

FUTURE URANIUM USE FOR POWER GENERATION

The role of uranium in the energy mix in the United States will vary little into the next century unless radical changes are made in ordering new nuclear power reactors. If none are ordered, a marked decrease in nuclear electrical power will take place in about 30 years as old plants are decommissioned (fig. 8).

The future role of uranium in the world energy mix may be 3 to 24 times the current usage according to Pool (1994b), who studied the long-term, large-scale nuclear fuel requirements. The presently identified uranium resources in conventional-type deposits and by-product phosphorite sources, and the available weapons material are a sufficient supply for 500 years for current requirements for capacities equal to existing nuclear power plants.

FUTURE U.S. URANIUM PRODUCTION

The future of uranium production in the United States will depend largely upon the political and social attitudes relative to the acceptance of nuclear electrical power plants, the necessity of nuclear-power-plant waste facilities, and the dangers of possible global warming related to continued use of fossil fuels for electrical power generation. Utility decisions to build new, safe, and lower cost nuclear reactor plants more quickly as replacement and new base-load plants in the latter part of this century and into the next are the key elements for the future. The choice for individual utilities is either coal or uranium. And, finally, the world market for uranium will influence the mining of uranium in the United States.

To illustrate the near future, a review of the uranium mining industry during the past few years will be worthwhile. Production of uranium in the United States doubled to 6,000,000 pounds U_3O_8 in 1995 compared to the 1993 value of 3,000,000 pounds (EIA, 1996), then at its lowest level. This was brought about mainly when, in 1994, the U.S Department of Commerce amended the 1993 U.S./Russia Suspension Agreement to limit Russian uranium imports to be equal to purchases of newly produced U.S. uranium. Russian imports will be limited to 4 million pounds U_3O_8 each year until 2003 (TradeTech, 1995, 1996; Pool, 1996). This level of increased uranium production is expected to continue well into the 21st century. It is unlikely that the United States will ever again become a major source of newly mined uranium; in fact, its standing in world production may decrease from the present 4th position to a lower position. On the other hand, the United States could become a major source of uranium supply from downgraded HEU in weapons stockpiles. A decision to market the surplus highly enriched uranium (HEU) inventory was expected in 1996 (TradeTech, 1995, p. 118). The Department of Energy has set up the private United States Enrichment Corporation (USEC) to produce and market SWU (separative work units) (TradeTech, 1995, p. 16).

A widening gap between demand and supply for uranium worldwide developed in 1995 (Pool, 1996; NEA/OECD, 1996). In 1995, world consumption was 156.1 million pounds U_3O_8 compared to world production of 85.3 million pounds, the largest gap to date and a sign of rapid depletion of existing inventories (IAEA, 1996). In the United States in 1995, the annual nuclear fuel requirement to generate 23 percent of our electricity was about 43 million pounds, which was only one-seventh fulfilled by domestic production. The spot price for uranium rose from an all-time low of \$7.25/pound U_3O_8 in October 1991 (Pool, 1992) to \$16.10/pound in April 1996 (TradeTech, 1996). Because of higher prices, domestic producers should be able to increase their production and share in the requirements. Expansion of present and addition of new ISL (in situ leach) mining operations in Texas, Wyoming, and Nebraska are expected as well as opening of mines that presently are on standby.

FUTURE OF NUCLEAR POWER REACTORS

Originally, nuclear power reactors were given 30-year licenses by The Atomic Act of 1954, but the Nuclear Regulatory Commission (NRC) in 1982 extended the operating license for commercial nuclear power plants to 40 years, beginning on the date of issuance. The year of expiration of 109 units and their graphed loss of capacity are shown in figures 8 and 9. In figure 8, the beginning date of 2002 reflects the reactors that came on line in 1962. It also reflects a large increase of new reactors in 1972 and later years and the last power plant to come on line in 1993. Only two plants are scheduled to shut down by 2008. A steady decrease in capacity is shown to begin in 2012 (fig. 9).

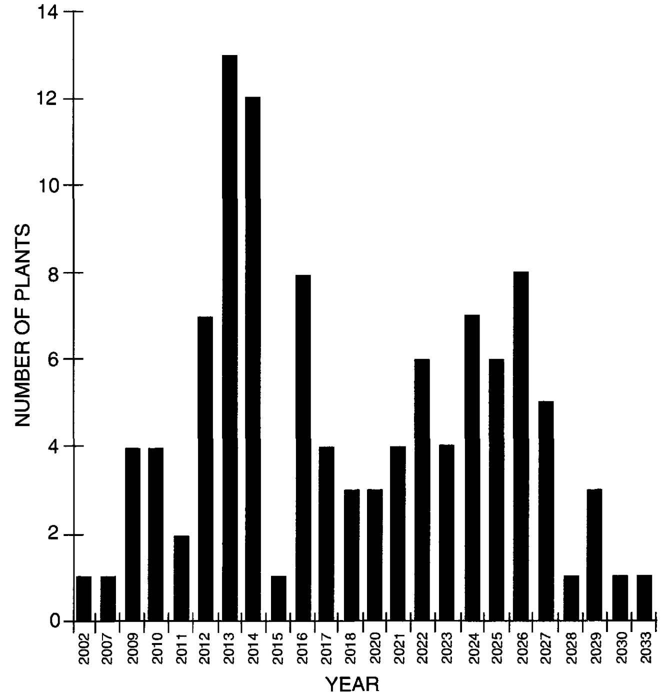

Figure 8. Number of U.S. nuclear power plant licenses expiring during the years 2002–2033. Expiration dates assume that all plants will apply for and be granted extension of licenses (20 pending). (Scott Peters, Nuclear Energy Institute, Washington, D.C., written commun., July 1995).

The questions of when and if any new reactors will be planned in the United States are dependent upon decisions of the utilities based on economics, public opinion, solution of waste-management problems of present reactors, Government policies, and political actions. The future of nuclear power reactors in the United States is less promising than in the rest of the world, which is moving ahead with aggressive nuclear electrical power programs. The main issue is the use of nuclear power for base-load electricity, whose main competition is coal, which has its own environmental problems. In the next 10 years, there will be a need to build many more base-load plants for increases in demand.

NEW REACTOR TECHNOLOGIES

The new generation of nuclear reactor designs (including the advanced pressurized light-water PWR, BWR, PHWR, and FBR; see Glossary) are to be significantly simplified, "passively safe" (i.e., they rely on natural circulation and actuation of check valves requiring no human action), smaller and modular (600 MWe), quicker to build, and lower in cost (Kabanov and others, 1992; Ahearne, 1993). There are more than 40 concepts being considered worldwide, mainly in the United States, Canada, Japan, France, Germany, Sweden, and Russia (some by international cooperation). Two American advanced nuclear plant designs based on plants already in operation throughout the world are the ABB Combustion Engineering Nuclear Systems advanced pressurized water reactor (APWR), Systems 80+, and the General Electric advanced boiling water reactor (ABWR), both rated at 1,300 MWe (Nuclear Energy Institute, 1995). In the United States, two principal modular, simple, passive designs of small size (600 MWe compared to 1,300 MWe) are the Westinghouse AP-600, which has been given NRC approval (Stinson, 1991), and the General Electric simplified boiling water reactor (SBWR) design that uses no pumps to circulate cooling water but relies on temperature differences and convection—this design is scheduled to receive final design approval in 1997 and certification in 1998 (Nuclear Energy Institute, 1995). Two new plants of another new, advanced, light-water, ABWR design by General Electric/Hitachi/Toshiba are being built in Japan for testing.

The U.S. Energy Policy Act of 1992, Code of Federal Regulations 10, enacted a "one-step" procedure that combined the construction permit and operating license of nuclear plants by the Nuclear Regulatory Commission (NRC). The new procedure ensures that all major issues—plant design, safety, siting, and public concerns—are settled before a utility starts plant construction. The procedure consists of three stages: (1) plant design certification, (2) early site approval, and (3) issuance of construction permit and operating license, all of which require extensive NRC reviews, opportunities for appropriate public participation, and final judicial review (Nuclear Energy Institute, 1995). Plant-design certifications are given for each new design and are perpetual. Recent case histories of the new-design plant constructions in Japan and South Korea record construction in 5-year time frames. A reasonable estimate of lead times for the establishment of new nuclear power plants in the United States is seen to be on the order of 5 to 7 years.

POTENTIAL CHANGES IN U.S. URANIUM EXPORT/IMPORT PATTERNS

Present export/import patterns are not expected to change significantly. However, major supplies of uranium from Russia will result from the dismantling of nuclear warheads that yield very large amounts of 3-percent U-235 from 80–90 percent U-235 in warheads. Most of this new supply of Russian uranium will be exported, and much of it will be exported to the United States. In 1994, U.S. imports of uranium were mainly from Canada, but large amounts were imported from Uzbekistan, Kazakhstan, Australia, and Kyrgyzstan (EIA, 1995b).

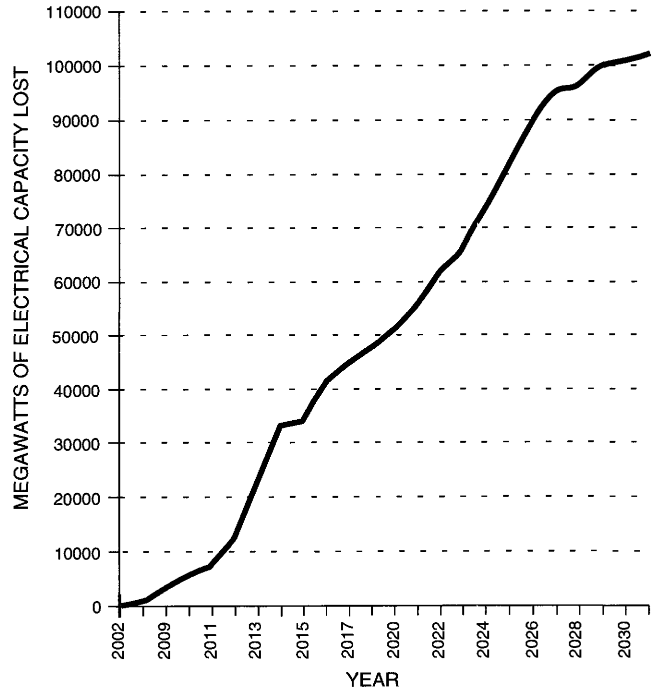

Figure 9. Cumulative megawatts electric capacity lost due to U.S. nuclear power plant license expirations during the years 2002–2033. Expiration dates assume that all plants will apply for and be granted license extensions (20 pending). (Scott Peters, Nuclear Energy Institute, Washington, D.C., written commun., July 1995.)

Export of natural uranium and enriched uranium of U.S. origin is controlled by the Nuclear Regulatory Commission (NRC) licenses. Safeguards against their use for nuclear explosives must be guaranteed. In 1994, exports of uranium amounted to about 18 million pounds of U_3O_8, much of which involved material previously imported for conversion, enrichment, and fuel fabrication (EIA, 1995b). Little of this material was of U.S. origin.

GEOLOGICAL URANIUM STUDIES THAT ADDRESS THE FUTURE ENERGY MIX

ENVIRONMENTAL STUDIES RELATED TO URANIUM

The need for new geologic studies of uranium ore deposits will remain low, except as they relate to solving environmental impact problems of inactive, active, and abandoned uranium mines. The Survey's environmental impact studies begun in late 1994 were discontinued in 1995. No future program support is planned.

RESOURCE ASSESSMENT OF URANIUM

Energy and mineral resource assessments are dynamic exercises that result in improved estimates with consideration of data on deposit depletions, new deposit and district discoveries, better knowledge of deposit size and grade distributions, new resource assessment methodologies and recovery technologies, and new geoscience research results. The experience of the recent assessment of U.S. oil and gas resources by the U. S. Geological Survey has shown that utilization of similar factors resulted in rigorous and more credible estimates than a previous assessment done only 6 years earlier (Gautier and others, 1995; U.S. Geological Survey National Oil and Gas Resource Assessment Team, 1995). The first and only national uranium assessment was the National Uranium Resource Evaluation (NURE) program, completed by the U.S. Department of Energy in 1980. Since then, new resource areas have been developed, new types of deposits have been discovered, new mining methods have become available, and new resource-estimating methodologies have been developed. The new areas and types of deposits that have been assessed using one new estimating method (Finch and McCammon, 1987; Finch and others, 1990; McCammon and Finch, 1993) include surficial uranium deposits in the State of Washington (Finch and McCammon, 1987) and solution-collapse breccia deposits in the Grand Canyon region (Finch and others, 1990). A new important roll-front deposit mining district has opened in Nebraska (Collings and Knode, 1984). Using the 1980 assessment of uranium endowment, the Energy Information Administration (EIA) makes annual calculations of the economic portion of the 1980 resources and the few new identified endowments (EIA, 1995b). Because of new discoveries of deposits and districts, new and improved assessment methodologies, and new geoscience research results, the original 17-year-old assessment is significantly out of date. A new national uranium resource assessment may be needed to prepare for a potential upswing in domestic uranium mining, which would decrease our dependence on foreign supplies.

GLOSSARY OF TERMS

Base-load: The minimum amount of electric power delivered or required over a given period of time at a steady rate.

Base-load plant: A plant commonly housing high-efficiency steam-electric units that is normally operated at a constant rate and continuously to take all or part of a minimum load of a system. These units are operated to maximize system mechanics and thermal efficiency and to minimize system-operating costs.

Boiling-water reactor (BWR): A light-water reactor in which water, used as both coolant and moderator, is allowed to boil in the core. The resulting steam can be used directly to drive a turbine.

Breeder reactor: A reactor that both produces and consumes fissionable materials, especially one that creates more fuel than it consumes. The new fissionable material is created by a process known as breeding, in which neutrons from fission are captured in fertile materials.

CANDU (PHWR): Canadian deuterium-uranium reactor (pressurized heavy water reactor) that uses natural uranium as a fuel and heavy water as a moderator and coolant. Heavy water contains a significantly greater proportion of heavy hydrogen (deuterium) atoms than ordinary water.

Capacity: The amount of electric energy delivered by a generator, station, or system as rated by the manufacturer.

Capacity factor: The ratio of the electricity produced by a generating unit, for the period of time considered, to the energy that could have been produced at continuous full-power operation during the same time.

Chain reaction: A sustaining series of nuclear fission reactions; neutrons produced by fission cause more fission.

Conversion: Changing yellowcake, U_3O_8, to UF_6 by a solvent extraction–fluorination process.

Energy mix: The historical and current proportions of various materials (coal, oil, gas, uranium, renewables, wood, etc.), forces (hydroelectric, wind, ocean currents, etc.), and processes (fusion, fission, solar, etc.) used to produce the total energy supply for a given geographic area.

Enrichment: The increase of one isotope in proportion to another, specifically U-235 over U-238 for nuclear reactors. Gaseous diffusion or other processes are typically used.

EUP: Enriched uranium product.

FBR (Fast breeder reactor): A reactor in which the fission chain reaction is sustained primarily by fast neutrons rather than by thermal or intermediate neutrons.

Fertile material: Material, principally U-238 and Th-232, not itself fissionable by thermal neutrons but which can be converted to fissile material by irradiation.

Fissile: Capable of being split by a low-energy neutron.

Fissionable: Capability of nuclei, such as uranium and plutonium, to be fissioned.

Fuel-cycle: The complete series of steps to supply fuel and dispose of wastes for nuclear reactors, including exploration, mining, milling, enrichment, conversion, fabrication, in-plant steam generation, interim storage, reprocessing, and perpetual storage.

Fusion: The process whereby the nuclei of light elements, especially isotopes of hydrogen (deuterium and tritium), combine to form the nucleus of a heavier element with the release of substantial amounts of energy.

GWe (Gigawatt-electric): One billion watts of capacity to generate electricity—a measure of power.

GWh: One billion watt hours—the product of power (GW) and its time of operation (hours) commonly reported for specific period of time, such as a year.

Half-life: The time it takes for one-half of a radioactive element to decay.

Heavy water: Water that contains deuterium atoms in place of hydrogen atoms; used as a moderator for reactor cores.

HEU: Highly enriched uranium, generally 80 to 90 percent U-235; used in weapons.

HLW (high-level waste): Consists mainly of spent fuel and material created by reprocessing spent fuel, and by the production of plutonium.

HTGR: High-temperature gas-cooled reactor.

In situ leach (ISL) mining: The in-place mining by chemical leaching of valuable elements of a mineral deposit without removing overburden or ore by installing a well and mining directly from the natural deposit thereby exposed to the injection and recovery of a fluid that causes the leaching, dissolution, or extraction of the mineral (EIA, 1995b).

Isotope: Different forms of the same chemical element that differ in the number of neutrons within a nucleus of the same number of protons; each isotope has slightly different physical and chemical properties by which they may be identified.

KWe: One thousand watts of electric capacity.

Lixiviant: A solvent that extracts soluble constituents from a solid material (rock) by washing or percolation.

Load (electric): The amount of electrical power delivered or required at any specific point or points on a system.

LWR (light-water reactor): A nuclear reactor that uses water as the primary coolant and moderator and slightly enriched uranium (approximately 3 percent U-235) as a fuel.

Moderator: A material, such as ordinary water, heavy water, graphite (crystalline form of carbon), used in a reactor to slow down high-velocity neutrons, thus increasing the chances of further fission.

MWe: One million watts of electric capacity.

Nuclear fission: The splitting of the nucleus of a heavy element by particle collision into a pair of fission fragments plus some neutrons (either spontaneous or induced).

Nuclear reactor: A device that sustains a controlled nuclear fission chain reaction (EIA, 1991).

Nucleus: The clump of protons and neutrons at the center of an atom that determines its identity and its physical and nuclear properties.

Nuclide: A species of atom characterized by the constitution of its nucleus, the number of neutrons, and the energy content; synonym of isotope.

Passive safety: Safety that is provided by the physical and chemical properties of a reactor system rather than mechanical safeguards or human intervention.

Peak-load plant: A plant based on low-efficiency steam power generating units, commonly gas turbines and diesels—normally used only during the peak-load times.

PHWR: Pressurized heavy-water reactor (see CANDU).

Plutonium, Pu: A man-made radioactive, heavy, metallic element with an atomic weight of 239 that is a product of fission in uranium-fueled reactors. Plutonium can be used in certain other reactors, such as the breeder reactors.

PWR (pressurized water reactor): A nuclear reactor in which heat is transferred from the core to a heat exchanger via water kept under high pressure so that high temperature can be maintained in the primary system without boiling the water. Steam is generated in the secondary circuit.

Radioactive decay: The process of releasing protons, neutrons, electrons, or energy to become a new atom, known as a daughter product.

Radionuclide: A radioactive isotope of an element, such as uranium-235, radium-226, radon-222, and tritium, a radioactive isotope of hydrogen.

RAR (reasonably assured resources): Refers to known uranium deposits of delineated size, grade, and configuration that could be recovered in the cost range using current mining and processing technology.

Reclamation: The process of restoring the surface environment to acceptable preexisting conditions by surface contouring, equipment removal, well plugging, revegetation, and filling and eliminating ponds (Energy Information Administration, 1995b). (See restoration.)

Restoration: The returning of all affected land and ground water to its pre-mining quality for its pre-mining use by employing the best practical technology (EIA, 1995b).

SWU (separative work units): The amount of work to separate isotopes U-235 and U-238 expressed in cost US$ per kgU as UF_6.

Thorium: A natural radioactive metallic element with an atomic weight of 232 that can be bred into a fissile isotope, U-233, in certain reactors.

tU: metric tons uranium.

Uranium: A natural, heavy, radioactive metallic element with an atomic weight of 238 whose two principal isotopes are U-235, an indispensable ingredient in nuclear reactors, and U-238 also important as a fertile material.

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Published in the Central Region, Denver, Colorado
Manuscript approved for publication May 5, 1997
Edited by Richard W. Scott, Jr.
Figures 1, 2, 5, 8, and 9 compiled and (or) modified by Warren I. Finch
Computer graphics prepared by George M. Garcia and Richard P. Walker
Photocomposition by Norma J. Maes

☆ U.S. GOVERNMENT PRINTING OFFICE: 1997 - 673-048 / 20092 REGION NO. 8

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ISBN 060788720-6

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