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Plutonium as an Energy Source

BY ARJUN MAKHIJANI

Over the past few years, the dismantlement of excess nuclear warheads has left the United States and Russia with large stocks of plutonium and highly enriched uranium (HEU). These surpluses have re-ignited the debates around the world about the use of plutonium as an energy source and provided new arguments for continued assistance to on-going plutonium projects. This article reviews the basic facts regarding plutonium use and provides some cost and technical analysis of the issue.

Uranium and plutonium resource basics

For all practical purposes, uranium-235 is the only naturally-occurring fissile material (one that can sustain a chain reaction and can fuel nuclear reactors). However, uranium-235 makes up only about 0.7 percent of natural uranium ore. Almost all the rest is another isotope, uranium-238, which cannot sustain a chain reaction.

But although uranium-238 is not a fissile material, it can be converted into fissile plutonium-239 in a nuclear reactor. This property has led nuclear proponents to see uranium-238 as the key to the long-term future of nuclear energy. In fact, reactors can be designed so that they produce more fissile material from uranium-238 in the form of plutonium than they consume in the course of power production. Such reactors have come to be called "breeder reactors" and uranium-238 a "fertile" material. Promoters of nuclear power have used the expression "magical energy source" to describe a breeder

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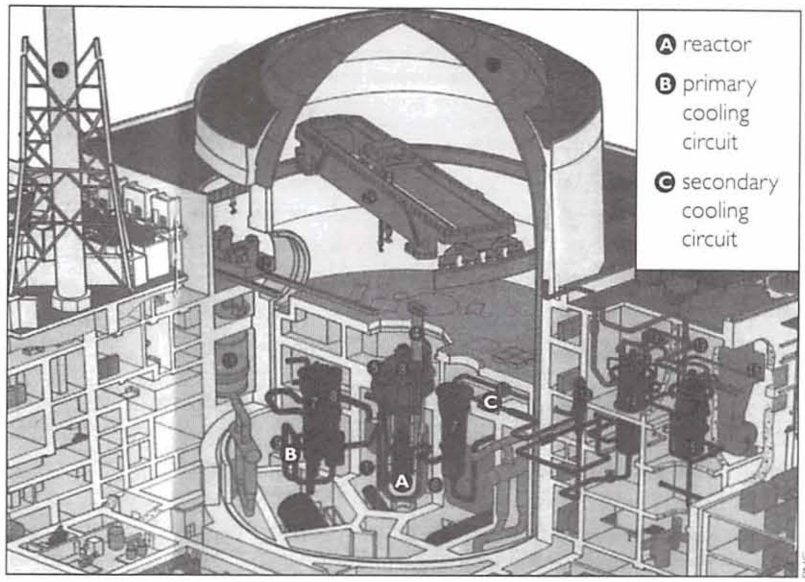

▲ *A cut-away view of the Japanese "Monju" fast breeder reactor. The two circuits contain sodium coolant with the secondary, non-radioactive loop drawing heat from the primary loop. The December, 1995 sodium leak occured in the secondary circuit.*

INSIDE

EDITORIAL

IEER Recommendations on Plutonium Management

Disposition of world-wide plutonium stockpiles is an urgent problem. While many speak of reprocessing and using plutonium to fuel nuclear reactors as "recycling," IEER believes that vitrification, not use as fuel, is the best method of plutonium disposition. Russia and the U.S. are now dismantling thousands of nuclear warheads, but have not yet implemented an effective strategy for the disposition of surplus military plutonium. Meanwhile, France, Britain, Japan, Russia, and India add to the stockpiles by continuing to produce new stocks of weapons-usable commercial plutonium by reprocessing commercial reactor spent fuel

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IEER's "Nuclear Material Dangers" Program

Since its establishment in 1985, the Institute for Energy and Environmental Research (IEER) has provided clear, accurate information, analysis, and training to individuals and organizations in the United States. The widely-recognized integrity of IEER's technical analysis has solidified our reputation as a key resource on nuclear-related issues for all concerned people. Our reports, on issues from environmental harm caused by nuclear weapons production to plutonium disposition to non-proliferation and disarmament issues, are valued by policy-makers, activists, academics, and journalists.

In early 1996, IEER launched "Nuclear Material Dangers," a global outreach program, with the release of the Russian translation of our report, *Fissile Materials in a Glass, Darkly*. This new project will provide an international audience with the same accurate and understandable technical information that is the foundation of our reputation in the United States. Through a media outreach program consisting of Washington press briefings with international correspondents, as well as press teleconferences with journalists around the world, we hope to draw greater public attention to nuclear and energy issues. Our first Washington briefing was held in April 1996, and focused on possible joint US-Russian measures to reduce the dangers posed by plutonium and highly enriched uranium (HEU) stocks.

Over the course of the project, selected IEER materials will be translated into Russian, French, Chinese, and Japanese. Some of our materials are already available in languages other than English. We also plan to post translated articles and summaries of reports to international e-mail lists beginning in late 1996, and enhance our World Wide Web page to include links in other languages. By reaching activists and journalists in their own languages, IEER aims to provide the public with the tools to effectively address problems related to nuclear materials and technologies. An informed public can pressure current and potential nuclear weapons states to stop making nuclear weapons-usable materials and developing technologies that could exacerbate proliferation problems.

Energy & Security is the cornerstone of the Nuclear Material Dangers project. It is, in part, modeled after our existing newsletter, *Science for Democratic Action*, which is distributed primarily within the United States. Since our goal is to make information accessible to readers in their own languages, *Energy & Security* is a multilingual publication, published in English, Russian, French, Japanese, and Chinese. Subsequent issues will contain inserts covering issues relevant to the region or country of distribution, and will include guest articles by scientists and activists from around the world. This issue explores different energy options, with a special look at nuclear power and its role in global energy production. Our next issue, to be published in December, will address reprocessing of spent fuel and plutonium.

—ANITA SETH

Energy & Security

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The Institute for Energy and Environmental Research
6935 Laurel Avenue, Takoma Park, MD 20912, USA
Phone: (301) 270-5500 FAX: (301) 270-3029
Internet address: ieer@ieer.org
Web address: http://www.ieer.org

The Institute for Energy and Environmental Research (IEER) provides the public and policy-makers with thoughtful, clear, and sound scientific and technical studies on a wide range of issues. IEER's aim is to bring scientific excellence to public policy issues to promote the democratization of science and a healthier environment.

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reactor electricity production system because the amount of fuel at the end of production would be greater than at the beginning.[1]

In the 1950s and 1960s, uranium was thought to be a very scarce resource. Scientists realized that uranium resource requirements for a power system based on breeder reactors would be far lower than for one based on once-through use of uranium. For instance, the amount of natural uranium needed over the life of a 1,000 megawatt[2] power plant with a light water reactor (LWR—the most common nuclear reactor), is roughly 4,000 metric tons. By contrast, only about 40 metric tons are required for a breeder reactor of the same size. This hundred-fold theoretical reduction in resource requirements convinced proponents of nuclear power that breeder reactors, along with the recovery of plutonium from irradiated reactor fuel (reprocessing), would be at the heart of the magical nuclear energy future, when nuclear power would be "too cheap to meter."[3] At that time, projections of nuclear power use were very high. In the early 1970s, the U.S. expected an installed nuclear capacity by the year 2000 of 1,000,000 megawatts. However, U.S. capacity is now only 10% of those projections (about 100,000 megawatts) and will not increase by the year 2000 (see Table 3 on p. 7 for additional data).

> Technical, economic, political, environmental, and military realities have all combined to make a plutonium-based energy system economically impractical, environmentally dangerous, diplomatically difficult, and militarily risky.

FROM REACTORS TO WEAPONS?

- The size of the plutonium core in the bomb that exploded over Nagasaki would fit easily into an adult's hand.
- The current amount of separated commercial plutonium is enough to make 20,000 to 30,000 crude but highly effective nuclear weapons.
- By the year 2000, the total amount of separated plutonium in the civilian sector is expected to surpass the total amount of plutonium in the world's nuclear arsenals.

Theoretical arguments in favor of breeder reactors still provide inspiration to nuclear establishments all over the world. But technical, economic, political, environmental, and military realities have all combined to make a plutonium-based energy system economically impractical, environmentally dangerous, diplomatically difficult, and militarily risky.

Technical and economic complications

Discussion in this article focuses on the sodium-cooled breeder reactor (also called a fast neutron reactor)—the main breeder reactor design that has been developed. Tens of billions of dollars have been spent on research, development, and demonstration of this technology in a number of countries, including the United States, Russia, France, Britain, India, Japan, and Germany. But the technology has not yet reached the commercial stage of even moderately reliable power production and breeding of fuel. Breeder reactors total a capacity of roughly 2,600 megawatts, which is only 0.8 percent of the world's nuclear power capacity of about 340,000 megawatts (see pie chart on p. 13). In turn, nuclear power plants account for 12 percent of the world's total electrical capacity. Not only have "breeder" reactors produced only a minuscule fraction of nuclear electricity; they have also failed to produce a significant amount of net fissile material. Indeed, it is possible that "breeder" reactors have so far been net consumers of fissile material.

Almost half of the world's breeder reactor capacity is in a single reactor, the Superphénix in France, which has faced serious operating problems and is not currently run as a breeder reactor. Rather, it is now a net burner of fissile material, used mainly as a research facility for studying the fission of plutonium and other similar elements called actinides. Another 10 percent of breeder capacity is in the 280-megawatt Monju reactor

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1 A similar production of fuel is possible by converting non-fissile thorium-232 into fissile uranium-233 (which does not occur in nature in significant quantities), but development of uranium-233 breeders is even less advanced than that of plutonium breeders. For more technical information on nuclear power reactors, see Arjun Makhijani and Scott Saleska, *The Nuclear Power Deception*, Institute for Energy and Environmental Research, Takoma Park, Maryland, 1996.

2 All figures for reactor capacity are in megawatts electrical unless otherwise specified. A 30-year life and 70 percent capacity factor is assumed. Figures are rounded and adapted from John R. Lamarsh, *Introduction to Nuclear Engineering*, Second Edition (Reading, Massachusetts: Addison-Wesley Publishing Company, 1983).

3 The idea of nuclear energy which would be "too cheap to meter" was actually Cold War propaganda. Even in the 1950s nuclear engineers never believed that nuclear power could be made truly cheap. See IEER report, *The Nuclear Power Deception*.

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in Japan, which had an accident in December 1995, only eight months after its start up.

Most breeder reactors outside of France and Japan have operated on uranium fuel rather than the more difficult plutonium fuel. Russia's BN600 sodium-cooled reactor has been fueled primarily with highly enriched uranium and the BN350 in Kazakhstan now runs on medium-enriched uranium.

A number of problems have plagued the design and operation of breeder reactors:

- Breeder reactors are more difficult to control than light water reactors because runaway nuclear reactions (including complete loss of control, or "prompt criticalities") can occur far more easily in fast breeder reactors than in light water and other reactors that use slow neutrons for the chain reaction.
- Sodium, while it is an excellent coolant, reacts violently with air and explodes on contact with water. These and other properties raise severe safety issues, design complications, and operating difficulties. For instance, air and moisture must be kept out of the two necessary sodium loops.
- The presence of plutonium as a fuel in breeder reactors raises security risks that require more safeguards than are necessary with LWRs.
- Fabrication of plutonium fuel is far more costly than fabrication of uranium fuel due to higher radioactivity of, and safeguards requirements for plutonium.
- Extraction of plutonium from reactor fuel to enable its reuse in reactors (reprocessing), is costly and raises many safety, security, and environmental issues. (Reprocessing will be covered in the next issue of *Energy & Security*.)
- The greater risk of catastrophic accidents and the more serious potential consequences of such accidents necessitate greater safety measures.

Most breeder reactor programs are now suspended or stopped due to the high capital costs and operating problems discussed above. They have been abandoned or cut back to a low-level research stage in the United States, Germany, and Britain. The Japanese program has had a severe setback due to the December 1995 sodium-leak accident at the Monju plant. The plant is not expected to be on line for several years, if ever. There are no current plans for new breeder reactors in France. Britain and Germany have pulled out of the European Breeder Reactor project. India's program has so far produced only a small pilot plant. Russian plans for breeder reactors are stalled for lack of money.

> MOX fuel would cost about $500 million more than uranium fuel over the life of a reactor, even if the plutonium itself were free.

The expense and technical difficulties of breeder reactors, reprocessing, and plutonium fuel fabrication have led to far higher net costs for breeder reactors than for reactors that load only uranium as a fuel. Moreover, uranium is far more abundant than was presumed in the 1950s and 1960s. Instead of rising, uranium prices have, on the average, declined in real terms over the last several decades (see table below, left).

Furthermore, in the past ten years, spot market prices (the open market price at any given time) have been significantly lower than contract prices. For instance, in 1990 spot prices were about $30 per kilogram of uranium—just half of the contract price (in 1995 dollars). In the past couple of years spot prices have ranged between $20 and $40 per kilogram. Low uranium prices are also partly due to reduced demand because the number of nuclear power reactors built has been far fewer than projected.

CONTRACT PRICE FOR URANIUM ORE IN 1995 DOLLARS

(all figures are rounded)*

Year	Price U.S. $/kg U
1960	100
1970	50
1980	90
1990	60

* We have used the producer price index for converting current uranium prices to 1995 dollars.

Value and cost of plutonium

While electricity systems based on breeder reactors have not been built, it is still possible to use plutonium as a fuel in light water and other power reactors not designed to breed plutonium. In any case, about one-fourth to one-third of the energy in an LWR is derived from plutonium created in the course of reactor operation from the uranium-238 in the fuel rods. Further, the spent fuel rods from LWRs typically contain about 0.7 percent fissile isotopes of plutonium. This plutonium, while far less than the amount of

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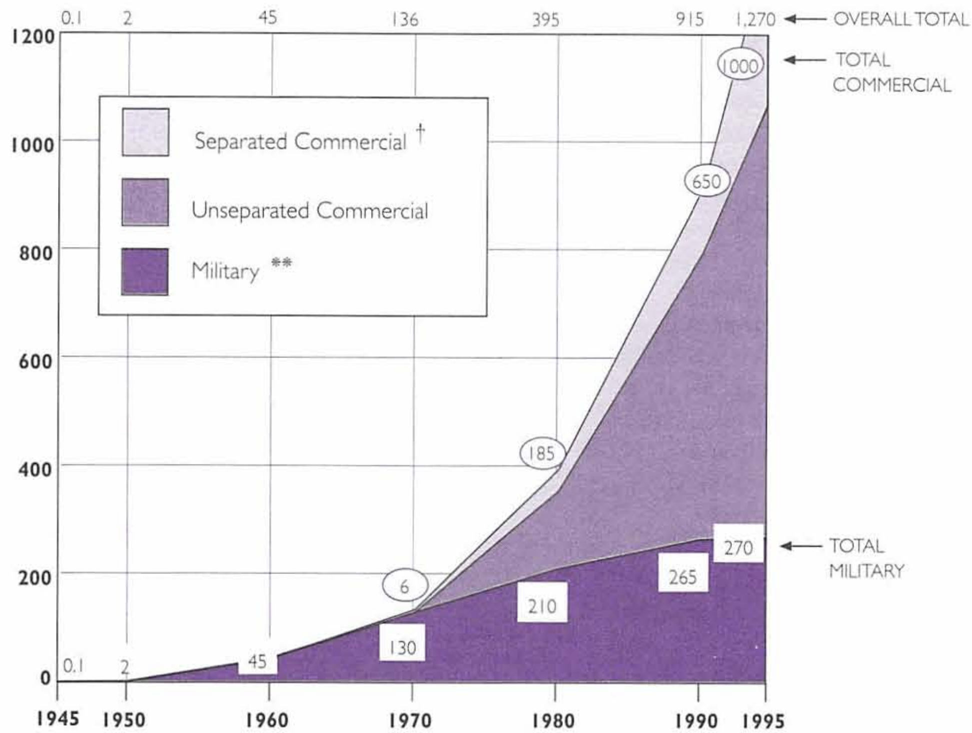
HISTORICAL WORLD PLUTONIUM INVENTORIES, METRIC TONS*



* All figures are rounded either to one significant figure or to the nearest 5 metric tons. The total is not rounded further.

**No country besides the U.S. has released historical military plutonium production data. All other military data are rough estimates. We have assumed a figure of 150 metric tons of military plutonium for Russia in the 1990 and 1995 totals. Recent data from Russia indicate that the figure may be lower, at about 130 metric tons (rounded).

† Separated commercial plutonium is owned by the only countries that are currently reprocessing: France, Britain, Japan, Russia, India. In addition, countries that have no current reprocessing have contracts for reprocessing with France and Britain, and also own substantial commercial plutonium stocks. They are: Germany, Belgium, Holland, Italy, and Switzerland. The United States also has a relatively small stock of commercial plutonium from its West Valley reprocessing plant in New York, which was shut down in 1972.

Source: Arjun Makhijani and Scott Saleska, *The Nuclear Power Deception* (Takoma Park, Maryland: Institute for Energy and Environmental Research, 1996).

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fissile material used in the reactor, can be re-extracted for use as fuel.

However, most reactors are not designed to operate on pure plutonium. The total amount of fissile material (uranium-235 plus fissile isotopes of plutonium) must be kept below the design level—in the vicinity of five percent for most LWRs. The plutonium is put into oxide form, mixed with depleted uranium oxide (mainly uranium-238 with about 0.2 percent uranium-235) to make a mixed oxide fuel ("MOX fuel"). Thus, it would appear that even without breeder reactors, plutonium can be useful as a nuclear reactor fuel.

While this argument is theoretically correct from the point of view of physics, it fails on economic grounds. To determine a practical economic value for plutonium, we must take into account the costs of processing and fabricating it into usable fuel and compare them to the costs of other fuels. The most detailed, recent independent analysis done on this subject was a study of reactor options for plutonium disposition published by the U.S. National Academy of Sciences (NAS) in 1995.

The NAS report estimated the cost of processing and fabricating low enriched uranium oxide reactor fuel (4.4 percent enrichment) at about $1,400 per kilogram in 1992 dollars, assuming a natural uranium price of $55 per kilogram. The costs of MOX fuel fabrication, assuming that the plutonium was free (that is, obtained as surplus from the nuclear weapons program), would

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Nuclear Power and its Role in Global Electricity and Energy

COMPILED BY ANITA SETH

Table 1 lists countries in order of the percentage of electricity they derive from nuclear power. This table actually contains two separate measures of electricity: capacity and generation. Capacity refers to the manufactured rating of the generation equipment installed in a country, and is measured in megawatts (MW). Generation refers to the energy output over a given period of time (in this case, one year) and is measured in kilowatt-hours (kWh). Tables 1 and 2 show gross electricity generation, including transmission and distribution losses.

Table 2 compares nuclear power to other sources of electricity. While fossil fuel generated electricity is by far the most common, representing over 60 percent of world-wide electricity, on a regional basis other energy sources can supply a majority of the electricity. In South America, hydroelectricity accounts for 80 percent of all electricity produced, over four times as much as fossil fuel electricity, and over fifty times as much as nuclear power.

TABLE 1: NUCLEAR POWER (1993)

Country	Nuclear as Percentage of Gross Electricity Generation (rounded)	Gross Electricity Generation (million kWh)	Gross Capacity (MW)
France	78	368,188	59,020
Belgium	60	41,927	5,485
Sweden	43	61,395	9,912
Spain	36	56, 060	7,020
S. Korea	36	58,138	7,616
Ukraine	33	75,243	12,818
Germany	29	153,476	22,657
Japan	28	249,256	38,541
United Kingdom	28	89,353	11,894
United States	19	610,365	99,061
Canada	18	94,823	15,437
Russia	12	119,186	21,242
World*	18	2,167,515	340,911

* World totals include countries not individually listed.

Sources: *Energy Statistics Yearbook: 1993* (New York: United Nations, 1995).

TABLE 2: GLOBAL ELECTRICITY GENERATION—BY TYPE

(in million kWhe)

	Fossil Fuel	Hydro	Nuclear	Geothermal and Other	Total
World	7,669,958	2,376,106	2,167,515	47,131	12,260,710
Africa	281,518	50,531	7,200	340	339,589
N. America	2,491,646	641,208	709,994	30,195	3,873,043
USA	2,236,388	276,463	610,365	22,676	3,145,892
S. America	97,291	410,479	8,192	–	515,962
Asia	2,403,166	526,107	351,498	9,356	3,290,127
China	685,153	151,800	2,500	–	839,453
India	279,000	70,667	6,800	52	356,519
Japan	550,181	105,470	249,256	1,798	906,705
Europe	2,237,226	708,654	1,090,631	5,640	4,042,151
France	35,366	67,894	368,188	–	471,448
Germany	350,656	21,465	153,476	124	525,721
Russia	662,199	175,174	119,186	28	956,587

Source: *Energy Statistics Yearbook: 1993* (New York: United Nations, 1995).

BRIAN SMITH

Table 3 looks at the broader context of not just electricity production, but all commercial energy consumption. The 700 million people of Africa, representing about 13 percent of world population, only consumed 3 percent of the world's commercial energy in 1993. By contrast, North America and Europe, where about one-fifth of the world's people live, accounted for almost two-thirds of all commercial energy consumption in 1993.

Among commercial energy sources, the reliance on fossil fuels is clear. 90 percent of energy in the world comes from fossil fuels (mainly coal, petroleum, and natural gas). However, certain countries obtain a very significant percentage of their energy from nuclear power. In France, for example, nuclear power accounts for about 44% of total energy consumption in 1993.

TABLE 3: GLOBAL COMMERCIAL ENERGY CONSUMPTION 1993

(in petajoules)*

	Solids	Liquids	Natural Gas	Nuclear**	Other Elec.**	Total
World	93,981	119,407	77,921	23,599	9,966	324,873
Africa	3,130	3,859	1,548	78	195	8,805
N. America	20,056	40,070	26,474	7,730	3266	97,598
USA	18,863	32,093	22,362	6,645	1684	81,751
S. America	616	5,456	2,461	89	1478	10,095
Asia	42,131	34,132	13,443	3,827	2260	95,830
China	23,540	4,886	661	27	547	29,679
India	6,281	2,264	460	74	255	9,338
Japan	3,545	8,579	2,223	2,714	443	17,505
Europe	26,231	34,095	33,109	11,874	2569	107,852
France	610	3,204	1,307	4,009	244	9,153
Germany	4,115	5,158	2,699	1,671	78	13,724
Russia	6,636	6,802	14,745	1298	631	30,042

* Solids include hard coal, lignite, peat, and oil shale. Liquids include crude petroleum and natural gas liquids. Other electricity is primarily hydro-electricity, but also includes geothermal, wind, tide, wave, and solar sources. Nuclear electricity has been converted to thermal energy equivalent using a factor of 1,000 kWh (electrical) = .372 metric tons coal.

**Does not include imports and exports.

Note: Table 3 lists energy inputs (consumption of primary energy), while Table 2 lists energy outputs (in the form of electricity). This is the reason for the apparent disparity between the figures in the "Nuclear" and "Other Elec." (primarily hydro-electricity) columns in this table, and those in the "Hydro" and "Nuclear" columns in Table 2. Electricity generation from heat energy (like nuclear) is only about one-third as efficient as electricity generation from mechanical energy (like hydro). While the amount of electricity produced from nuclear and hydro power sources are about equal, the nuclear inputs are three times greater than the hydro inputs. To make energy figures comparable, the other column should be increased to about 27,000 petajoules.

Source: *Energy Statistics Yearbook: 1993* (New York: United Nations, 1995)

◀ *A group of Zond 2-40 (550 kW) turbines installed in a wind farm near Davis, Texas. Clean, renewable wind power is a good alternative for economical, sustainable energy in areas with high wind speeds.*

TABLE 4: ENERGY FROM BIOMASS BURNING (1985)

	petajoules	percentage of total energy
World	54,800	14.7
Industrialized Countries*	6,900	2.8
Developing Countries*	48,000	38.1

* The category "Industrialized Countries" includes U.S./Canada, Europe, Japan, Australia and New Zealand, and the former Soviet Union. The heading "Developing Countries" includes Latin America, Africa, Asia (minus Japan), and Oceania (minus Australia and New Zealand).

Source: Thomas B. Johansson, Henry Kelly, Amulya K. N. Reddy, and Robert H. Williams, *Renewable Energy: Sources for Fuels and Electricity* (Washington, DC: Island Press, 1993), pp. 594–5.

Numbers in Tables 1–3 are based on the most recent United Nations data available. These tables take into account only commercial energy use, and thus leave out traditional sources of energy, such as wood, animal dung and crop residues (collectively known as biomass) which are used for cooking and heating. Biomass burning accounts for almost 15 percent of the world's energy consumption. In developing countries, reliance on biomass for energy is even greater: biomass burning is the largest source of energy, making up about 38 percent of total energy use. Because these fuels are non-monetized, their value and the extent of their use are often overlooked. Yet they are the only available energy source for hundreds of millions of people. One crucial energy source not included in these numbers is the energy intake by draft animals, which plays an especially significant role in Asia.

Biomass burning in its current form is inefficient compared to fossil fuels, and creates health and environmental problems. With investment of money and research, biomass fuels could be converted into modern energy forms to provide a cleaner, more efficient, and renewable base of energy, preferable to fossil fuel and nuclear energy.

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Comparison of Fossil Fuels and Nuclear Power
A Tabular Sketch

BY ARJUN MAKHIJANI

The qualitative comparisons in this table are premised on the assumption that facilities are run with reasonable attention to environmental protection so far as routine operations and waste management are concerned. The effects could be (and often are) far worse if this is not true. The statements about climate change in the table only refer to incremental risks from adopting a particular strategy. Both nuclear and renewable strategies will involve risks beyond those we have already incurred because of the time required for the transition to a future energy strategy.

The Earth appears to have the capacity to absorb carbon dioxide emissions at a level of 3 gigatons per year, although the exact level of tolerance and absorption is uncertain. Today's emissions total about 9 gigatons, about two-thirds of which is due to fossil fuels. The remainder is the result of biomass burning.

Besides carbon dioxide emissions, fossil fuel mining and technologies for controlling emissions other than carbon dioxide to the air and water contribute to

	Nuclear with breeders	**Nuclear, once-though uranium use**	**Fossil Fuels, present approach**	**Limited fossil fuels and renewables**
Resource base, present economics*	indefinite future	50 to 100 years, possibly more	a few hundred years	indefinite future
Resource base, including very low-grade resources	not required	indefinite future	thousands of years	not required
incremental climate change risk	none**	none	potentially catastrophic	none if fossil fuels are largely phased out
potential consequences of catastrophic accidents	severe: long-lasting effects over large regions	severe: long-lasting effects over large regions	no consequences for large regions but may be locally severe; effects generally short-term	no consequences for large regions but may be locally severe; effects generally short-term
air pollution, routine operations	relatively low	relatively low	severe to moderate, depending on control technology	moderate to low depending on control technology
water pollution, routine operations	potentially serious at mines and mills, but limited due to low uranium requirements; potentially serious at waste disposal sites	often serious at mines, mills, and uranium processing sites (includes radioactive and non-radioactive pollutants); potentially serious at waste disposal sites	often serious at coal mines; serious at some oil fields (includes non-radioactive and radioactive pollutants, notably radium-226 near many oil-wells)	potentially very low
Risk of nuclear weapons problems	yes	yes, but less than with a breeder reactor system	none	none

* See text

**Questions have been raised about the effect of krypton-85 from extensive reprocessing necessary for a breeder reactor system on cloud formation and hence potential climate change. However, krypton-85 can be removed from exhaust gases by cryogenic cooling.

environmental degradation, which is often very severe in its local and regional impacts. Further, fossil fuel use in the present mode presents risks of climate change that may be catastrophic and irreversible. Of the fossil fuels, natural gas provides the highest level of energy content per unit of carbon emissions. However, natural gas could not by itself fulfill global energy requirements with current technology, especially taking into account that the energy needs for a majority of the world's population are unmet today. Moreover, natural gas (methane) leakage from pipelines contributes to global warming to a much greater (although not well understood) extent than carbon dioxide on a molecule-for-molecule basis.

Under today's conditions, nuclear power has far lower routine emissions than energy from burning fossil fuels. However, it presents hazards of its own, notably the risk of accidents like Chernobyl, with severe, long-lasting consequences over huge regions. In addition, the security risks posed by large inventories of nuclear weapons-usable materials have no counterpart in fossil fuels.

Clearly, neither nuclear nor extensive fossil fuel use is currently conducive to sound environmental and security policy. In addition, neither breeder reactors nor renewables (the two possible sources of an indefinite energy supply) are economical at present fuel prices so as to immediately constitute the basis of global energy supply. What are the options for a safe, sustainable, and ecological energy supply for the future?

If fossil fuel use can be reduced and biomass burning done on a renewable basis so that emissions are below 3 gigatons per year of carbon, fossil fuels would be a sounder form of energy than nuclear, but would need to be accompanied by other energy sources. Economical, environmentally-sound carbon sinks, which would allow carbon dioxide to be absorbed and stored or disposed of without being released to the atmosphere as a gas, could also make fossil fuels a better energy source. Fossil fuels can be used at reduced levels as transition fuels to a renewable energy economy, or at higher levels if carbon sinks prove to be economical.

For example, natural gas could serve as a transition fuel to hydrogen derived from solar energy, since the infrastructure for use would be similar for the two gaseous fuels. Natural gas can be complemented by renewable energy sources such as solar energy, biomass fuels (renewably produced and used), and wind energy. Wind energy and solar energy are economical under some circumstances (such as areas with high wind speed or high insolation and low precipitation). The resource base for these technologies could extend to the indefinite future under "present economics" with a reduction in the cost of these technologies or an increase in uranium or coal and oil prices. Moderate fossil fuel use (with engineering measures to prevent releases of carbon dioxide gas into the atmosphere) and renewable energy sources joined with increased energy efficiency measures provide the best alternative for economical, sustainable energy in the future.

RECOMMENDATIONS

FROM PAGE 1

(extracting plutonium and uranium from fuel irradiated in nuclear reactors). While the U.S. is not reprocessing for military or commercial reasons, it has nonetheless succumbed to pressures to continue the flow of money into military nuclear installations. In February 1996, it restarted a military reprocessing plant at the Savannah River Site, citing the need for "environmental management," although reprocessing is the worst option for spent fuel management from the point of view of protecting environmental, public, and worker health.[1]

The many economic, technical, environmental, and security arguments against plutonium use have not convinced those who fervently believe that plutonium is an energy treasure that will play a long-term role in the world's energy economy. Moreover, these plutonium advocates are in positions of considerable influence in key countries, including Russia, France, Japan, Britain, and, to a lesser extent, the United States.

Bridging the U.S.-Russian Gap on Plutonium

The U.S. and Russian leaders have fundamental disagreements on whether plutonium is an asset or a liability. The Russian government's view is that plutonium represents an important energy resource and an economic treasure, while many U.S. leaders like Energy Secretary Hazel O'Leary and Presidential Science Advisor Dr. John H. Gibbons see plutonium excess to military requirements as a liability.

Studies by the U.S. National Academy of Sciences in 1994 and 1995 concluded that there would be net costs to using plutonium in reactors, even after the revenues from the sale of electricity were taken into account. These net costs would be of the same order of magnitude as the cost of plutonium vitrification. Of course, there are institutions in the United States, such as the American Nuclear Society, whose beliefs on plutonium are closer to the official Russian view. Further, there is

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[1] See Noah Sachs, Risky Relapse into Reprocessing (Takoma Park, Maryland: Institute for Energy and Environmental Research, Jan. 1996).

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still a strong sentiment in the United States, including in the Department of Energy, to use plutonium as mixed uranium-plutonium oxide fuel (MOX fuel) in existing power reactors. Similar sentiments have also been expressed by Russian leaders.

The issue of plutonium's long-term worth cannot be resolved today. But we can separate the short- and medium-term issues from the long-term energy issues. Most independent studies that have carefully taken the costs of reprocessing and fuel fabrication into account have concluded that because of the abundance of cheap uranium, plutonium is not now an economical fuel and will not be for the foreseeable future (see main article). IEER shares this conclusion. Taking into account the reality of cheap uranium and urgent security concerns, we believe that there can be a basic agreement to put plutonium into non-weapons-usable form today, while creating a mechanism to use it as an energy source in the long-term, should the economics and non-proliferation conditions change enough to warrant it.

VITRIFICATION OF PLUTONIUM

In order to assure that plutonium will not be used to make nuclear weapons, it is necessary to put it into a non-weapons-usable form. One way of accomplishing this is to mix it with a large quantity of molten glass and pour it into metal containers to form glass logs. This process is called vitrification. Plutonium concentration in the glass could range from a fraction of one percent to several percent. A low concentration makes it harder to steal or re-extract the plutonium, but increases the number of glass logs requiring storage. Re-extraction of plutonium from glass can be accomplished without very complex processing. In order to make the plutonium more difficult to recover, and hence more proliferation-resistant, it can be mixed with highly radioactive fission products, such as cesium-137 or mixed fission products from previous reprocessing plant operations. Such gamma-emitting fission products would provide a lethal radiation dose to anyone trying to steal a glass log containing plutonium. However, this approach would also make it more expensive to re-extract the plutonium, should that be required in the future. A middle-ground solution would be to vitrify plutonium with other elements like thorium-232 and put the mixture in a container that has been made highly radioactive by the use of cesium-137 to make it resistant to theft.

We have two principal recommendations regarding plutonium in the short- and medium-term:

- Excess military plutonium and all commercial plutonium should be vitrified in a manner that would make it very difficult to steal and very hard for non-governmental parties to re-extract and make into nuclear weapons. "Vitrification" would dilute plutonium with large quantities of molten glass (and other materials) to make glass logs. The containers of the glass logs (or the logs themselves) should be made very radioactive so that they would be difficult to steal.
- All reprocessing plants that produce weapons-usable materials, including military and commercial reprocessing plants, should be closed in order to stop the increase in stocks of weapons-usable materials.

The U.S. and Russian governments can address the energy issues relating to fissile materials by creating mechanisms that would respond to the concerns of those who believe that plutonium could be a very valuable energy resource in the long-term. We recommend two complementary actions:

- The creation of an international reserve of uranium fuel for power reactors as a means of assuring its long-term, reasonably priced supply. This reserve would be created from surplus military highly enriched uranium.
- Financial guarantees for re-extraction of plutonium from a vitrified state, should an impartial panel ever decide that it is an economical fuel for power generation. This way, the Russian and other governments can preserve the option of using plutonium in the future, should it become economical.

These steps should assuage concerns regarding nuclear reactor fuel supply and allow vitrification to proceed in the short-term. The funds and financial guarantees for these activities would come from the U.S. government, European Community countries, and Japan.

U.S.-Russian Collaboration

There are some encouraging signs for the pursuit of sound non-proliferation policies in Russia and the United States. The U.S. is not reprocessing commercial spent fuel (though it is operating a military reprocessing plant) and has begun hot tests on its high-level waste vitrification plants at the Savannah River Site in South Carolina and at West Valley in New York state. Russia has considerably more experience in high-level radioactive waste vitrification than the United States, with an operating plant at Chelyabinsk-65. Russia is also

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conducting plutonium vitrification experiments on plutonium residues unsuitable for use as fuel at the Radium Institute in St. Petersburg. The advanced work in Russia along with ongoing research in the U.S. laboratories, such as facilities at the Savannah River Site and Oak Ridge National Laboratory, can provide the basis for active, mutually-rewarding cooperation on one of the most urgent issues of our time.

Presidents Clinton and Yeltsin should decide now to vitrify plutonium to prevent its diversion into the black market. As a first step, Russia and the United States should establish two joint vitrification pilot plants—one in each country—as part of technical collaboration program on fissile materials security. The U.S. and Russia should agree to shut down their reprocessing plants and not to use plutonium in reactors. They could then work together to persuade other countries to shut down their reprocessing plants.

Only a U.S.-Russian partnership in weapons-usable materials management will prompt other governments to pursue proliferation-resistant and environmentally sound management options, and to shift employment into these areas, away from problem technologies like reprocessing. The potential diversion of plutonium from either military or commercial stocks is a global problem requiring a global solution.

—ARJUN MAKHIJANI

GLOSSARY

breeder reactor: A reactor that is designed to produce more fissile material than it consumes. Most breeder reactors use fast neutrons for sustaining the nuclear chain reaction, and are therefore called "fast breeders." A fast reactor that does not produce more fissile materials than it consumes is called a "fast neutron reactor."

burn-up: The amount of energy that has been generated from a unit of nuclear fuel; usually measured in megawatt-days thermal per metric ton of initial heavy metal (MWdth/MTIHM)

electron: A negatively-charged elementary particle.

fertile material: Material that is not fissile, but which can be converted into a fissile material. Uranium-238 and thorium-232 are the principal fertile materials.

fissile material: Material whose nucleus can be fissioned when it absorbs a low energy (ideally zero energy) neutron. Fissile materials can sustain nuclear chain reactions.

fissionable material: Material that can undergo nuclear fission when bombarded by a high-energy neutron. Most fissionable materials that are not fissile cannot sustain chain reactions.

half-life: The amount of time it takes half of a given quantity of a radioactive element to decay.

isotope: A variant of an element that has the same number of protons but a different number of neutrons in the nucleus. Isotopes of elements have the same atomic numbers, but different mass numbers.

moderator: A material used in a nuclear reactor to slow down the fast neutrons emitted in the process of fission.

neutron: A neutral elementary particle that occurs in the nuclei of elements (except ordinary hydrogen). Free neutrons decay into a proton, an electron and an anti-neutrino. A neutron is about 1,838 times heavier than an electron.

nuclear fission: The splitting of a nucleus of a heavy element into two lighter nuclei, generally accompanied by the release of one or more neutrons and energy.

proton: An elementary particle with a positive charge equal to that of an electron, but which is about 1,836 times heavier than an electron.

reactor core: The core of a reactor, consisting of the fuel, moderator (in the case of thermal reactors), and coolant.

reprocessing: The separation of irradiated nuclear fuel into uranium, plutonium, and fission products.

thermal reactor: A reactor that uses thermal (or slow) neutrons to sustain the chain reaction.

vitrification: The process of making glass. In the context of plutonium and nuclear waste management, it means the mixing of a material with molten glass in order to render it immobile, safe for storage, and not easily usable for weapons.

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be about $1,900 per kilogram in 1992 dollars, exclusive of taxes and insurance.[4] The higher cost of MOX means that annual fuel costs for a full MOX core would be approximately $15 million more than uranium fuel per year for a 1,000 megawatt reactor, or about $450 million over its operating life (in 1992 dollars), even if the plutonium were free. This amounts to about $500 million in 1995 dollars. Further, the costs of disposing of MOX spent fuel are likely to be higher than those for uranium spent fuel because the MOX spent fuel will be more radioactive and contain two to three times more residual plutonium.

It is clear that so long as uranium prices are relatively low, the use of MOX fuel is uneconomical even under the most favorable circumstances: when the plutonium itself is free and uranium is assumed to be more expensive than current spot market prices. The cost difference is even greater when the cost of reprocessing is taken into account, because reprocessing would add hundreds of millions of dollars to lifetime fuel costs for each reactor.

> The value of plutonium on a black market as a raw material for nuclear weapons would undoubtedly be far greater than its value as a fuel.

As the NAS pointed out in a 1994 study, the fact that plutonium has a fuel value in physical terms does not make it economically practical. The oil present in shale rock also has a physical fuel value. It is the cost of extracting oil from shale relative to petroleum in oil fields that precludes oil shale, like plutonium, from having an economic value as a fuel. In addition, plutonium poses some proliferation liability which, although difficult to quantify, is a serious cost.

Proliferation Dangers

Although civilian plutonium has a different isotopic composition from plutonium that has been produced for weapons, it can be used to make a nuclear explosive, as demonstrated in a successful 1962 test by the United States Atomic Energy Commission. Continued reprocessing and use of plutonium pose a two-fold proliferation danger. First, growing stockpiles of commercial separated plutonium undermine disarmament commitments under international treaties. Even if carried out for commercial reasons, reprocessing of plutonium can be perceived as simply adding to weapons-usable materials stockpiles. In the short-term, this could undermine effective global negotiations on a fissile material cut-off, and in the long-term, the Non-Proliferation Treaty, in which, under Article VI, signatories commit to "pursue negotiations in good faith on effective measures relating to the cessation of the arms race at an early date and to nuclear disarmament. . ."

Second is the danger plutonium being diverted to a black market. The fuel value of plutonium is determined by the price of uranium. Assuming a price of $40 per kilogram of natural uranium, uranium-235 is worth about $5,600 per kilogram. Since the energy per fission from plutonium-239 and uranium-235 is about the same, the theoretical fuel value of fissile plutonium can be put at $5,600 per kilogram. Reactor-grade plutonium also contains non-fissile isotopes, reducing its value to about $4,400 per kilogram.[5] Six to ten kilograms of reactor-grade plutonium would suffice to make a nuclear bomb, making the fuel value of one bomb's worth of plutonium is between $26,400 and $44,000. However, the value of the plutonium would undoubtedly be far greater than this on a potential black market where the objective would be to make a weapon. The danger of plutonium diversion to a black market is particularly acute in Russia where the weakening of central control, combined with the rise of organized crime and poor economic conditions heighten the chances of diversion.

Long-term energy issues

The economic facts regarding plutonium are now so clear that they are not in serious dispute so far as short- and medium-term energy issues are concerned. But supporters of plutonium as an energy source cite long-term energy needs as a reason to create and maintain an infrastructure for the use of plutonium.

Current estimates of uranium resources at $80 per kilogram of uranium (still well below the price at which MOX fuel may be competitive) are estimated at about 3.3 million metric tons, enough for about six or seven decades of once-through fuel use at present levels of nuclear power production. These estimates do not take into account the intense exploratory activity that accompanies real increases in prices. The history of petroleum and natural gas exploration is instructive. The price increases in 1973-74 resulted from production-limiting and price-fixing policies adopted by the Organization of Oil Exporting Countries (OPEC). However, the price jump spurred new exploration

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[4] Panel on Reactor-Related Options for the Disposition of Excess Weapons Plutonium. Committee on International Security and Arms Control, Management and Disposition of Excess Weapons Plutonium—Reactor-Related Options (Washington, DC: National Academy Press, 1995), pp. 290, 294.

[5] Typical LWR spent fuel contains about 0.2 percent non-fissile plutonium isotopes and 0.7 percent fissile isotopes.

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activity, and the number of oil exporting countries and oil availability increased so substantially that the real price of petroleum is lower today than it was in 1974. Uranium prices have tended to decline in real terms (with the exception of a period in the 1970s, when uranium prices followed the upward trend of oil prices), and so current estimates of uranium resources may be biased downwards.

Whatever one's views about the future of nuclear power, it makes little sense to invest huge amounts of money in using plutonium as a fuel today, when any potential economic use is many decades away, at best. Plutonium use makes even less sense when viewed in the context of scarce economic resources, which can be better invested in areas with better environmental and security characteristics and a higher return, such as natural gas- or biomass-fueled power plants, natural gas-assisted solar electricity generation, and improved efficiency of energy use.

UNITS OF MEASURE

watt: A metric unit used to measure the rate of energy generation or consumption. One horsepower is equal to 746 watts.

joule: A metric unit of energy, equal to one watt of power operating for one second.

kilo-: One thousand. A kilowatt is a common measure for electrical power capacity.

kilowatt-hour (kWh): A unit of energy equal to 3.6 million joules. It is the amount of energy generated by a one-kilowatt source operating for one hour.

mega-: One million. A megawatt (MW) is a common measure of generating capacity for large power plants. When used by itself in the context of electrical generation, it generally refers to electrical generating capacity.

giga-: One billion (or 10^9). One gigawatt electrical (equal to 1000 MW) is the approximate capacity of a large nuclear power plant.

tera-: One trillion (or 10^{12}).

peta-: One thousand trillion (or 10^{15}). Energy use on a large scale is often measured in petajoules. One metric ton of coal equivalent (U.N. standard) is approximately 29 billion joules. Therefore one petajoule is equivalent to about 34,500 metric tons of coal.

exa-: One million trillion (or 10^{18}).

GLOBAL ENERGY

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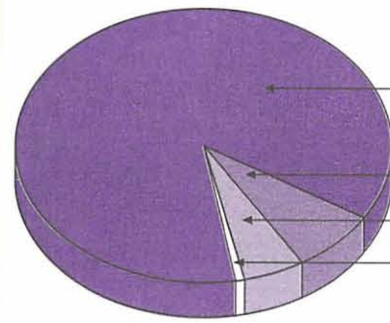
ELECTRICITY PRODUCTION CAPACITY OF VARIOUS REACTORS



* Pressurized water reactors (PWRs) account for 219,391 MWe and boiling water reactors (BWRs) for 75,519 MWe.

** A small amount of electrical capacity (less than 0.1%) is accounted for by other types of reactors.

Sources: Uranium Institute website (http://www.uilondon.org/reastats.html). The figure for fast breeder reactors is taken from Nuclear Power Reactors in the World (Vienna: International Atomic Energy Agency, April 1995). 280 MWe have been added to account for the Monju reactor in Japan which began operating in April 1995 but is now shut.

TABLE 4: NUCLEAR REACTOR STATUS BY REGION (AS OF MAY 1996)

	Operating*	Under Construction	Construction Suspended
Africa	2	0	0
USA	110	0	6
Other N. America	24	0	2
S. America	3	2	0
Japan	52	2	0
Other Asia	31	15	1
France	56	4	0
Other W. Europe	94	0	0
E. Europe	20	4	6
Russia	29	3	7
Ukraine	15	2	3
Other FSU	5	0	0
TOTAL	441	32	25

* Includes five reactors that were not operating but were licensed as of May 1996, in the United States, Armenia, Canada, Germany and India. Also includes four reactors that had achieved criticality but were not yet on line: two in Japan, and one each in the United States and Romania.

Source: Uranium Institute website (http://www.uilondon.org/netpower.html)

SELECTED IEER PUBLICATIONS

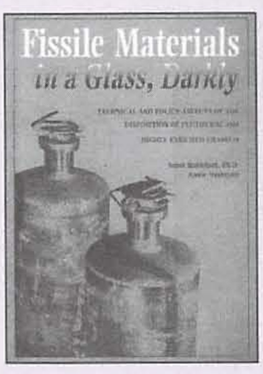
Nuclear Wastelands
A Global Guide to Nuclear Weapons Production and Its Health and Environmental Effects

MIT Press, 1995
(produced with IPPNW)
edited by Arjun Makhijani, Howard Hu, and Katherine Yih

A handbook for scholars, students, policy makers, journalists, and peace and environmental activists, providing concise histories of the development of nuclear weapons programs of every declared and de-facto nuclear weapons power. The thorough documentation and analyses bring to light governmental secrecy and outright deception that have camouflaged the damage done to the very people and lands the weapons were meant to safeguard.

No future research into nuclear weapons will be credible unless it refers to this study.
—Jonathan Steel, *The Guardian* (UK), August 9, 1995

Hardbound, 666 pages. List price: $55.00. Readers discount price: $40.00



Fissile Materials In a Glass, Darkly

IEER Press, 1995
by Arjun Makhijani and Annie Makhijani

Now available in Russian

IEER's report analyzes the options for disposition of plutonium and highly enriched uranium and recommends policies designed to put these materials into non-weapons-usable forms as rapidly as possible. It urges that the U.S. adopt vitrification of plutonium as its disposition option (rather than using it in reactors) in order that it may persuade countries still separating plutonium from civilian spent fuel to stop doing so.

If there is one thing that I have encountered in this area [the disposition of fissile materials], it's the dearth of practical choices that we have at the moment, and that's why I was so enthusiastic . . . about the report.
— Tom Grumbly, Assistant Secretary for Environmental Restoration and Waste Management, U.S. Department of Energy

Paperback, 126 pages. Price: $12

Plutonium: Deadly Gold of the Nuclear Age

by IPPNW and IEER
International Physicians Press, 1992

Paperback, 178 pages. Price: $17 . Also available in Japanese, French and German.

Radioactive Heaven & Earth
The Health and Environmental Effects of Nuclear Weapons Testing In, On, and Above the Earth

by IPPNW and IEER
Apex Press/Zed Books, 1991

Paperback, 193 pages • Price: $17

The Nuclear Safety Smokescreen
Warhead Safety and Reliability and the Science Based Stockpile Stewardship Program

IEER Report, 1996

Price: $10.
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PLUTONIUM ISSUES

Abrahms, C. W., M.D. Patridge, and J. E. Widrig. ***International Nuclear Waste Management Fact Book.*** Richland, Washington: Pacific Northwest National Laboratory (for the U.S. Dept. of Energy), November 1995.

This small-format book provides comprehensive country by country data on nuclear facilities, institutions and personnel. Scope: Global.

Albright, David , Frans Berkhout, and William Walker. ***World Inventory of Plutonium and Highly Enriched Uranium 1992.*** Oxford and New York: Oxford University Press, 1993.

The most comprehensive, reliable source of public information on weapons-usable plutonium and highly enriched uranium, with a considerable amount of historical information. Some of the more recent data are published in this newsletter. Scope: Global.

Berkhout, Frans, Anatoli Diakov, Harold Feiveson, Helen Hunt, Marvin Miller, and Frank von Hippel. **"Disposition of separated plutonium."** *Science & Global Security* 3, Nos. 3–4 (March 1993): pp. 161–213.

Provides a detailed analysis of plutonium disposition options, including safeguarded storage, MOX-fuel, and vitrification, as well as a discussion of the sources of separated plutonium. Scope: Global

Chow, Brian G., and Kenneth A. Solomon. ***Limiting the Spread of Weapon-Usable Fissile Materials.*** Santa Monica, CA: RAND, 1993.

Contains cost analysis of plutonium use in reactors, showing that there would be net costs to MOX use because the price of uranium is low. Scope: Global.

U.S. Department of Energy. ***Plutonium: The First Fifty Years—United States Plutonium Production, Acquisition and Utilization from 1944 to 1994.*** Washington, D.C.: U.S. Department of Energy, February 1996.

Part of the "openness initiative" of U.S. Energy Secretary Hazel O'Leary to make public formerly secret data on various nuclear weapons related activities. It contains a remarkable amount of information on U.S. plutonium, including detailed site specific data. Data on U.S. imports and exports of plutonium are provided. Scope: Mainly U.S.

U.S. Department of Energy. ***Plutonium Working Group Report on Environmental, Safety and Health Vulnerabilities Associated with the Department's Plutonium Storage,*** Draft. Washington, D.C.: U.S. Department of Energy, Publication Number DOE/EH-0415, September 1994.

Discusses the problems arising from storage of various chemical forms of plutonium and plutonium residues left at the end of the Cold War. Problems with deterioration of storage containers, such as formation of flammable gases due to radiolysis are also discussed. Scope: U.S.

For copies of Department of Energy materials, contact:

U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Kobayashi, Keiji. ***Kousoku Zoushokuro Monju*** (FBR Monju). Nanatsumori Shokan, 1994. In Japanese.

Provides technical information on fast breeder reactors, as well as details about specific fast breeder programs around the world, with a focus on the Monju reactor.

National Academy of Sciences. ***Management and Disposition of Excess Weapons.*** Washington, D.C.: Committee on International Security and Arms Control, 1994. In English and Russian.

Provides a thorough review of the options for disposition of surplus weapons plutonium in the United States. It recommends three options for consideration: use of plutonium as mixed plutonium-uranium oxide fuel, vitrification of plutonium, and deep borehole emplacement of plutonium. It points out that even use of plutonium as a fuel will result in a net cost due to the low price of uranium and the high cost of MOX fuel fabrication. Scope mainly U.S., but discussion of connected Russian aspects of the issue. See our article "Plutonium as an Energy Source" for information on the related 1995 report.

For copies of NAS reports, contact:

Committee on International Security and Arms Control
U.S. National Academy of Sciences
2101 Constitution Avenue, NW
Washington, DC 20055
cisac@nas.edu

SEE **BIBLIOGRAPHY** ON PAGE 16

FROM PAGE 15

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Contains estimates of production of weapons usable fissile materials in the U.S. and Russia prior to the declassification initiatives of recent years. There is useful information on estimation techniques. In particular, Soviet plutonium production is estimated using estimates of the krypton-85 emitted by world-wide reprocessing plants. Very useful for understanding estimation tools used by non-government scientists to help persuade governments to be more open with data.

The planning and production of *Energy & Security* have been greatly facilitated by regular advice from friends around the world. Our effectiveness also depends to a large extent on your suggestions. We welcome comments from our readers, and will publish selected letters in future issues, space permitting. We reserve the right to abbreviate letters, and will indicate if text has been cut.

ENERGY ISSUES

Flavin, Christopher, and Nicholas Lenssen. ***Power Surge: Guide to the Coming Energy Revolution.*** New York and London: W.W. Norton & Company, 1994.

Covers the state of renewable energy sources in detail.

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A quarterly journal focusing on renewable and sustainable energy technologies. The paper version is available in Russian. The English version (available only in electronic form) is edited by the Center for Renewable Energy and Sustainable Technology (CREST) in Washington, D.C., and can be accessed through their web page at http://solstice.crest.org.

Goldemberg, Jose, Thomas B. Johansson, Amulya K. N. Reddy, and Robert H. Williams, eds. ***Energy for a Sustainable World.*** New York: John Wiley & Sons, 1988; and Johansson, Thomas B., Henry Kelly, Amulya K. N. Reddy, and Robert H. Williams. ***Renewable Energy: Sources for Fuels and Electricity.*** Washington, D.C.: Island Press, 1993.

These books present detailed discussion and analysis of present energy use and of energy alternatives for the future.

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