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2

The Nuclear Industry: "Smoking Cigarettes to Keep the Weight Off"

The nuclear era began with a whimper, not a bang, on December 7, 1942. Amidst the polished wooden floors of a war-appropriated squash court at the University of Chicago, Enrico Fermi inserted about 50 tons of uranium oxide into 400 carefully constructed graphite blocks. A small puff of heat exhibited the first self-sustaining nuclear reaction, many bottles of Chianti were consumed, and nuclear energy was born.[1]

The relative simplicity of the first human-induced nuclear reaction, however, obscures just how complicated fission is at producing electricity. After exploring the current status of the nuclear industry, this chapter describes the basic components of the nuclear fuel cycle: uranium mining, milling, and conversion and enrichment; reactor design and construction; operation; fuel processing, storage, and waste sequestration; and decommissioning. It then elaborates some of the drivers behind the current push for the expansion of nuclear power.

Current Status of the Nuclear Industry

Ever since the first experimental nuclear reactor produced electricity in 1951 in Idaho, the first commercial nuclear facility went online in 1956 at Calder Hall in the United Kingdom, the first demonstration plant in the

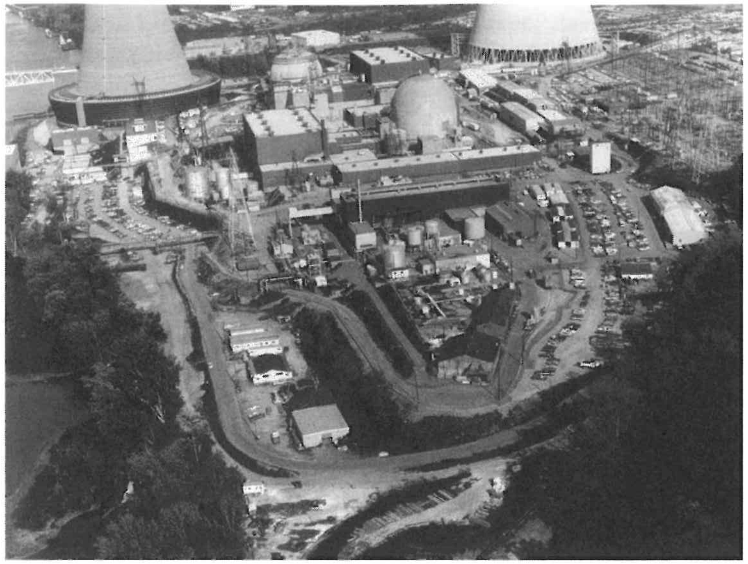

Figure 1: **The 60-MW Nuclear Power Plant at Shippingport, Pennsylvania**

United States was completed at Shippingport in 1957 (Figure 1), and the first American commercial nuclear plant was built in 1963, nuclear energy has been touted as the modern solution to the world's growing demand for energy.

As Table 1 shows, as of April 2010, a total of 31 countries operated 432 nuclear reactors constituting 369 GW of installed capacity. Together, these reactors produced about 15% of the world's electricity, or 2,560.6 billion kWh. In the US alone, which had almost one-quarter of the world's reactors, nuclear facilities accounted for almost 20% of national electricity generation. In France, 76% of electricity came from nuclear sources; and nuclear energy contributed more than 20% of national power production in Germany, Japan, South Korea, Sweden, and Ukraine. As Figure 2 shows, the US, France, Japan, Russia, South Korea, and Germany produced almost three quarters of the nuclear electricity in the world in 2008. Collectively, the global fleet of commercial nuclear power plants needed about 68,000 metric tons of uranium to operate for one year, and it represented roughly 12,600 reactor-years of experience. Moreover, 56 countries operated 284 research reactors and a further 220

Table 1: Commercial Nuclear Power Generation, Reactors, and Fuel Requirements[2]

Country	Nuclear Electricity Generation (2008)		Operating Reactors (April 2010)		Reactors Under Construction (April 2010)		Uranium Required (2010)	Technology	Supplier(s)
	billion kWh	percent electricity	No.	MWe	No.	MWe	(metric tons)		
Argentina	6.8	6.2	2	935	1	692	123	Heavy water reactor	Siemens, Atomic Energy of Canada Limited
Armenia	2.3	39.4	1	376	0	0	55	Vodo-Vodyanoi Energetichesky Reactor	Russia
Belgium	43.4	53.8	7	5,943	0	0	1,052	Pressurized water reactor	Framatome
Brazil	14.0	3.1	2	1,901	0	0	311	Pressurized water reactor	Westinghouse, Siemens
Bulgaria	14.7	32.9	2	1,906	0	0	272	Vodo-Vodyanoi Energetichesky Reactor	Russia
Canada	88.6	14.8	18	12,679	2	1,500	1,675	Heavy water reactor	Atomic Energy of Canada Limited
China	65.3	2.2	11	8,587	21	22,960	2,875	Pressurized water reactor, heavy water reactor,	Framatome, Atomic Energy of Canada Limited, China,

(Continued)

Table 1: (*Continued*)

Country	Nuclear Electricity Generation (2008)		Operating Reactors (April 2010)		Reactors Under Construction (April 2010)		Uranium Required (2010) (metric tons)	Technology	Supplier(s)
	billion kWh	percent electricity	No.	MWe	No.	MWe			
								Vodo-Vodyanoi Energetichesky Reactor	Russia
Czech Republic	25.0	32.5	6	3,686	0	0	678	Vodo-Vodyanoi Energetichesky Reactor	Russia
Finland	22.0	29.7	4	2,696	1	1,600	1,149	Boiling water reactor, pressurized water reactor, Vodo-Vodyanoi Energetichesky Reactor	Russia, Asea, Westinghouse
France	418.3	76.2	58	63,236	1	1,630	10,153	Pressurized water reactor	Framatome
Germany	140.9	28.3	17	20,339	0	0	3,453	Pressurized water reactor, boiling water reactor	Siemens

(*Continued*)

Table 1: (*Continued*)

Country	Nuclear Electricity Generation (2008)		Operating Reactors (April 2010)		Reactors Under Construction (April 2010)		Uranium Required (2010) (metric tons)	Technology	Supplier(s)
	billion kWh	percent electricity	No.	MWe	No.	MWe			
Hungary	14.0	37.2	4	1,880	0	0	295	Vodo-Vodyanoi Energetichesky Reactor	Russia
India	13.2	2.0	19	4,183	4	2,572	908	Heavy water reactor, Vodo-Vodyanoi Energetichesky Reactor, fast breeder reactor	Atomic Energy of Canada Limited, India, Russia
Iran	0	0	0	0	1	915	148	Vodo-Vodyanoi Energetichesky Reactor	Russia
Japan	240.5	24.9	54	47,102	1	1,373	8,003	Boiling water reactor, pressurized water reactor	Westinghouse, General Electric, Hitachi, Mitsubishi, Toshiba

(*Continued*)

Table 1: (*Continued*)

Country	Nuclear Electricity Generation (2008)		Operating Reactors (April 2010)		Reactors Under Construction (April 2010)		Uranium Required (2010) (metric tons)	Technology	Supplier(s)
	billion kWh	percent electricity	No.	MWe	No.	MWe			
Lithuania	9.1	72.9	0	0	0	0	0	Reactor Bolshoy Moshchnosty Kanalny	Russia
Mexico	9.4	4.0	2	1,310	0	0	253	Boiling water reactor	General Electric
Netherlands	3.9	3.8	1	485	0	0	107	Pressurized water reactor	Siemens
Pakistan	1.7	1.9	2	400	1	300	68	Heavy water reactor, pressurized water reactor	Canada, China
Romania	7.1	17.5	2	1,310	0	0	175	Heavy water reactor	Atomic Energy of Canada Limited
Russia	152.1	16.9	32	22,811	8	6,380	4,135	Reactor Bolshoy Moshchnosty Kanalny, Vodo-Vodyanoi Energetichesky Reactor	Russia

(*Continued*)

Table 1: (*Continued*)

Country	Nuclear Electricity Generation (2008)		Operating Reactors (April 2010)		Reactors Under Construction (April 2010)		Uranium Required (2010) (metric tons)	Technology	Supplier(s)
	billion kWh	percent electricity	No.	MWe	No.	MWe			
Slovakia	15.5	56.4	4	1,760	2	840	269	Vodo-Vodyanoi Energetichesky Reactor	Russia
Slovenia	6.0	41.7	1	696	0	0	145	Pressurized water reactor	Westinghouse
South Africa	12.7	5.3	2	1,842	0	0	321	Pressurized water reactor	Framatome
South Korea	144.3	35.6	20	17,716	6	6,700	3,804	Pressurized water reactor, heavy water reactor	Atomic Energy of Canada Limited, Westinghouse, South Korea
Spain	56.4	18.3	8	7,448	0	0	1,458	Pressurized water reactor, boiling water reactor	Westinghouse, General Electric, Siemens
Sweden	61.3	42.0	10	9,399	0	0	1,537	Pressurized water reactor, boiling water reactor	Westinghouse, Asea

(*Continued*)

Table 1: *(Continued)*

Country	Nuclear Electricity Generation (2008)		Operating Reactors (April 2010)		Reactors Under Construction (April 2010)		Uranium Required (2010)	Technology	Supplier(s)
	billion kWh	percent electricity	No.	MWe	No.	MWe	(metric tons)		
Switzerland	26.3	39.2	5	3,252	0	0	557	Pressurized water reactor, boiling water reactor	Westinghouse, General Electric, Siemens
Ukraine	84.3	47.4	15	13,168	0	0	2,031	Vodo-Vodyanoi Energetichesky Reactor	Russia
United Kingdom	52.5	13.5	19	11,035	0	0	2,235	Gas-cooled reactor, pressurized water reactor	United Kingdom, Westinghouse
United States	809.0	19.7	104	101,119	1	1,180	19,538	Pressurized water reactor, boiling water reactor	Westinghouse, General Electric, Babcock & Wilcox, Combustion Engineering
Total	2,560.6	—	432	369,200	50	48,642	67,783		

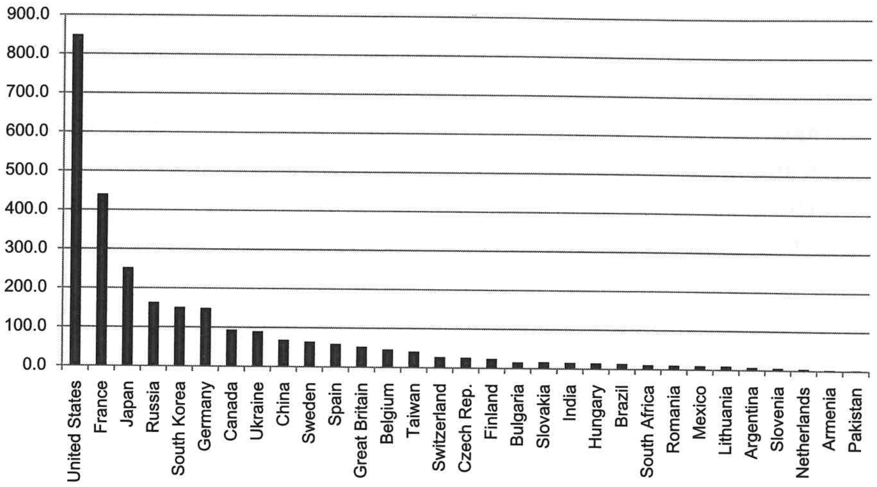

Figure 2: Global Nuclear Electricity Production (TWh) in 2008[3]

reactors were used to power ships and submarines, bringing the world total to almost 1,000 reactors.

As Table 1 also reveals, commercial operators rely on a mix of technologies and suppliers — mostly light water reactors (especially pressurized water reactors) and heavy water reactors — to produce electricity. Light water reactors constitute more than 80% of the world's fleet. Light water reactors in this context use ordinary water, so-called "light" water in the early days of the industry to distinguish it from "heavy" water (which replaces a hydrogen atom with deuterium). Light water reactors have two basic types: a pressurized water reactor and a boiling water reactor. A pressurized water reactor has a nuclear core that heats water under pressure and passes it through a boiler; in a boiling water reactor, the water boils above the nuclear reaction and directly creates steam to turn a turbine.[4]

Nuclear engineers often describe four generations of nuclear plant design. The first generation refers to the experimental reactors designed in the 1940s and 1950s. These rather small "Atoms for Peace"-era plants are now almost all shut down. Only six Generation I units were still operating in 2007 — a series of small, 250-MW, gas-cooled nuclear power plants in the UK.

The second generation of nuclear plants refers to most commercial reactors now in operation, including the light water reactor fleet found in the US and Europe, predominately comprised of pressurized water reactors and boiling water reactors. These reactors were mostly designed in the 1960s and built in the 1970s.

The third generation encompasses advanced reactor designs that operate at slightly higher temperatures or according to different designs, such as pebble bed modular reactors, Canadian deuterium uranium reactors, European pressurized water reactors, and advanced boiling water reactors. These advanced reactors, sometimes referred to as "Generation III" or "Generation III+" technology, emerged from public-private research in the 1980s and early 1990s. While Generation III reactors are not currently used widely by the industry, their use is expected to grow significantly between 2020 and 2040. The difference between Generation III and Generation IV designs is sometimes blurred by Generation III proponents attempting to receive Generation IV research funds.

Research on the fourth generation of nuclear reactors, often called "Generation IV" systems, began in the late 1990s under the Advanced Fuel Cycle Initiative, previously called the Advanced Accelerator Applications Program. Under the Advanced Fuel Cycle Initiative, the US started researching advanced reactor designs and fuel cycles along with Belgium, China, the Czech Republic, France, Germany, Hungary, India, Japan, the Netherlands, Poland, the Russian Federation, South Korea, Switzerland, and the European Commission. The program morphed into the Nuclear Energy Research Initiative (NERI) in 1999, a project headed by the US Department of Energy (DOE) to explore research in four areas (explained in Table 2). Under the NERI, the DOE alone sponsored 46 research projects involving national laboratories, universities, and industry and foreign research partners.

The DOE's approach to Generation IV research transformed once again in 2002, when President George W. Bush announced a nuclear program aptly called the "Generation IV International Forum" (GIF). At the heart of the GIF lies the Global Nuclear Energy Partnership, a program created in 2006 to promote nuclear energy abroad by exploring export opportunities for American technology firms. Ten countries currently announce and share their research efforts annually at the GIF: Argentina, Brazil, Canada, France, Japan, South Africa, South Korea, Switzerland, the UK, and the US. Generation IV research initially started by considering a slate of 20 different reactor designs, but has since been narrowed down to only six designs: very-high-temperature reactors, gas-cooled fast reactors, sodium-cooled fast reactors, supercritical water-cooled reactors, lead-cooled reactors, and molten salt reactors. These designs, while differing in specific engineering, have six common themes: (1) they are intended to produce reactors operating either at very high temperatures or in a fast neutron/breeder fuel cycle that attempts to recycle spent fuel; (2) they attempt to improve the environmental performance of reactors by minimizing the need for mined uranium and lessening the environmental footprint of power plants; (3) they plan to improve waste management by recycling or minimizing the fuel that they do use; (4) they try to enhance proliferation resistance by making it impossible to steal weapons-grade material; (5) they intend to improve safety and reliability; and (6) they attempt to minimize financial risk and improve the economics of plant construction and operation.

In short, the theory is that future Generation IV nuclear technology would operate differently than conventional units by utilizing fuel cycles with higher temperatures or different forms of fuel, minimizing

Table 2: Objectives of "Next Generation" Nuclear Research and Development

Area	Objective
Construction	Moving away from onsite construction of power plants to a more standardized manufacturing approach with simplified designs that would be more suited to mass production
Proliferation resistance	Creating fuel core designs that operate for at least 15 years without refueling to minimize the risk of theft of fissile materials
Safety	Improving operational procedures and maintenance requirements to minimize the incidence of human operator error
Waste disposal	Designing new fuel cycles to minimize the creation of nuclear waste and operate on alternative forms of fuel

environmental damage and the creation of waste, decreasing the amount of fissile material from the fuel cycle available for weapons, improving safety, and lowering the price of nuclear power plants. However, Generation IV reactors are also the furthest from commercialization. They are completely experimental, with engineers and scientists still working out theoretical concepts, most of which have not been proven in practice. The next stage in Generation IV research, if possible, would likely be the construction of experimental reactors around 2015 or 2020. Then, if successful, commercialization and wide-scale deployment of Generation IV technologies would begin by 2040 at the earliest. (As later chapters note, though, Generation IV reactors have been called "paper reactors" because it is likely they may only exist on paper.)

The Basics of the Nuclear Fuel Cycle

Engineers generally classify nuclear fuel cycles into two types: once-through and closed. Conventional reactors operating on a once-through mode discharge spent fuel directly into disposal. Reactors with reprocessing in a closed fuel cycle separate waste products from unused fissionable material so that it can be recycled as fuel. Reactors operating on closed cycles extend fuel supplies and have advantages in terms of storage of waste disposal, but have disadvantages in terms of cost, short-term reprocessing issues, proliferation risk, and fuel cycle safety.[5]

Despite these differences, both once-through and closed nuclear fuel cycles involve at least five interconnected stages: the front end of the cycle where uranium fuel is mined, milled, converted, enriched, and fabricated; the construction of the plant itself; the operation and maintenance of the facility; the back end of the cycle where spent fuel is conditioned, (re)processed, and stored; and a final stage where plants are decommissioned and abandoned mines are returned to their original state. All sorts of diagrams and figures have been drawn to illustrate the nuclear fuel cycle; two of my favorite are presented in Figures 3 and 4. As both figures indicate, the nuclear fuel cycle is long and complex, though not all stages of the fuel cycle are present in all reactors. Canadian-designed heavy water CANDU reactors, for instance, do not need uranium enrichment, as they rely on natural uranium as fuel.[6]

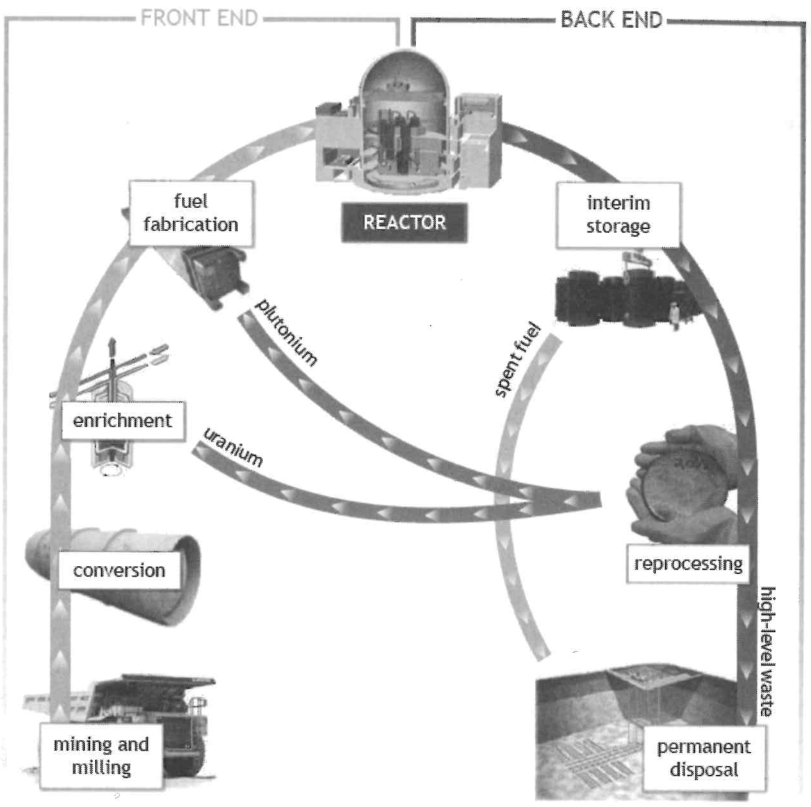

Figure 3: Front-End/Back-End Representation of the Nuclear Fuel Cycle[7]

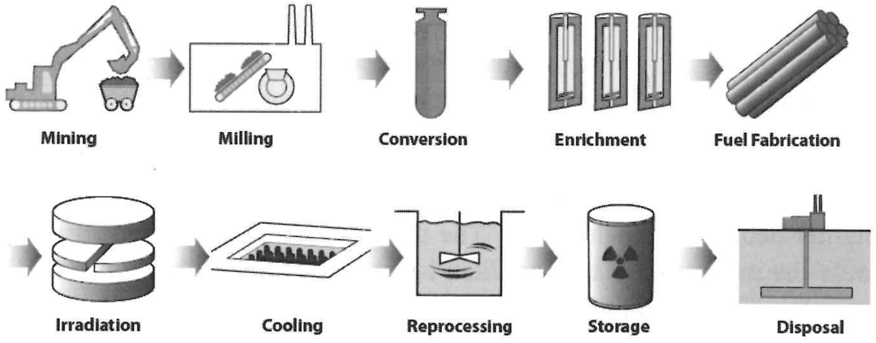

Figure 4: Linear Representation of the Nuclear Fuel Cycle[8]

The Front End

The front end of the cycle begins with uranium, the primary fuel for nuclear power plants. It is widely distributed in the earth's crust and the ocean in minute quantities, with the exception of concentrations rich enough to constitute ore. Uranium is mined both at the surface and underground; and after it is extracted, it is crushed, ground into fine slurry, and leached in sulfuric acid. Uranium is then recovered from solution and concentrated into solid uranium oxide, often called "yellowcake," before it is converted into uranium hexafluoride and heated. Then, hexafluoride vapor is loaded into cylinders where it is cooled and condensed into a solid before undergoing enrichment through gaseous diffusion or gas centrifuge.

Uranium Mining

Starting at the mine, rich ores may embody concentrations of uranium oxide as high as 10%, but 0.2% or less is usual and most uranium producers will consider mining ores with concentrations higher than 0.0004%. A majority of the usable soft ore found in sandstone has a concentration between 0.2% and 0.01%; while hard ore found in granite has a lower uranium content, usually about 0.02% or less. Uranium mines are typically open-cast pits (up to 250 m deep) or underground. A third extraction technique involves subjecting natural uranium to *in situ* leaching, whereby hundreds of tons of sulfuric acid, nitric acid, and ammonia are injected into the strata and then pumped up again after 3–25 years, yielding uranium from treated rocks.

Uranium Milling

Mined uranium must undergo a series of metallurgical processes to crush, screen, and wash the ore, letting the heavy uranium settle as the lighter debris is funneled away. The next step is the mill, often situated near the mine, where acid or alkali baths leach the uranium out of the processed ore, producing a bright yellow powder called yellowcake, which is about 75% uranium oxide (its chemical form is U_3O_8). In cases where ores have a concentration of 0.1%, the milling must grind 1,000 tons of rock to extract one ton of yellowcake; both the oxide and the tailings (the 999 tons of remaining rock) remain radioactive, requiring treatment. Acids must be neutralized with limestone and made insoluble with phosphates, the environmental consequences of which are discussed in Chapter 5.[9]

Uranium Conversion and Enrichment

Next comes conversion and enrichment, where a series of chemical processes are conducted to remove the remaining impurities and to convert yellowcake into the necessary compounds for fuel pellets and assemblies. Enrichment is needed to increase the percentage of the isotope uranium-235 to higher levels needed for most types of reactors. Natural uranium contains about 0.7% uranium-235; the rest is mainly uranium-234 or uranium-238. In order to bring the concentration of uranium-235 up to at least 3.5% for typical commercial light water reactors or about 4–5% for other modern reactors, the oxide must be enriched. The process begins by converting uranium to uranium hexafluoride (UF_6 or "hex").

A variety of enrichment processes have been demonstrated in the laboratory, including:

- gaseous diffusion;
- thermal diffusion;
- gas centrifuge separation;
- atomic vapor laser isotope separation;
- molecular laser isotope separation;
- separation of isotopes by laser excitation;
- aerodynamic isotope separation;
- electromagnetic isotope separation;
- plasma separation; and
- chemical separation.

The two dominant commercial enrichment methods are gaseous diffusion and centrifuge separation.[10] Table 3 shows that 21 large uranium enrichment facilities were either operational or under construction as of late 2009.

Table 3: Large Uranium Enrichment Facilities

Country	Name/Location	Process	Capacity (Thousands of Separative Work Units/Year)
Brazil	Resende Enrichment	Centrifuge	120
China	Lanzhou 2	Centrifuge	500
China	Shaanxi Enrichment Plant	Centrifuge	500
France	Georges Besse	Diffusion	10,800
France	Georges Besse II	Centrifuge	7,500
Germany	Gronau	Centrifuge	2,000
India	Rattehallib	Centrifuge	10
Iran	Natanz	Centrifuge	150
Japan	Rokkasho Enrichment Plant	Centrifuge	1,050
Netherlands	Almelo	Centrifuge	4,000
Pakistan	Kahutab	Centrifuge	20
Russia	Angarsk	Centrifuge	2,600
Russia	Nouvouralsk	Centrifuge	9,800
Russia	Zelenogorsk	Centrifuge	5,800
Russia	Seversk	Centrifuge	4,000
United Kingdom	Capenhurst	Centrifuge	5,000
United States	Paducah	Diffusion	11,300
United States	Portsmouth	Diffusion	7,400
United States	National Enrichment Facility	Centrifuge	3,000
United States	American Centrifuge Plant	Centrifuge	3,500
United States	Idaho Falls Enrichment Plant	Centrifuge	3,000

Gaseous diffusion, developed during the Second World War as part of the Manhattan Project, accounts for about 45% of world enrichment capacity. The diffusion process funnels hex through a series of porous membranes or diaphragms. The lighter uranium-235 molecules move faster than the uranium-238 molecules and have a slightly better chance of passing through the pores in the membrane. The process is repeated many times in a series of diffusion stages called a cascade, with the enriched UF_6 withdrawn from one end of the cascade and the depleted UF_6 removed at the other end. The gas must be processed through some 1,400 stages before it is properly enriched.

The gas centrifuge process, first demonstrated in the 1940s, feeds hex into a series of vacuum tubes, and accounts for about 45% of world enrichment capacity. When the rotors are spun rapidly, the heavier molecules with uranium-238 increase in concentration towards the outer edge of the cylinders, with a corresponding increase in uranium-235 concentration near the center. To separate the two isotopes, centrifuges rotate at very high speeds, with spinning cylinders moving at roughly one million times the acceleration of gravity.

In the US, the gaseous diffusion plant at Paducah, Kentucky, primarily does enrichment; while Europe and Russia utilize mostly centrifuge methods.[11] The remaining nuclear fuel (about 10%) comes from the recycling of nuclear weapons. After enrichment, about 85% of the oxide comes out as waste in the form of depleted hex, also known as enrichment tails, which must be stored. Each year, for instance, France creates 16,000 tons of enrichment tails that are then exported to Russia or added to the existing 200,000 tons of depleted uranium within the country.[12]

The 15% that emerges as enriched uranium is converted into ceramic pellets of uranium dioxide (UO_2), packed in zirconium alloy tubes, and bundled together to form fuel rod assemblies for reactors. Fuel fabrication involves tightly pressing UO_2 powder into small pellets and then sintering them to form a ceramic. Fuel elements and assemblies are often exposed to even more ionizing radiation through accelerators and cyclotrons — a process known as irradiation — to bombard atoms with particles so as to produce a chain reaction. To supply enough enriched fuel for a standard 1,000-MW reactor for 1 year, about 200 tons of natural uranium has to be processed.

Construction

The construction phase of the nuclear lifecycle involves the fabrication, transportation, and use of materials to build generators, turbines, cooling towers, control rooms, transformers, substations, and other infrastructure. A typical nuclear plant contains some 50 miles of piping (welded 25,000 times) and 900 miles of electrical cables. Thousands of electric motors, conduits, batteries, relays, switches, operating boards, condensers, and fuses are needed for the system to operate. Cooling systems necessitate valves, seals, drains, vents, gauges, and fittings. Structural supports, firewalls, radiation shields, spent fuel storage facilities, and emergency backup generators must remain in excellent condition. Temperatures, pressures, power levels, radiation levels, flow rates, cooling water chemistry, and equipment performance must all be constantly monitored. A common nuclear plant needs 170,000 tons of concrete, 32,000 tons of steel, 1,363 tons of copper, and a total of 205,464 tons of other materials. Many of these are energy- and carbon-intensive: 1 ton of aluminum has a carbon equivalent of more than 10,000 tons of CO_2; 1 ton of lithium, 44,000 tons; and 1 ton of silver, 913,000 tons.[13] Some of the constraints surrounding the construction of new nuclear power plants are discussed in Chapters 3 and 5.

Operation

The operation phase of the lifecycle encompasses the energy needed to manage the cooling and fuel cycles of the plant, as well as the energy needed for its maintenance and backup generators. Indirect energy use includes the provision of power during reactor outages, repairs, and shutdowns.

The heart of the operating nuclear facility is the reactor, which generates electricity through the fission, or splitting, of uranium and plutonium isotopes. The nuclear reaction inside a nuclear power plant is identical to a nuclear weapon explosion, except the reactor releases the energy slowly over months instead of in one awesome, terrifying moment. In a nuclear reactor, the fission process does not take place one atom at a time. Uranium has the rare and productive property that, when it is struck by a neutron, it splits into two and produces more neutrons. If one uranium-235 atom collides with an atom of uranium-238 (one of the other isotopes of uranium), it may stay there and induce a couple of decay cycles to produce plutonium-239. Plutonium-239, sharing the same property as uranium-235, splits when struck by neutrons to act as additional fuel. The process can be controlled by a moderator consisting of water or graphite to speed the reaction up, and neutron-absorbing

control rods to slow it down. Most nuclear reactors around the worl have a present lifetime of 30–40 years, but produce electricity at full power for no more than 24 years.[14]

Daily work at a typical nuclear power plant is carried out by between 200 and 1,000 people, although the number jumps significantly during refueling and maintenance. During some phases, planned work activities are truly immense, ranging from several hundred to several thousand operations and tasks per hour; and during an outage, more than 90,000 work orders can occur for one or more tasks.[15]

The Back End

The back end of the nuclear fuel cycle involves fuel processing, interim storage, and permanent sequestration of waste.

Fuel Processing and Reprocessing

Spent fuel must be conditioned for reactors operating on a once-through fuel cycle, and reprocessed for those employing a closed fuel cycle. Eventually, radioactive impurities such as barium and krypton, along with transuranic elements such as americium and neptunium, clog the uranium inducing a nuclear reaction. After a few years, fuel elements must be removed and fresh fuel rods inserted. In France and the UK, where reprocessing continues, spent uranium is stored for hopeful use at a later date in fast breeder reactors, plutonium is recycled into mixed oxide (MOX), and the remaining fissile waste is vitrified (i.e. chemically transformed into a glass to make the waste inert). This method of reprocessing — plutonium-uranium extraction (PUREX) — involves chemically separating uranium and plutonium. A significant fraction of the plutonium stockpiles is intended to be used for MOX fuel fabrication at two industrial-scale facilities: Areva's Melox plant in Marcoule, France; and British Nuclear Group's Sellafield MOX plant in the UK. These facilities blend uranium and plutonium powders at high temperatures to create MOX pellets, which are then loaded into fuel assemblies. Researchers have recently proposed a newer method of reprocessing called uranium extraction plus (UREX+), which keeps uranium and plutonium together in the fuel cycle to avoid separating out pure plutonium. Some of the problems with reprocessing are elaborated in Chapter 4.

Interim Storage

The term "nuclear waste" technically includes six categories of waste: spent nuclear fuel, high-level waste, transuranic waste (the three most important or radioactive), as well as low-level waste, mixed waste, and uranium mill tailings. Spent nuclear fuel refers to fuel rods that have been irradiated in a nuclear reactor, meaning they contain active and short-lived fission products such as cesium and strontium as well as long-lived radionuclides. High-level waste refers to highly radioactive material resulting from the reprocessing of spent nuclear fuel, that is, the chemical processes that break down fuel rods into uranium and plutonium. Transuranic waste refers to any type of waste that has more than 100 nanocuries of alpha-emitting transuranic isotopes with half-lives greater than 20 years per gram of waste, excluding high-level waste.[16] All six types of waste must be continually tracked and monitored. Figure 5 shows an inspection of nuclear waste in the US.

To handle spent nuclear fuel and high-level waste, scientists and engineers have designed two primary types of storage: wet and dry. Wet storage pools involve placing spent fuel assemblies in racks in pools of water that are made of concrete and lined with stainless steel or epoxy-based paints. The pool is enclosed within a building, and radioactivity in water is kept as low as possible.[17] The pools themselves can become quite deep, with at least three meters of water covering the top of fuel assemblies to provide radiation shielding.[18] Operators often add boron and other neutron-absorbing materials to the water to prevent the fuel from starting a chain reaction. About 90% of spent fuel globally is currently stored in wet pools.

Figure 5: Workers at the US Department of Energy Inspecting Low-Level Nuclear Waste in Nevada

Dry storage of spent fuel differs from wet storage, as it uses gas or air (often enhanced with helium or nitrogen to limit oxidation) instead of water as a coolant, and metal or concrete as a radiation barrier. Fuel must be stored in wet pools for several years, usually at least a decade, before they become cool enough for dry storage. Dry storage vaults use metal tubes and cylinders to store fuel, remove heat through forced air convection, and have the building itself act as a radiation shield.[19] Although there are many different cask types, those in the US typically hold 20–24 pressurized water reactor fuel assemblies, sealed in a helium atmosphere inside the cask to prevent corrosion. Decay heat is transferred by helium from the fuel to fins on the outside of the storage cask for cooling.

Permanent Sequestration of Waste

The final stage of the back end of the cycle involves the sequestration of nuclear waste. Permanent geological repositories must provide protection against every plausible scenario in which radionuclides might reach the biosphere or expose humans to dangerous levels of radiation. These risks include groundwater seeping into the repository, the corrosion of waste containers, the leaching of radionuclides, and the migration of contaminated groundwater toward areas where it might be used as drinking water or for agriculture.

Decommissioning

The last stage of the nuclear lifecycle involves the decommissioning and dismantling of the reactor, as well as reclamation of the uranium mine site. After a cooling-off period that may last as long as 50–100 years, reactors must be dismantled and cut into small pieces to be packed in containers for final disposal. Nuclear plants have an operating lifetime of 40 years, but decommissioning usually takes at least 60 years.[20] While it will vary along with the technique and the reactor type, the total energy required for decommissioning can be as much as 50% more than the energy needed for original construction. At uranium mines, the overburden of rock covering the area must be replaced and replanted with indigenous vegetation, and radioactive tailings must be treated and contained before land can be reclaimed.

Drivers of Nuclear Power Expansion

Why have countries spent billions of dollars collaborating on nuclear technology? Of all the daunting global challenges facing the electricity sector, three seem to be most significant: the need to provide basic energy services to the world's poor; the need to find sources of energy that are less greenhouse gas-intensive; and the need to keep costs low, both for ratepayers and for governments. Proponents of nuclear power believe it is the only technology that can satisfy all three of these critical needs (although Chapter 8 raises serious doubts as to the legitimacy of these drivers).

Fighting Energy Poverty

Denying electricity and the services it can provide to those in need promotes discrimination in the vein of what is sometimes called "environmental racism." At least one billion people — roughly one sixth of the global population — have little to no access to electricity.[21] Without electricity, millions of women and children are typically forced to spend significant amounts of time searching for firewood, and then combusting wood and charcoal indoors to heat their homes or prepare meals. The health consequences alone of this combustion are monumental. Scientists estimate that indoor air pollution kills 2.8 million people every year — almost equal to the number of people dying annually from HIV/AIDS. Close to one million of these deaths (910,000, to be precise) occur in children under the age of five, who must suffer their final months of life dealing with debilitating respiratory infections, chronic obstructive pulmonary disease, and lung cancer.[22] In essence, nuclear power is seen as one of the few options that can prevent a form of "energy apartheid" whereby people in the Western world use large amounts of energy, have higher standards of living, and enjoy longer life expectancies, while those in undeveloped nations have no access to energy and die earlier.[23]

Climate Change and the Environment

Proponents of nuclear power believe that it is a much better option for generating power without releasing significant amounts of greenhouse gases or toxic pollution. Greenhouse gas emissions are expected to increase approximately 135% in the US and Canada by 2030 from today's levels under a business-as-usual scenario.[24] As Robert K. Dixon, former Head of the Technology Policy Division at the International Energy Agency (IEA), declared in 2008, "Without substantial technology and policy changes, fossil fuels will remain fuels of choice well into the future."[25]

Advocates of nuclear power have therefore framed nuclear energy as an important part of any solution aimed at fighting climate change and reducing greenhouse gas emissions. The Nuclear Energy Institute, discussing India and China, reminded the public that "it is important to influence them to build emission free sources of energy like nuclear."[26] When President George W. Bush signed the Energy Policy Act in August 2005, he remarked that "only nuclear power plants can generate massive amounts of electricity without emitting an ounce of air pollution or greenhouse gases."[27] The late Mr. Nicholas Ridley, former Secretary of State for the Environment in the UK, was even more explicit, stating on BBC television: "There is absolutely no doubt that if you want to arrest the Greenhouse Effect you should concentrate on a massive increase in nuclear generating capacity. Nuclear power stations give out no sulfur and carbon dioxide, so they are the cleanest form of power generation."[28]

Even some former nuclear power skeptics have embraced the efficacy of nuclear power as a solution to the global climate crisis. Patrick Moore, co-founder of Greenpeace and once a vocal opponent of nuclear power, has publicly stated that "nuclear energy . . . remains the only practical, safe and environmentally friendly means of reducing greenhouse gas emissions and addressing energy security."[29] Similarly, the environmentalist James Lovelock goes so far as to argue that nuclear power is one of the only options that can meet electricity demand as we transition to cleaner energy sources, and that its risks are "insignificant compared with the real threat of intolerable and lethal heat-waves" associated with climate change.[30] (Problems with this line of thinking are presented in Chapter 5.)

Also, one supposed benefit to nuclear power plants is that they produce an incredibly small volume of waste and pollution compared to fossil-fueled power stations. The impact on human health and environmental quality from fossil fuel combustion is more immediately drastic than that from nuclear power, since nuclear waste becomes less toxic with time as radioactive materials decay, whereas the chemicals emitted from fossil fuels become quickly ingested by humans and other organisms. As Hans Blix, former Director General of the International Atomic Energy Agency (IAEA), succinctly put it:

> A 1,000 megawatt equivalent (MWe) coal plant with optimal pollution abatement equipment will annually emit into the atmosphere 900 tons of sulfur dioxide, 4,500 tons of nitrous oxide, 1,300 tons of particulates, and 6.5 million tons of carbon dioxide. . . . By contrast, a nuclear plant of 1,000 MWe capacity produces annually some 35 tons of highly radioactive spent fuel.[31]

One study estimated that the waste generated by a large nuclear plant per year was 2 million times smaller by weight and 1 billion times smaller by volume than the waste from a coal-burning plant.[32] Such attributes make nuclear power attractive to some advocates wishing to produce electricity with minimal damage to the environment.[33]

Economics and Cost

Nuclear power plants do have very low historical production costs, and recently have improved their performance due to better capacity factors and operating procedures. They key word here is *historical*: many of these plants have been operating for years, and their capital costs have all but

been paid off. (On the disadvantageous side, nuclear power plants have long construction lead times and are exposed to cost overruns, and future plants will likely be much more expensive than the ones already built. This is discussed in Chapter 4.)

Although particular production costs will differ by design, site requirements, and the rate of capital depreciation, the existing light water reactors — which make up a majority of the world's nuclear power fleet — produce electricity at costs between 2.5 cents/kWh and 7 cents/kWh. This makes them cheaper than almost any other source of electricity on the global market today.[34] Some coal plants and hydroelectric facilities also produce power at as cheaply as 2 cents/kWh, but most other sources of supply tend to cost more than 5 cents/kWh.

A second advantage concerns improvements in operational performance and maintenance, due largely to decades of research and development along with government subsidies. The World Nuclear Association reported that existing plants in the US, for example, improved their capacity factor by 40% from 1990 to 2008, with the average plant now operating 91.1% of the time.[35]

The industry has incorporated research findings on human factors and safety culture through groups and organizations such as the IAEA and the World Association of Nuclear Operators (WANO), created after the Chernobyl accident in 1986.[36] These efforts have produced dividends, as evidenced by one meta-survey of nuclear power plant performance that found existing plants were getting safer. The study noted that, industry-wide, 1.04 accidents occurred per 200,000 worker hours in 1990 but only 0.28 accidents occurred in 2003.[37] The study noted that better occupational safety and health regulations in Europe and North America, improved medical knowledge, and better emergency care and first aid techniques have reduced the likelihood of accidents and lessened their impact when they do occur.

Plans for Nuclear Expansion

Consequently, many believe that nuclear power is set for rapid expansion. Indeed, nuclear power plants are already being planned or constructed in the US, Europe, and Asia.

In the US, over the past two decades, nuclear power plants have been quietly but surely expanding their generating capacity. The Nuclear Regulatory Commission (NRC) approved 2,200 MW of capacity upgrades to existing nuclear plants between 1988 and 1999, and nuclear facilities are seeking approval for another 842 MW.[38] Following the 2002 unveiling of the DOE's "Nuclear Power 2010 Program," targeted at demonstrating "new regulatory processes leading to a private sector decision by 2005 to order new nuclear power plants for deployment in the United States in the 2010 timeframe," three large utilities — Exelon, Entergy, and Dominion — filed early site permits for the construction of new nuclear plants in Illinois, Texas, and Virginia, respectively.[39] The Energy Policy Act of 2005 also significantly bolstered plans for nuclear power by extending liability limits for nuclear accidents under the Price–Anderson Act for another 20 years, authorizing the construction of new DOE research reactors, and establishing hefty loan and insurance programs to make the construction of new nuclear reactors more attractive. After the Act was passed, between 2005 and 2007 the NRC received notices of application for at least 28 new nuclear units from a plethora of utilities and energy consortia, and 30 applications for new reactor units were filed by the close of 2009.[40]

In Europe, utilities operate 145 nuclear reactors throughout 15 of the 27 countries in the European Union, for a total of 131,820 MW of installed capacity which provided 31% of electricity generated in 2007.[41] France plans to replace 58 reactors with new Generation III pressurized water reactors at a rate of 1,600 MW per year. Even Ukraine, the site of the worst nuclear accident in the technology's history, is planning to construct 22 new nuclear power plants by 2030. In East and South Asia, there are 109 nuclear power reactors in operation, 18 under construction, and plans to build another 110. If one takes government proclamations at face value, 319 new nuclear power plants have been planned and proposed for a total of 325,488 MW of capacity, which would need more than 64,000 additional tons of uranium each year to operate.[42]

The fastest growth in nuclear generation is expected to occur in China, India, Japan, and South Korea. The Chinese Academy of Sciences has even embarked on an ambitious public relations campaign to make nuclear power more popular. Chinese operators already have five units under construction and 50 proposed by 2020, and they plan to quadruple nuclear capacity from 7.6 GW in 2008 to more than 40 GW by 2020. India, which meets only 3% of electricity demand with nuclear power, planned a tenfold increase from 700 MW to 7280 MW by 2010 (though this has not yet occurred). Japan, which currently operates 55 commercial light water reactors, is seeking to increase its share of nuclear electricity from about 30% in 2008 to 40% over the next two decades. Japanese utilities thus have two plants under construction and 11 more planned. South Korea, which currently operates 16 reactors, has six under construction and eight more planned by 2015, implying a 100% increase in nuclear power generation.

Even developing countries in Southeast Asia are attempting to embrace nuclear power. Under a Regional Cooperative Agreement signed in 1972, Australia, Bangladesh, China, India, Indonesia, Japan, Malaysia, Mongolia, Myanmar, New Zealand, Pakistan, the Philippines, Singapore, South Korea, Sri Lanka, Thailand, and Vietnam have agreed to promote cooperative research and training in nuclear-related fields.[43] Vietnam is aiming for its first nuclear plant by 2015; Malaysia has plans for its first nuclear power plant by 2020; Thailand is planning to install 4 GW of nuclear capacity by 2020; and Indonesia's 4-GW Mount Muria plant is currently on hold, but is scheduled to start construction in 2011 and become operational by 2018. In other parts of the world, 30 nuclear plants are being built in 12 countries, with additional units in the planning stages for Argentina, Brazil, the Czech Republic, Finland, France, Mexico, Peru, Romania, and Russia.

As the chapters to follow show, however, many of these planned and proposed nuclear power plants will never be built. Despite all of the recent efforts to research, design, plan, construct, operate, and upgrade nuclear power plants, transitioning to an energy economy based on significant expansions in nuclear power would bring serious consequences. The remaining chapters in the book will document how nuclear power plants create massive external costs that are not subsumed by ratepayers or even present generations. Nuclear facilities rely almost entirely on government subsidies for construction, storage, and liability. While, historically, the costs of nuclear power plants appear to be low, in the near future the cost of building new nuclear plants will be outrageously high, and the promise of Generation IV reactors is entirely theoretical and will require billions of dollars in further research before the industry can construct even an experimental reactor.

In the end, a nuclear reactor, despite all of its complexities, is merely another way to boil water to generate electricity. Relying on nuclear reactions, uranium mines, enrichment facilities, and the like is an incredibly complicated way to do what other technologies accomplish by harnessing the power of wind or the kinetic energy of falling water. One commentator joked that relying on nuclear energy to meet the growing demand for electricity is akin to "smoking cigarettes to keep the weight off."[44] Or, as Christian Parenti put it:

> Nuclear fission is a mind-bogglingly complex process, a sublime, truly Promethean technology. Let's recall: it involves smashing a subatomic particle, a neutron, into an atom of uranium-235 to release energy and more neutrons, which then smash other atoms that release more energy and so on infinitely, except the whole process is controlled and used to boil water, which spins a turbine that generates electricity. . . . In this nether realm, where industry and science seek to reproduce a process akin to that which occurs inside the sun, even basic tasks — like moving the fuel rods, changing spare parts — become complicated, mechanized and expensive. Atom-smashing is to coal power, or a windmill, as a Formula One race-car engine is to the mechanics of a bicycle.[45]

As we shall also see in Chapter 7, many advantages exist by relying on the bicycle.

Endnotes

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[3] Source: Antony Froggatt, "Nuclear Self-Sufficiency — Can Nuclear Power Pave the Road Towards Energy Independence?," Presentation to the "Towards a Nuclear Power Renaissance" Conference in Potsdam, Germany, March 4–5, 2010.

[4] Victor Gilinsky, Marvin Miller, and Harmon Hubbard, *A Fresh Examination of the Proliferation Dangers of Light Water Reactors* (Washington, D.C.: Nonproliferation Policy Education Center, October 22, 2004). Gilinsky *et al.*, interestingly, also note: "In the 1950s, before the advent of nuclear power plants, the United States tried to control the uranium market by buying up uranium at high prices. This naturally encouraged exploration that demonstrated that uranium was plentiful and negated the US effort at control. With easy access to uranium but lacking indigenous uranium enrichment facilities, Britain, France, and Canada opted for reactor designs that utilized natural uranium fuel and heavy water or graphite as the neutron moderator. In the late 1950s and early 1960s, they interested Italy, Japan, India, and other countries in heading in this direction. Not only did this threaten America's competitive position but it also threatened to spread a type of reactor that lent itself easily to production of plutonium. In fact the first British and French power reactors were based on their military plutonium production reactors. America's advantage was two-fold. The United States had developed a compact, and therefore relatively low-cost, LWR [light water reactor] design based on a naval propulsion reactor design. And the United States had invested heavily in gaseous diffusion plants in Tennessee, Kentucky, and Ohio to enrich uranium for weapons. The LWR could only operate on enriched uranium, that is, uranium more concentrated in the active uranium-235 isotope than natural uranium. By virtue of its huge enrichment capacity, the United States had an effective monopoly on the production of this fuel. Moreover, as the cost of the plants had been largely assigned to the military budget, the United States decided to sell the stuff at low prices that did not defray the massive investment. It was a price that at the time no other country could even hope to offer in the future. From the point of view of customers, it was a deal that was hard to refuse, even if it came with US control conditions. Ultimately, the amount of engineering invested in these designs and the depth of experience with them overwhelmed any conceptual advantages other reactor types may have had. While not the exclusive choice — Canada and India continued developing the natural uranium/heavy water designs that evolved into the CANDU reactor — the LWR became the standard reactor type around the world. In the late 1960s France switched to LWRs, and Britain did later. Other European manufacturers in Germany and Sweden chose LWRs. The Soviets eventually did, too."

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3

Safety and Reliability: Dealing with "Normal Accidents"

An ironic moment occurred on March 31, 1979. That evening, then-US Secretary of Energy James Schlesinger was testifying before the American Congress on ways to expedite the licensing process for nuclear reactors, arguing that onerous requirements were no longer needed given the inherent safety of new designs. At the same time, the Nuclear Regulatory Commission (NRC) Chairman Joe Hendrie was transmitting evacuation orders to Governor Richard L. Thornburgh in Pennsylvania because of the accident at Three Mile Island (TMI). Unknown to Schlesinger, the NRC had long suspected that an accident would occur at TMI, previously ordering the shutdown of five similarly designed nuclear power plants based on errors discovered in a computer program used to assess the stresses on power plant pipes and cooling systems during an earthquake. A few days before the accident in March 1979, NRC inspectors had even warned the Commissioner that the TMI design was unsafe and should be shut down immediately. The NRC was in the process of considering what to do when the accident occurred.[1]

The story does not end there. Rather than admit to the inherent flaws with their reactor designs, the nuclear industry ran a sleek public relations campaign a few months after the accident featuring the physicist Edward Teller in newspaper and television advertisements. In these advertisements,