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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, Teller solemnly told viewers (or, in newspaper versions, expressed in very large bold-faced type) that "I was the only victim of Three Mile Island." Even though Teller was nowhere near Pennsylvania at the time of the accident, he claimed that he suffered a heart attack a few weeks later because he had been working tirelessly to refute senseless anti-nuclear propaganda.[2]

The lessons from this story are numerous and possibly prophetic. It reveals that various organizations promoting nuclear power do not always share information and can make mistakes (as in the Secretary of Energy believing designs to be safe when the NRC did not). It shows that some scientists and engineers involved in the industry, such as Teller, have optimistic views about atomic energy and intolerance for skepticism. It demonstrates that nuclear reactors are extremely dangerous when they malfunction. It also implies that the nuclear industry will utilize public opinion and savvy media techniques to insulate itself from criticism.

This chapter explores the safety and reliability concerns with existing and new nuclear power plants. It looks at the historical record of incidents and accidents, current risks with the global reactor fleet, and future risks with new reactors. It also explores an often-ignored component, namely the scarcity of high-quality materials and skilled labor to build and operate nuclear units, and finally discusses the technical challenges related to finding high-quality uranium fuel and a declining energy payback ratio.

Safety and Accidents

While the Chair of the Public Information Committee of the American Nuclear Society has publicly stated that "the industry has proven itself to be the safest major source of electricity in the Western world,"[3] the history of nuclear power proves otherwise. The safety record of nuclear plants is lackluster at best. For one salient example, consider that Ukraine still has a Ministry of Emergency, some 24 years after the Chernobyl nuclear disaster warranted its creation. This section focuses on historical accidents at nuclear facilities, with a special emphasis on two of the most famous accidents at Chernobyl and TMI, as well as the risk of future accidents.

Whenever one talks about safety culture, nuclear accidents, and reliability, it is important to be clear about the terms. Part of the confusion stems from how one defines an accident. The NRC and the nuclear community generally separate unplanned events into two classes: incidents and accidents. Incidents are unforeseen events and equipment failures that occur during normal plant operation, resulting in no offsite releases of radiation or severe damage to equipment; accidents refer to either offsite releases of radiation or severe damage to plant equipment.[4] The International Nuclear and Radiological Event Scale communicates the significance of a nuclear and radiological event through a ranking system of seven levels: levels 1–3 are "incidents" while levels 4–7 are "accidents," with a "level 7 major accident" consisting of "a major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures."[5] The Paul Scherrer Institute manages an Energy-Related Severe Accident Database (ENSAD), which takes a slightly different approach. For the ENSAD, a severe accident is one which involves one of the following: at least 5 fatalities, at least 10 injuries, 200 evacuees, 10,000 tons of hydrocarbons released, more than 25 km^2 of cleanup, or more than US$5 million in economic losses.[6]

Under the classifications of accidents from the NRC, the International Nuclear and Radiological Event Scale, and even the ENSAD, the number of nuclear accidents is low. However, if one redefines an accident to be an incident that results in either the loss of human life or more than US$50,000 of property damage, a very different picture emerges. One study identified no less than 76 nuclear accidents meeting this definition, totaling more than US$19 billion in damages worldwide, from 1947 to 2008.[7] These accidents accounted for 41% of all accident-related property damages globally. Such accidents involved meltdowns, explosions, fires, and loss of coolant, and occurred during both normal operation and extreme emergency conditions (such as droughts and earthquakes). Another index of nuclear power accidents that included costs beyond death and property damage — such as injury to or irradiation of workers and malfunctions that did not result in shutdowns or leaks — documented 956 incidents from 1942 to 2007.[8] Yet another study documented that, between the 1979 accident at TMI and 2009, there were more than 30,000 mishaps at US nuclear power plants alone, many with the potential to have caused serious meltdowns.[9] Researchers at American University even calculated at least

124 "hazardous incidents" at nuclear units in India between 1993 and 1995.[10] The 200 nuclear facilities in France, including power plants, uranium enrichment and conversion plants, reprocessing plants, fuel fabrication plants, surface repositories for waste, and experimental sites for geologic disposal, declare in total 700–800 serious incidents or significant safety events each year.[11]

One of the first accident studies, conducted by the US Atomic Energy Commission in 1975, looked at the performance of early nuclear plants in terms of occupational injury and death over 32 years of development. They documented 111 accidents involving unplanned releases of radioactivity that exposed 317 people to excess radiation as high as 80,000 rads ("safe" levels are fiercely debated, but are generally less than 10 rads). The study described 321 total fatalities, of which 184 occurred during construction, 212 during operations, and 16 during inspections and government functions (the sums do not match, as one fatality could fall into multiple categories), along with a total of 19,225 injuries not involving radiation for an unusually high frequency rate of 2.75 injuries per million man-hours.[12] Such incidents and accidents not only harm human beings, but also take their toll on operating performance. Using data from US, French, Belgian, German, Swedish, and Swiss nuclear power plants, one study found mean durations of continual operation from 35 to 88 days, meaning these plants saw scores of unplanned outages, half of which were related to equipment failure.[13] Adato *et al.* also cited more than 200 serious accidents and partial meltdowns in commercial nuclear power plants from 1960 to 1980 in the US.[14] Even the Paul Scherrer Institute's ENSAD, despite defining accidents differently, suggested that the latent effects of the Chernobyl disaster make nuclear power 41 times more dangerous than equivalently sized coal, oil, natural gas, and hydroelectric projects.[15]

The above figures tend to be conservative, as they frequently do not include accidents and incidents at research reactors and other parts of the nuclear fuel chain. Mistakes are not limited to reactor sites. For example, accidents at the Savannah River reprocessing plant have already released 10 times as much radioiodine than the accident at TMI; and a fire at the Gulf United plutonium facility in New York in 1972 scattered an undisclosed amount of plutonium into residential neighborhoods, forcing the plant to shut down permanently.[16] A similar fire at the Rocky Flats reprocessing plant in Colorado released hundreds of pounds of plutonium oxide dust into the surrounding environment. When United Nuclear Corporation's uranium mine tailings dam near Church Rock, New Mexico, burst in July 1979, it released 93 million gallons of radioactive water and 1,000 tons of radioactive sediment into local rivers. Outside of military weapons testing, this accident remains the single largest release of radioactive materials in the US. Almost 2,000 Navajo were directly affected with undrinkable water, while sheep and livestock were heavily contaminated with lead-210, polonium-210, thorium-230, and radium-236.[17] At the Mayak Industrial Reprocessing Complex in the Southern Urals, Russia, the overheating of a storage tank with nitrate acetate salts exploded in 1957, releasing a massive amount of radioactive material over 20,000 km^2 in Chelyabinsk and Sverdlovsk, causing the evacuation of 272,000 people. In September 1994, an explosion at the Serpong research reactor in Indonesia was triggered by the ignition of methane gas that had seeped from packages being removed from a laboratory storage room, which exploded when a worker lit a cigarette.[18]

Accidents have also occurred when nuclear reactors are shut down to be refueled or when fuel is to be transitioned into storage. In 1999, operators were beginning to load spent fuel into dry storage at the Trojan Reactor in Oregon when they found that the zinc-carbon coating intended to protect against borated water had started producing hydrogen, causing a small explosion. Similar hydrogen explosions have occurred at the Palisades plant in Michigan and the Point Beach reactor in Wisconsin, when operators were trying to weld casks shut. Follow-up investigations identified poor quality assessment, not following procedures, and failure to document previous repairs to casks as the likely causes.[19]

Onsite accidents at nuclear reactors and fuel facilities, unfortunately, are not the only cause of concern. The August 2003 blackout on the US East Coast revealed that more than a dozen nuclear reactors in the US and Canada were not properly maintaining backup diesel generators. In Ontario, during the blackout, reactors designed to automatically unlink from the grid and remain in standby mode instead went into full automatic shutdown, with only two of 12 reactors shutting down as planned. Because they must connect to another source of electricity to keep coolant circulating, all nuclear facilities maintain several backup diesel generators onsite for use in the event of a power loss. From September 2002 to August 2003, plant operators declared emergency diesel generators inoperable in 15 reported instances. In seven of those cases, a complete shutdown of the plant was required; and on four of those occasions, all backup generators failed at the same time. In April 2003, the Cook nuclear plant in Western Michigan shut down when emergency water flow to all four diesel generators was blocked by an influx of fish on cooling-system intake screens. These examples suggest that relying on backup systems to respond to blackouts presents a great likelihood of failure and can themselves create dangerous situations. More worryingly, since spent fuel ponds do not receive backup power from emergency diesel generators, when offsite power goes down, pool water cannot be recirculated to prevent boiling, evaporation, and exposure of fuel rods; the result is an increased risk of pool fires and explosions.[20]

Even research facilities have their own set of safety problems. Operators at the RA-2 Facility in Constituyentes, Argentina, mistakenly placed two fuel elements in the same graphite reflector, causing a criticality excursion that killed one person and injured two others. The Henry L. Stimson Center has documented numerous criticality accidents at research reactors to date, including 11 loss-of-flow accidents, 6 loss-of-cooling accidents, 25 erroneous handlings or failures of equipment, and 2 special events that have so far resulted in 21 deaths spread across the US, the Soviet Union, Japan, Argentina, and Yugoslavia.[21] The nonpartisan Government Accountability Office (GAO) recently found that 31 research facilities with reactors or nuclear materials were operating in the US for extended periods of time in noncompliance with nuclear safety licensing requirements.[22] The GAO concluded that:

> The Department of Energy has structured its independent oversight office, the Office of Health, Safety, and Security (HSS), in a way that falls short of meeting our key elements of effective independent oversight of nuclear safety. . . . HSS falls short of fully meeting our five key elements of effective oversight of nuclear safety: independence, technical expertise, ability to perform reviews and require that its findings are addressed, enforcement authority, and public access. First, we found that HSS has no role in reviewing the safety basis for new high-hazard nuclear facilities, no routine site presence, and its head is not comparable in rank to the program office heads. Second, HSS does not have some technical expertise in nuclear safety review and has vacancies in critical nuclear safety positions. Third, HSS lacks basic information about nuclear facilities, has gaps in its site inspection schedule, and does not routinely ensure that its findings are effectively addressed. Fourth, HSS enforcement actions have not prevented some recurring nuclear safety violations. Finally, HSS restricts public access to nuclear safety information.[23]

Such trends are worrying, to say the least, as the national laboratories in the US are often prized for having highly trained nuclear specialists. If these specialists cannot conform to safety standards, it raises serious questions about how operators and researchers in other countries can.

The author's own compilation reveals 99 nuclear accidents totaling US$20.5 billion in damages worldwide from 1952 to early 2010 (see Table 1). Looking at only relatively recent accidents, these numbers translate to more than one incident and US$330 million in damages every year for the past three decades. When compared to fatalities from other energy sources, nuclear power ranks as the second most fatal source of energy supply (after hydroelectric dams) and is ranked higher than oil, coal, and natural gas systems. Fifty-seven accidents have occurred since the Chernobyl disaster in 1986; and almost two-thirds (56 out of 99) of all nuclear accidents have occurred in the US, refuting the notion that accidents are relegated to the past or to countries without America's modern technologies or industry oversight. While only a few accidents globally involved fatalities, those that did collectively killed more people than have died in commercial US airline accidents since 1982.

Some of these accidents would be laughable if not for their seriousness, and include:

- A maintenance worker at the North Anna nuclear plant in Virginia cleaning the floor in an auxiliary building who caught his shirt on a circuit breaker, tripping the reactor and causing a four-day shutdown;
- An employee changing a light bulb in a control panel at Rancho Seco in California who accidentally dropped it into the reactor, short-circuiting sensor arrays and leading to an increase in pressure that almost cracked the reactor vessel;

Table 1: 99 Major Nuclear Power Accidents from 1952 to 2010[24]

Date	Location	Description	Fatalities	Cost (in US$ million (2006))
December 12, 1952	Chalk River, Ontario, Canada	Hydrogen explosion damages reactor interior, releasing 30 kg of uranium oxide particles	0	$45
October 8, 1957	Windscale, United Kingdom	Fire ignites plutonium piles and destroys surrounding dairy farms	33	$78
May 24, 1958	Chalk River, Ontario, Canada	Fuel rod catches fire and contaminates half of the facility	0	$67
July 26, 1959	Simi Valley, California, United States	Partial core meltdown takes place at the Santa Susana Field Laboratory's Sodium Reactor Experiment	0	$32
January 3, 1961	Idaho Falls, Idaho, United States	Explosion at the National Reactor Testing Station	3	$22
October 5, 1966	Monroe, Michigan, United States	Sodium cooling system malfunctions at the Enrico Fermi demonstration breeder reactor, causing partial core meltdown	0	$19
May 2, 1967	Dumfries and Galloway, Scotland	Fuel rod catches fire and causes partial meltdown at the Chaplecross Magnox nuclear power station	0	$76
January 21, 1969	Lucens, Canton of Vaud, Switzerland	Coolant system malfunctions at an underground experimental reactor	0	$22
May 1, 1969	Stockholm, Sweden	Malfunctioning valve causes flooding in the Agesta pressurized heavy water nuclear reactor, short-circuiting control functions	0	$14

(*Continued*)

Table 1: (*Continued*)

Date	Location	Description	Fatalities	Cost (in US$ million (2006))
July 16, 1971	Cordova, Illinois, United States	An electrician is electrocuted by a live cable at the Quad Cities Unit 1 reactor on the Mississippi River	1	$1
August 11, 1973	Palisades, Michigan, United States	Steam generator leak causes manual shutdown of pressurized water reactor operated by the Consumers Power Company	0	$10
March 22, 1975	Browns Ferry, Alabama, United States	Fire burns for seven hours and damages more than 1,600 control cables for three nuclear reactors, disabling core cooling systems	0	$240
November 5, 1975	Brownsville, Nebraska, United States	Hydrogen gas explosion damages the Cooper Nuclear Facility's boiling water reactor and an auxiliary building	0	$13
February 22, 1977	Jaslovske Bohunice, Czechoslovakia	Mechanical failure during fuel loading causes severe corrosion of reactor and release of radioactivity into the plant area, necessitating total decommission	0	$1,700
June 10, 1977	Waterford, Connecticut, United States	Hydrogen gas explosion damages three buildings and forces shutdown of the Millstone-1 pressurized water reactor	0	$15
February 4, 1979	Surry, Virginia, United States	Virginia Electric Power Company manually shuts down Surry Unit 2 in response to replace failed tube bundles in steam generators	0	$12

(*Continued*)

Table 1: (*Continued*)

Date	Location	Description	Fatalities	Cost (in US$ million (2006))
March 28, 1979	Middletown, Pennsylvania, United States	Equipment failures and operator error contribute to loss of coolant and partial core meltdown at the Three Mile Island nuclear reactor	0	$2,400
July 25, 1979	Saclay, France	Radioactive fluids escape into drains designed for ordinary waste, seeping into the local watershed at the Saclay BL3 Reactor	0	$5
September 12, 1979	Mihama, Japan	Fuel rods at the Mihama Nuclear Power Plant unexpectedly bow and damage the fuel supply system	0	$11
March 13, 1980	Loir-et-Cher, France	A malfunctioning cooling system fuses fuel elements together at the Saint Laurent A2 reactor, ruining the fuel assembly and forcing an extended shutdown	0	$22
November 22, 1980	San Onofre, California, United States	A worker cleaning breaker cubicles at the San Onofre pressurized water reactor contacts an energized line, electrocuting him to death	1	$1
February 11, 1981	Florida City, Florida, United States	Florida Power & Light manually shuts down Turkey Point Unit 3 after steam generator tubes degrade and fail	0	$2
March 8, 1981	Tsuruga, Japan	278 workers are exposed to excessive levels of radiation during repairs of the Tsuruga nuclear plant	0	$3
February 26, 1982	San Clemente, California, United States	Southern California Company shuts down San Onofre Unit 1 out of concerns for an earthquake	0	$1

(*Continued*)

Table 1: (*Continued*)

Date	Location	Description	Fatalities	Cost (in US$ million (2006))
March 20, 1982	Lycoming, New York, United States	Recirculation system piping fails at Nine Mile Point Unit 1, forcing a 2-year shutdown	0	$45
March 25, 1982	Buchanan, New York, United States	Multiple water and coolant leaks cause damage to steam generator tubes and main generator, forcing the New York Power Authority to shut down Indian Point Unit 3 for more than one year	0	$56
June 18, 1982	Seneca, South Carolina, United States	Feedwater heat extraction line fails at the Oconee 2 pressurized water reactor, damaging the thermal cooling system	0	$10
February 12, 1983	Fork River, New Jersey, United States	Oyster Creek nuclear plant fails safety inspection and is forced to shut down for repairs	0	$32
February 26, 1983	Pierce, Florida, United States	Workers discover a damaged thermal shield and core barrel support at St. Lucie Unit 1, necessitating a 13-month shutdown	0	$54
September 7, 1983	Athens, Alabama, United States	Tennessee Valley Authority discovers extensive damage to the recirculation system pipeline, requiring an extended shutdown	0	$34
September 23, 1983	Buenos Aires, Argentina	Operator error during fuel plate reconfiguration causes meltdown in an experimental test reactor	1	$65

(*Continued*)

Table 1: (*Continued*)

Date	Location	Description	Fatalities	Cost (in US$ million (2006))
December 10, 1983	Plymouth, Massachusetts, United States	Recirculation system piping cracks and forces the Pilgrim nuclear reactor to shut down	0	$4
April 14, 1984	Bugey, France	Electrical cables fail at the command center of the Bugey nuclear power plant and force a complete shutdown of one reactor	0	$2
April 18, 1984	Delta, Pennsylvania, United States	Philadelphia Electric Company shuts down Peach Bottom Unit 2 due to extensive recirculation system and equipment damage	0	$18
June 13, 1984	Platteville, Colorado, United States	Moisture intrusion causes 6 fuel rods to fail at the Fort St. Vrain nuclear plant, requiring an emergency shutdown from the Public Service Company of Colorado	0	$22
September 15, 1984	Athens, Alabama, United States	Safety violations, operator error, and design problems force a 6-year outage at Browns Ferry Unit 2	0	$110
March 9, 1985	Athens, Alabama, United States	Instrumentation systems malfunction during startup, convincing the Tennessee Valley Authority to suspend operations at all three Browns Ferry units	0	$1,830
June 9, 1985	Oak Harbor, Ohio, United States	Loss of feedwater provokes the Toledo Edison Company to inspect the Davis-Besse facility, where inspectors discover corroded reactor coolant pumps and shafts	0	$23

(*Continued*)

Table 1: (*Continued*)

Date	Location	Description	Fatalities	Cost (in US$ million (2006))
August 22, 1985	Soddy-Daisy, Tennessee, United States	Tennessee Valley Authority Sequoyah Units 1 and 2 fail NRC inspection due to failed silicon rubber insulation, forcing a 3-year shutdown, followed by water circulation problems that expose workers to excessive levels of radiation	0	$35
December 26, 1985	Clay Station, California, United States	Safety and control systems unexpectedly fail at the Rancho Seco nuclear reactor, ultimately leading to the premature closure of the plant	0	$672
April 11, 1986	Plymouth, Massachusetts, United States	Recurring equipment problems with instrumentation, vacuum breakers, instrument air system, and main transformer force an emergency shutdown of Boston Edison's Pilgrim nuclear facility	0	$1,001
April 26, 1986	Kiev, Ukraine	Mishandled reactor safety test at the Chernobyl nuclear reactor causes steam explosion and meltdown, necessitating the evacuation of 300,000 people from Kiev and dispersing radioactive material across Europe	4,056	$6,700
May 4, 1986	Hamm-Uentrop, Germany	Operator actions to dislodge a damaged fuel rod at an experimental high-temperature gas reactor release excessive radiation to 4 km^2 surrounding the facility	0	$267

(*Continued*)

Table 1: (*Continued*)

Date	Location	Description	Fatalities	Cost (in US$ million (2006))
May 22, 1986	Normandy, France	A reprocessing plant at Le Hague malfunctions, exposing workers to unsafe levels of radiation and forcing five to be hospitalized	0	$5
March 31, 1987	Delta, Pennsylvania, United States	Philadelphia Electric Company shuts down Peach Bottom Units 2 and 3 due to cooling malfunctions and unexplained equipment problems	0	$400
April 12, 1987	Tricastin, France	Areva's Tricastin fast breeder reactor leaks coolant, sodium, and uranium hexachloride, injuring seven workers and contaminating water supplies	0	$50
May 4, 1987	Kalpakkam, India	Fast breeder test reactor at Kalpakkam has to shut down due to the simultaneous occurrence of pump failures, faulty instrument signals, and turbine malfunctions that culminate in a refueling accident that ruptures the reactor core with 23 fuel assemblies, resulting in a 2-year shutdown	0	$300
July 15, 1987	Burlington, Kansas, United States	A safety inspector dies from electrocution after contacting a mislabeled wire	1	$1
December 17, 1987	Hesse, Germany	Stop valve fails at the Biblis Nuclear Power Plant and contaminates the local area	0	$13

(*Continued*)

Table 1: (*Continued*)

Date	Location	Description	Fatalities	Cost (in US$ million (2006))
December 19, 1987	Lycoming, New York, United States	Fuel rod, waste storage, and water pumping malfunctions force the Niagara Mohawk Power Corporation to shut down Nine Mile Point Unit 1	0	$150
March 29, 1988	Burlington, Kansas, United States	A worker falls through an unmarked manhole and electrocutes himself when trying to escape	1	$1
September 10, 1988	Surry, Virginia, United States	Refueling cavity seal fails and destroys the internal pipe system at Virginia Electric Power Company's Surry Unit 2, forcing a 12-month outage	0	$9
March 5, 1989	Tonopah, Arizona, United States	Atmospheric dump valves fail at Arizona Public Service Company's Palo Verde Unit 1, leading to a main transformer fire and emergency shutdown	0	$14
March 17, 1989	Lusby, Maryland, United States	Inspections at Baltimore Gas & Electric's Calvert Cliff Units 1 and 2 reveal cracks at pressurized heater sleeves, forcing extended shutdowns	0	$120
September 10, 1989	Tarapur, Maharashtra, India	Operators at the Tarapur nuclear power plant discover that the reactor had been leaking radioactive iodine through its cooling structures and discover radiation levels of iodine-129 more than 700 times the normal level; repairs to the reactor take more than one year	0	$78

(*Continued*)

Table 1: (*Continued*)

Date	Location	Description	Fatalities	Cost (in US$ million (2006))
November 24, 1989	Greifswald, East Germany	Electrical error causes a fire in the main trough that destroys control lines and 5 main coolant pumps, and almost induces a meltdown	0	$443
November 17, 1991	Scriba, New York, United States	Safety and fire problems force the New York Power Authority to shut down the FitzPatrick nuclear reactor for 13 months	0	$5
April 21, 1992	Southport, North Carolina, United States	NRC forces the Carolina Power & Light Company to shut down Brunswick Units 1 and 2 after emergency diesel generators fail	0	$2
May 13, 1992	Tarapur, Maharashtra, India	A malfunctioning tube causes the Tarapur nuclear reactor to release 12 curies of radioactivity	0	$2
February 3, 1993	Bay City, Texas, United States	Auxiliary feedwater pumps fail at South Texas Project Units 1 and 2, prompting a rapid shutdown of both reactors	0	$3
February 27, 1993	Buchanan, New York, United States	New York Power Authority shuts down Indian Point Unit 3 after the AMSAC system fails	0	$2
March 2, 1993	Soddy-Daisy, Tennessee, United States	Equipment failures and broken pipes cause the Tennessee Valley Authority to shut down Sequoyah Unit 1	0	$3

(*Continued*)

Table 1: (*Continued*)

Date	Location	Description	Fatalities	Cost (in US$ million (2006))
March 31, 1993	Bulandshahr, Uttar Pradesh, India	The Narora Atomic Power Station suffers a fire at two of its steam turbine blades, damaging the heavy water reactor and almost leading to a meltdown	0	$220
December 25, 1993	Newport, Michigan, United States	Detroit Edison Company is prompted to shut down Fermi Unit 2 after the main turbine experiences catastrophic failure due to improper maintenance	0	$67
April 6, 1994	Tomsk, Russia	Pressure buildup causes mechanical failure at the Tomsk-7 Siberian Chemical Enterprise plutonium reprocessing facility, exploding a concrete bunker and exposing 160 onsite workers to excessive radiation	0	$44
January 14, 1995	Wiscasset, Maine, United States	Steam generator tubes unexpectedly crack at the Maine Yankee nuclear reactor, forcing the Maine Yankee Atomic Power Company to shut down the facility for 1 year	0	$62
February 2, 1995	Kota, Rajasthan, India	The Rajasthan Atomic Power Station leaks radioactive helium and heavy water into the Rana Pratap Sagar River, necessitating a 2-year shutdown for repairs	0	$280

(*Continued*)

Table 1: (*Continued*)

Date	Location	Description	Fatalities	Cost (in US$ million (2006))
May 16, 1995	Salem, New Jersey, United States	Ventilation systems fail at Public Service Electric & Gas Company's Salem Units 1 and 2	0	$34
February 20, 1996	Waterford, Connecticut, United States	Leaking valve forces the Northeast Utilities Company to shut down Millstone Units 1 and 2; further inspection reveals multiple equipment failures	0	$254
September 2, 1996	Crystal River, Florida, United States	Balance-of-plant equipment malfunction forces the Florida Power Corporation to shut down Crystal River Unit 3 and make extensive repairs	0	$384
September 5, 1996	Clinton, Illinois, United States	Reactor recirculation pump fails, prompting the Illinois Power Company to shut down the Clinton boiling water reactor	0	$38
September 20, 1996	Seneca, Illinois, United States	Service water system fails and prompts Commonwealth Edison to close LaSalle Units 1 and 2 for more than 2 years	0	$71
September 9, 1997	Bridgman, Michigan, United States	Ice condenser containment systems fail at Indiana Michigan Power Company's D.C. Cook Units 1 and 2	0	$11
May 25, 1999	Waterford, Connecticut, United States	Steam leak in feedwater heater causes manual shutdown and damage to the control board annunciator at the Millstone Nuclear Power Plant	0	$7
June 18, 1999	Shika, Ishikawa, Japan	Control rod malfunction sets off an uncontrolled nuclear reaction at Shika Nuclear Power Station's Unit 1	0	$34

(*Continued*)

Table 1: (*Continued*)

Date	Location	Description	Fatalities	Cost (in US$ million (2006))
September 29, 1999	Lower Alloways Creek, New Jersey, United States	Major freon leak at the Hope Creek Nuclear Facility causes the ventilation train chiller to trip, releasing toxic gas and damaging the cooling system	0	$2
September 30, 1999	Ibaraki Prefecture, Japan	Workers at the Tokaimura uranium processing facility try to save time by mixing uranium in buckets, killing 2 and injuring 1,200	2	$54
December 27, 1999	Blayais, France	An unexpectedly strong storm floods the Blayais-2 nuclear reactor, forcing an emergency shutdown after injection pumps and containment safety systems fail from water damage	0	$55
January 21, 2002	Manche, France	Control systems and safety valves fail after improper installation of condensers, forcing a 2-month shutdown	0	$102
February 16, 2002	Oak Harbor, Ohio, United States	Severe corrosion of control rod forces a 24-month outage of the Davis-Besse reactor	0	$143
October 22, 2002	Kalpakkam, India	Almost 100 kg of radioactive sodium at a fast breeder reactor leaks into a purification cabin, ruining a number of valves and operating systems	0	$30
January 15, 2003	Bridgman, Michigan, United States	A fault in the main transformer at the Donald C. Cook nuclear power plant causes a fire that damages the main generator and backup turbines	0	$10

(*Continued*)

Table 1: (*Continued*)

Date	Location	Description	Fatalities	Cost (in US$ million (2006))
April 10, 2003	Paks, Hungary	Damaged fuel rods hemorrhage spent fuel pellets, corroding a heavy water reactor	0	$37
August 9, 2004	Fukui Prefecture, Japan	Steam explosion at the Mihama Nuclear Power Plant kills 5 workers and injures dozens more	5	$9
April 19, 2005	Sellafield, United Kingdom	20 metric tons of uranium and 160 kg of plutonium leak from a cracked pipe at the Thorp nuclear fuel reprocessing plant	0	$65
May 16, 2005	Lorraine, France	Substandard electrical cables at the Cattenon-2 nuclear reactor cause a fire in an electricity funnel, damaging safety systems	0	$12
June 16, 2005	Braidwood, Illinois, United States	Exelon's Braidwood nuclear station leaks tritium and contaminates local water supplies	0	$41
August 4, 2005	Indian Point, New York, United States	Entergy's Indian Point Nuclear Plant, located on the Hudson River, leaks tritium and strontium into underground lakes from 1974 to 2005	0	$30
March 6, 2006	Erwin, Tennessee, United States	Nuclear fuel services plant spills 35 liters of highly enriched uranium, necessitating a 7-month shutdown	0	$98
December 24, 2006	Jadugoda, India	One of the pipes carrying radioactive waste from the Jadugoda uranium mill ruptures and distributes radioactive material more than 100 km^2	0	$25

(*Continued*)

Table 1: (*Continued*)

Date	Location	Description	Fatalities	Cost (in US$ million (2006))
July 18, 2007	Kashiwazaki, Japan	The Tokyo Electric Power Company announces that its Kariwa nuclear plant has leaked 1,192 liters of radioactive water into the Sea of Japan after being damaged by a 6.8-magnitude earthquake	0	$2
June 4, 2008	Ljubljana, Slovenia	Slovenian regulators shut down the Krsko nuclear power plant after the primary cooling system malfunctions and coolant spills into the reactor core	0	$1
June 14, 2008	Fukushima Province, Japan	A 7.2-magnitude earthquake cracks reactor cooling towers and spent fuel storage facilities, spilling 19 liters of radioactive wastewater and damaging the Tokyo Electric Power Company's No. 2 Kurihara Power Plant	0	$45
July 4, 2008	Ayrshire and Suffolk, United Kingdom	Two British Energy nuclear reactors (the Largs and the Sizewell B facilities) shut down unexpectedly after their cooling units simultaneously malfunction, damaging emergency systems and triggering blackouts	0	$10
July 13, 2008	Tricastin, France	The nuclear power operator Areva reports that dozens of liters of wastewater contaminated with uranium are being accidentally poured on the ground and run off into a nearby river	0	$7

(*Continued*)

Table 1: (*Continued*)

Date	Location	Description	Fatalities	Cost (in US$ million (2006))
March 15, 2009	Oskarshamn, Sweden	A maintenance worker repairing a shut-down reactor at the Oskarshamn Nuclear Power Plant dies after falling from the top of the turbine hall	1	$0
August 12, 2009	Gravelines, France	Assembly system fails to properly eject spent fuel rods from the Gravelines Nuclear Power Plant, causing the fuel rods to jam and the reactor to shut down	0	$2
August 27, 2009	St. Petersburg, Russia	A cracked discharge accumulator and malfunctioning feed pump force the Leningrad Nuclear Power Plant Reactor Number 3 to close for extended repairs	0	$110
February 1, 2010	Montpelier, Vermont, United States	Deteriorating underground pipes from the Vermont Yankee nuclear power plant leak radioactive tritium into groundwater supplies in Vermont, resulting in the eventual shutdown of the plant	0	$700

Note: An "accident" is defined as an incident that resulted in either the loss of human life or more than US$50,000 of property damage.

- A blown fuse on a sump pump at the Indian Point facility in New York, rendering the cooling system incapable of removing water leaking into the reactor, forcing a week-long shutdown;
- A technician testing for air leaks with a candle who accidentally dropped it and caused a fire that burned 1.6 million electrical cables, forcing a three-month shutdown at the Browns Ferry nuclear plant in Alabama;
- A nest of field mice causing an electrical fire that shut down the San Onofre nuclear facility in California for one week; and
- A three-year shutdown of the Davis-Besse nuclear power plant in Ohio after inspectors found excessive degradation of the pressure-vessel head of the reactor, but only after inspecting the wrong reactor by mistake.[25]

Other incidents include improper soldering preventing electricity and water from flowing properly in separate and supposedly independent backup systems; plastic floats that leaked, filled up, and sank (in that order) so that they all provided the same wrong indication of liquid level within the cooling system of a reactor; and supposedly independent equipment all being water-damaged from being stored together outdoors. Still others involve redundant safety systems all being disabled by the same contaminated lubricating oil, an entire system of independent cooling pipes all freezing because one thermostat on a protective heater had been improperly wired, and a four-week shutdown and a 24-hour blackout occurring after a stray cat wandered into a reactor vessel and shorted a circuit. The lesson appears to be that complicated technological systems, like reactors, have unavoidable problems — something Charles Perrow calls "normal accidents."[26]

Perrow argues that such accidents have three common themes, none of which bode well for nuclear power plants. First, no matter how well a system is designed, operator error is still a very common causal factor of system accidents. People are fallible, even those at nuclear power plants. Some nuclear employees will not be the best workers; many are fired for breaking the law, and in one case a construction crew put a safety inspector in the hospital for suggesting repairs. The Chair of the NRC once remarked that the nuclear industry "shows a surprising lack of professionalism."[27] The construction of one nuclear power plant in the US was prone to 111 separate flaws that cost an additional US$2.5 billion to repair; and employees and contractors used intimidation and deception, all part of industrial life, to try and hide their shoddy work.

Second, great events and accidents almost always have very small beginnings. Nuclear power plants are so complex that relatively simple things — shirttails, fuses, light bulbs, mice, cats, and candles — can disrupt the entire system. Even minor changes can have grave implications. Examples outside of the energy sector include a 29-cent switch that burned out by improper testing being responsible for the failure of Apollo 13, an O-ring causing the explosion of the *Challenger* in 1986, and a technician dropping a socket wrench down an Arkansas nuclear missile silo in 1980 and causing an explosion which ejected a Titan warhead into a nearby field. Given the right events, multiple and unexpected interactions can lead to system-wide failure.

Third, most failures are those of organizations more than technology, i.e. people managing or operating technologies in particular ways. Perhaps the best evidence here comes from a cross-cultural comparison of pressurized water reactors operating in the US, France, Germany, and Sweden, which found that cultural differences in operations have far-reaching implications for plant safety and nuclear power regulation.[28] The study identified meaningful differences in how facilities were regulated. The US style was more "command and control" and was based on strict adherence to the law, with inspectors forbidden to fraternize with staff, and with a highly legalistic, formalized system where operators rotated among many positions to be experts at every job. This contrasted with the European structure, which let operators themselves manage plants but used penalties and fines to punish wrongdoers, and also did not rotate people to different positions so they could become specialized in a particular area.

Within each nuclear facility itself, the study found distinct subcultures, generally distinguished by operators and engineers. The engineering subculture characterized a nuclear plant as an abstract, analytical, deterministic, and static system where events and sequences were linear. Engineers envisioned a nuclear plant as a predictable machine that could be broken down into its pieces. The operator subculture shared a physical, holistic, empirical, and dynamic view of the plant, envisioning it as more integrated. Operators viewed the facility as an organism, with feelings and even personalities and complex linkages that invariably deviated from predictions.

While not formally stated as a conclusion, the study did raise questions about nuclear safety. It noted that struggles frequently occurred between engineering and operator subcultures over authority, especially with respect to operating procedures and access to the control room. It found that every plant (and even every shift) had its own personality and its own set of cultures at work, making it difficult to standardize approaches to management. US plants operated more like submarines; German plants, like spaceships; and French plants, like sophisticated industrial machinery. Swedish plants were decorated with amusing trolls; German plants, with Blaupunkt radios; and French control rooms, with free coffee. The problem was that changes to operating procedures often failed to take into account these cultural differences, meaning they were in essence "tinkering with a real time experiment with possible irreversible consequences."[29] The study also noted that, over time, both operators and engineers developed a unique bond with the plant, and so they tended to discount problems in the face of their trust. At one German reactor visited, operators trusted the plant so much that, when alarms went off, they started diagnosing what was causing the alarms to malfunction instead of looking at the plant. In the US, operators believed they had the skill to pilot operations by hand, turning off automatic controls; and in France, operators treated alarms so casually that familiarity led to contempt for the consequences of errors.

Other key anthropological work on nuclear power safety culture has revealed a tendency to see incidents not as accidents, but rather as new sources of information about how a nuclear system functions. Perhaps perversely, some operators may even welcome and see value in accidents and incidents, as they contribute to new knowledge about reactor and human performance.[30] This can create the norm at a particular plant that a reactor is "safest when running," thus contributing to the pressure to keep plants online and delay maintenance, and also to consider production of electricity first and safety second. To these operators, nuclear work is supposed to be fast and efficient, not "slowed down" by frivolous safety concerns.[31]

All of the factors — operator error, the potential for failures to cascade, differences in organizational behavior, and the proclivity to ride margins to learn about nuclear performance — show the sensitivity of nuclear power plants to even slight deviations from normal activity. Perrow concludes that such high-tech, dangerous systems are hopeless and should be abandoned, as the inevitable risks of failure outweigh any conceivable benefits.[32] The point here is not that systems fail — no technology is perfect — but that nuclear power systems are so radioactive and catastrophic when they break down that a billion-dollar asset can become a trillion-dollar liability in a matter of moments. Such problems cannot be designed around. As more proof, consider that the two most significant nuclear power accidents, Chernobyl and Three Mile Island, were human-caused and then exacerbated by more human mistakes.

Chernobyl, Ukraine

On the evening of April 25, 1986, evening-shift engineers at Chernobyl's Reactor No. 4 experimented with the cooling pump system to see if it could still function without auxiliary electricity supplies. In order to proceed with the test, the operators turned off the automatic shutdown system. At the same time, they mistakenly lowered too many control rods into the reactor core, dropping plant output too quickly. This stressed the fuel pellets, causing ruptures and explosions, bursting the reactor roof and sweeping the eruption outwards into the surrounding atmosphere. As air raced into the shattered reactor, it ignited flammable carbon monoxide gas and created a radioactive fire that burned for nine days and continued to release radiation for more than two weeks.[33]

Following the accident, 116,000 people were evacuated from a 30-km^2 exclusive zone constituting parts of Belarus, Ukraine, and Russia. The large city of Prypiat, Ukraine, had to be completely abandoned (see Figure 1). The Chernobyl meltdown distributed more than 200 times the radiation released by the atom bombs dropped on Nagasaki and Hiroshima. More than 5 million people, including 1.6 million children, were exposed to dangerous levels of radiation. About 246,000 km^2 of land was contaminated with iodine-131, ruthenium-106, cerium-141 and cerium-144, cesium-137, strontium-89 and strontium-90, and plutonium-239 — some of which will remain lethally radioactive for more than 10,000 years. At least 350,000 people had to be forcibly resettled from the area. Cesium and strontium severely contaminated agricultural products, livestock, and soil as far away as Japan and Norway; some milk in Eastern Europe is still undrinkable today.[34]

Figure 1: **The City of Prypiat, Ukraine, Abandoned After the Chernobyl Disaster in 1986**

Human error after the initial accident also exacerbated the situation and needlessly exposed millions of people to unhealthy levels of radiation. For example, the Soviet government did not begin evacuations until April 28, two full days after the accident, because plant operators had delayed reporting the accident to Moscow out of fear it would spoil forthcoming May Day celebrations, and then because national officials had planned on covering it up until a Swedish radiation monitoring station 800 miles northwest of Chernobyl reported radiation levels 40% higher than normal. Russian and Ukrainian disaster managers mistakenly sent hundreds of buses contaminated with radioactive iodine during the evacuation back into public transportation service in Kiev. Some members of the Russian military personally contaminated themselves, and their families, by rushing back into the disaster area in what they believed was a sign of bravery. This act extended a long tradition of Soviet troops exposing themselves to radiation as a sign of strength, including tanks intentionally driving through sites of nuclear weapons fallout and aircraft flying back into the fallout from atmospheric weapons testing. In what could qualify as a scene from a National Lampoon movie if the consequences were not so dire, a Russian helicopter crew quickly redeployed from Afghanistan was assigned to drop boric acid on the exposed fissile material above Chernobyl's shattered reactor only to crash into it, causing yet another radioactive explosion.[35] The leader of the Soviet delegation charged with estimating damages (and also the one with the most expertise), Valery Legasov, later committed suicide on the second anniversary of the accident because he was so disturbed by his report's findings.[36]

After this accident (and the subsequent errors), traces of radioactive deposits unique to Chernobyl were found in nearly every country in the northern hemisphere. The international community sponsored a US$1.4 billion decontamination project, including the construction of a massive sarcophagus and 131 hydroelectric installations to prevent contaminated water from flowing downstream on the Prypiat and Dnieper rivers. Soviet authorities strongly urged as many as 400,000 abortions in an effort to mitigate the reporting of birth defects.[37] The International Atomic Energy Agency (IAEA), working with the World Health Organization (WHO), attributed up to 4,000 deaths to the Chernobyl nuclear accident; whereas other studies put the number at 93,000 fatal cancer deaths throughout Europe, 140,000 in Ukraine and Belarus, and another 60,000 in Russia, for a total of 293,000.[38] Medical studies have since confirmed that the thyroid cancer tumors caused by the Chernobyl accident are the largest single number of cancers of one type caused by a single event on one date ever recorded.[39] As the United Nations Scientific Committee on the Effects of Atomic Radiation concluded in 2000, the 25-fold increase in the incidence of childhood thyroid cancers in cities around Chernobyl showed that "there can be no doubt about the relationship between the radioactive materials released from the Chernobyl accident and the unusually high numbers of thyroid cancers observed in the contaminated areas during the past 14 years."[40]

The consequences of the accident at Chernobyl, moreover, are far from over. The fallout from Chernobyl contaminated about 6 million hectares of forest in the Gomel and Mogilev regions of Belarus, the Kiev region of Ukraine, and the Bryansk region of the Russian Federation.[41] Three of the contaminants — cesium-137, strontium-90, and plutonium-239 — are extraordinarily robust and extremely dangerous. About 95% of these contaminants have accumulated in living trees, but 770 wildfires occurred in the contaminated zone from 1993 to 2001, each one releasing radioactive emissions far into the atmosphere.[42] A single, severe fire in 1992 burned 5 km^2 of land contaminated by Chernobyl (including 2.7 km^2 of the highly contaminated Red Forest next to the reactor), carrying highly toxic cesium dust particles into the upper atmosphere, distributing radioactive smoke particles thousands of kilometers, and exposing at least 4.5 million people to dangerous levels of radiation. Radiation levels were so high after the 1992 fire that scientists throughout Europe initially thought there had been a second meltdown at Chernobyl Reactor No. 1 or 2, which remained in operation until 2000.

Three Mile Island

On March 28, 1979, equipment failures and operator error contributed to a partial core meltdown at the Three Mile Island (TMI) nuclear reactor in Pennsylvania, causing US$2.4 billion in property damages. Technically, the meltdown at TMI was a loss-of-coolant accident. The primary feedwater pumps stopped running at TMI Unit 2, preventing the large steam generators at the reactor site from removing necessary exhaust heat. As the steam turbines and the reactor automatically shut down, contaminated water poured out of open valves and caused the core of the reactor to overheat, inducing a partial core meltdown.[43]

A commission chartered by President Carter to study the accident, however, found that human error played the most significant factor in the meltdown.[44] The commission stated that the TMI operators were not well trained, operating procedures were confusing, and administrators had failed to learn lessons in safety from past incidents at the plant. The commission concluded that "we have stated that fundamental changes must occur in organizations, procedures, and above all, in the attitudes of people. No amount of technical 'fixes' will cure this underlying problem."[45]

Several American regulatory agencies have conducted detailed studies of the radiological consequences of this accident, and a consensus has emerged that — while the average dose of exposure from the accident was 1 millirem, or one-sixth the exposure from a full set of chest x-rays — the situation came dangerously close to releasing catastrophic amounts of radioactivity. For example, when federal investigators arrived on the scene, they discovered two pieces of alarming news that had not been widely reported. First, the reactor core was more badly damaged than previously thought. Falling coolant levels in the reactor core had exposed the tops of fuel rods to the air, causing oxidation of the cladding used to protect the rods. The result was that radioactive gases like xenon-133, krypton-85, and iodine-131 had seeped out of cracks in the reactor. Second, a gas bubble nearly 1,000 cubic feet in size had developed at the top of the reactor. Apparently, the reactor core had reached high enough temperatures that the coolant water had decomposed into its primary elements, hydrogen and oxygen. Investigators feared that the bubble would continue to grow, forcing even more coolant water out of the reactor and allowing the core to reach temperatures of 5,000°C; at that point, the uranium fuel would begin to melt, risking a total core meltdown and a catastrophic release of the reactor's radioactive material.[46] The fact that TMI could withstand such an incident was a fluke: it had a double containment shell capable of containing a hydrogen explosion only because the commercial flight path to Harrisburg Airport passed over the plant.[47]

Future Accidents

The incidents at Chernobyl and TMI brought about sweeping changes to the industry. After the accidents, emergency response planning, reactor operator training, human factors engineering, radiation protection, and many other areas of nuclear power plant operations were reformed. Yet despite these reforms, the risk of future accidents is still unacceptably high, and current operators appear to have forgotten some of these lessons.

For instance, the US GAO conducted a survey of nuclear power plant safety, since in the US 103 operating commercial nuclear power plants located at 65 sites in 31 states provide roughly 20% of the country's electricity. After conducting physical inspections of plant equipment and assessing indicators of plant performance, the GAO found that a number of individual nuclear power plants were not performing within acceptable safety guidelines.[48] Another sample of US plants inspected by the NRC from May 1999 to April 2004 revealed 25 serious incidents at 23 separate facilities.[49] Yet another study of US nuclear reactors identified nearly 60 accidents or near misses — events that included radiation exposure, inhalation of toxic vapors, electrical shocks, and injuries during nuclear construction or maintenance — resulting "in serious worker injuries or facility damage."[50] Still another study performed by the agency in charge of monitoring the US Department of Energy's oversight of nuclear facilities, including research reactors and national laboratories, found that 31 of the 205 facilities did not meet government safety requirements, and that one-third of the facilities did not conform to guidelines concerning high-hazard nuclear waste.[51] The GAO identified 156 serious incidents from 2001 to 2005 at US nuclear power plants that included a litany of problems, ranging from unplanned changes in reactor power and failures of emergency diesel generators to inadequate maintenance and human mismanagement.[52]

Most recently, a 2009 assessment of nuclear power performance in the US warned that the technology has rushed "far ahead of its operating experience." The study noted that every state across the northern tier from Illinois to Maine has been involved in at least one nuclear accident. These involved quality assurance breakdowns, plant equipment sinking into the mud, fuel cladding failures, emergency core cooling system shortcomings, absence of emergency plans, radioactive leaks, and water contamination.[53] Safety problems have not been recognized; when they have been recognized, they have not been resolved; and the industry has not made significant strides towards addressing newly emerging threats like terrorism. As two environmental lawyers recently put it, "the nuclear industry in the United States is like the financial industry was prior to the crisis of 2008; there are many risks that are not being properly managed or regulated."[54]

These safety problems take their toll on performance and contribute to the likelihood of future accidents. Using some of the most advanced probabilistic risk assessment tools available, an interdisciplinary team at the Massachusetts Institute of Technology (MIT) identified possible reactor failures in the US and predicted that the best estimate of core damage frequency was around one every 10,000 reactor years. In terms of the expected growth scenario for nuclear power from 2005 to 2055, the MIT team estimated that at least four serious core damage accidents will occur and concluded that "both the historical and the PRA [probabilistic risk assessment] data show an unacceptable accident frequency." Furthermore, "[t]he potential impact on the public from safety or waste management failure . . . make it impossible today to make a credible case for the immediate expanded use of nuclear power."[55]

Another assessment conducted by the CEA (*Commissariat à l'énergie atomique et aux énergies alternatives*) in France tried to associate nuclear plant design with human error such that technical innovation could help eliminate the risk of human-induced accidents.[56] Two types of mistakes were deemed the most egregious: errors committed during field operations (such as maintenance and testing) that can cause an accident, and human errors made during small accidents that cascade to complete failure. There may be no feasible way to "design around" these risks. For example, when CEA researchers examined the safety performance of advanced French pressurized water reactors, they concluded that human factors would contribute to about one-fourth (23%) of the likelihood of a major accident.

Because of the lack of a permanent geologic repository for nuclear waste in the US at offsite storage facilities, operators have packed spent fuel more densely together at existing onsite storage pools. In some cases, such densities even approach those found in operating reactor cores and, if exposed to air for more than six hours, spent fuel rods will combust spontaneously.[57] Robert Alvarez and his colleagues have warned that recently discharged fuel could heat up rapidly and cause a fuel cladding fire that would disperse volatile fission products, such as cesium-137, over hundreds of miles.[58] Cooling water at these pools could be lost — the precursor to a fire — in a variety of ways: draining into other volumes through a malfunctioning of valves, pipes and gates breaking and unable to hold water, a large aircraft crash puncturing a shaft to cause leakage, or a shaped charge of explosive cracking concrete vessels.

Oddly, there is some evidence that the *newest* reactors and nuclear systems are the most prone to accidents. Dennis Berry, Director Emeritus of Sandia National Laboratories, explained that the problem with new reactors and accidents is twofold: scenarios arise that are impossible to plan for in simulations, and humans make mistakes. As he put it, "fabrication, construction, operation, and maintenance of new reactors will face a steep learning curve: advanced technologies will have a heightened risk of accidents and mistakes. The technology may be proven, but people are not."[59]

Indeed, nuclear engineer David Lochbaum noted that almost all serious nuclear accidents have occurred when operators have little experience with a plant, in essence making newest systems the riskiest.[60] In 1959, the Sodium Research Experiment reactor in California experienced a partial meltdown 14 months after opening. In 1961, the Sl1 reactor in Idaho was slightly more than two years old before a fatal accident killed everyone at the site. The Fermi Unit 1 reactor began commercial operation in August 1966, but had a partial meltdown only two months after opening. The St. Laurent des Eaux A1 reactor in France started in June 1969, but an online refueling machine malfunctioned and melted 400 pounds of fuel four months later. The Browns Ferry Unit 1 reactor in Alabama began commercial operation in August 1974, but experienced a fire that severely damaged control equipment six months later. The TMI Unit 2 reactor began commercial operation in December 1978, but had a partial meltdown three months after it started. The Chernobyl Unit 4 reactor started up in August 1984, but suffered the worst nuclear disaster in history on April 26, 1986, before the two-year anniversary of its operation. NRC files show about 3,000 incidents and events involving abnormal occurrences and violations of safety regulations each year at American nuclear plants, with most of these peaking in the 1970s (when the commercial nuclear fleet was the youngest).[61] The implication is that when nuclear power plant designs are "new," errors are more likely, not less.

Outside of the US, new designs such as the Superphénix fast breeder reactor in France — considered to be the cutting edge of nuclear technology — have been plagued by breakdowns, disappearing fuel, and other assorted problems so severe that the reactor operated only 174 days out of its first eight years.[62] The breeder reactor at Marcoule, France, was shut down in 1997 after a series of fuel rods jammed and could not be removed. Liquid sodium being emptied from the Rhapsodie breeder reactor caused an explosion that lifted up concrete slabs and sent them into the air, where they crashed into and killed operators.[63] The British similarly abandoned their prototype fast reactor after safety problems, and the Russians stopped research on their BN-350 reactor over design flaws. A German breeder reactor at Kalkar was completed in 1991, but never operated because of concerns about explosions; and the Japanese Monju reactor was shut down after a serious fire in December 1995.[64] India's fast breeder test reactor at Kalpakkam has seen multiple pump failures, shutdowns due to faulty instrument signals, and turbine malfunctions. In May 1987, two years after it started operation, an accident occurred during refueling whereby 23 fuel assemblies were knocked out of the core, causing a two-year shutdown.[65] Another accident occurred in 2002 after a defective valve leaked 75 kg of radioactive sodium into a purification cabin.[66] The safety assessment from the Atomic Energy Regulatory Board of India has long considered it the most dangerous reactor in the country.[67]

Another advanced design, the European pressurized water reactor, called the "flagship" of the next generation of designs, has encountered similar problems in Olkiluoto, Finland, an island on the Baltic Sea, where it is still being built. The Finnish nuclear safety watchdog STUK has reported 2,100 quality defects in the plant so far, and the project is US$2.4 billion overbudget and three years behind schedule.[68] Serious problems have arisen over the vast concrete foundation of the reactor building, which was found too porous and prone to corrosion.[69] Although the reactor was originally meant to be completed in the summer of 2009, Areva, the French company building it, will no longer make predictions on when it will be finished. In Flamanville, France, a "clone" of the Finnish reactor now under construction is also behind schedule and overbudget. There, nuclear safety inspectors discovered cracks in the concrete base and steel reinforcements installed in the wrong areas, and warned Électricité de France that the welders working on reactor components were not properly qualified.[70]

Indeed, several other factors seem to increase the risk of future accidents. The pressure to build new generators on existing sites to avoid complex issues associated with finding new locations can increase the risk of catastrophe, since there is a greater chance that one accident can affect multiple reactors. Nuclear power plants used to be sited more remotely (meaning an accident would affect less people), but now tend to be sited closer to population centers.[71] Sites that had once been remote when reactors started have become more populated over time; regions in which nuclear power is most attractive tend to be urban and have a limited number of remote locations; and substantial losses and costs are associated with remote transmission of nuclear power, creating an incentive to situate plants closer to points of electricity consumption. Nuclear waste storage is also becoming more dangerous, with many spent fuel pools packed with more fuel rods, making them hotter and more dense — hence, operators must add boron to the water pools to absorb neutrons, increasing the risk of criticality accidents.[72]

In addition, the industry has been trying to scale up reactor sizes and promote designs that operators have little experience with. These larger reactors tend to use more fuel and create more heat, meaning they have bigger cores containing larger quantities of dangerous fissionable materials, increasing the magnitude of any accident that could occur. The restructuring of electricity sectors around the world has motivated some nuclear operators to place profits before safety. Undue solicitude for profits of the licensee has played a large role in explaining the mishaps that have occurred at nuclear power plants. Put another way, nuclear power is least safe in environments where complacency and pressure to maximize profits are the greatest, yet the global trend appears headed in that direction.[73] It appears one can build nuclear power plants to be safe or to be cheap, but not both.

Lastly, some operators have begun to promote the automation of certain tasks in the control room to decrease human workload and improve system performance. However, numerous examples exist whereby automotive systems have only increased incidents and accidents, reduced operator awareness, increased monitoring and workload, and degraded manual operating skills.[74]

These factors are worrying, to say the least, given the outrageous severity of what a single serious accident can do. It was estimated that the meltdown of a single 500-MW reactor located 30 miles from a single city would cause the immediate death of between 3,400 and 45,000 people, injure roughly another 50,000, induce US$7 billion in property damage, and contaminate an area the size of Pennsylvania with unsafe levels of radiation.[75] This estimate was later revised upwards for being too conservative to 45,000 immediate deaths, 70,000 injuries, and US$17 billion or more in damages. More recent studies, looking at larger reactors in the 1,100-MW range, have noted that as many as 103,000 immediate fatalities could occur along with US$300 billion in damages.[76] A successful attack on the Indian Point power plant near New York City, apparently part of Al-Qaeda's original plan on September 11, 2001, would have resulted in 43,700 immediate fatalities and 518,000 cancer deaths and would have cost US$2 trillion to clean up.[77]

To put a serious accident in context, if 10 million people were exposed to radiation from a nuclear meltdown, about 100,000 would die from acute radiation sickness in six weeks. About 50,000 would experience acute breathlessness and 240,000 would develop acute hypothyroidism. About 350,000 men would be temporarily sterile, 100,000 women would stop menstruating, 100,000 children would be born mentally retarded, and there would be thousands of spontaneous abortions and more than 300,000 cancers to develop later.[78] In the US, the impact of an accident could be quite acute, since 80 million Americans live within 40 miles of a nuclear reactor, including those residing in some of the largest metropolitan areas in the country such as New York, Chicago, Detroit, Miami, Phoenix, Cleveland, Houston, and Philadelphia.[79]

A nuclear meltdown or reactor accident is not the only thing to worry about. The long-term impacts of a fuel cladding fire could be significantly *worse* than those of Chernobyl, with hundreds of billions of dollars of damage in addition to human deaths and environmental damage.[80] Storage facilities are not located inside containment buildings and are usually aboveground, making the consequences of an accident more severe. As one peer-reviewed study put it: "A loss of coolant … [at a storage pool] could result in a nuclear accident. A loss of coolant could cause rapid heating, and then the outside shell of the fuel rods could catch fire. The result could be significant dispersal of highly radioactive fission products."[81] Even the NRC estimated that the median consequences of a spent-fuel fire at a pressurized water reactor would result in 54,000–143,000 extra cancer deaths, 2,000–7,000 km^2 of agricultural land contaminated, and economic costs due to evacuation as high as US$566 billion.[82] Another study projected that one single pool fire would cause 24,000 lung cancer deaths and induce economic damages ten times as large as those caused by Hurricane Katrina.[83]

Materials and Labor

Separate from the risk of incidents and accidents, the lack of qualified and experienced nuclear staff serves as a technical challenge facing the nuclear industry. As Chapter 2 noted, a typical nuclear power plant can take 5–10 years to build; contain miles of pipes with thousands of welds; and require almost 1,000 miles of electrical cables and a prodigious number of electric motors, fuses, and circuits as well as radiation shields, spent fuel repositories, backup electricity generators, and firewalls. Building a single plant takes an enormous amount of expertise and about 10,000 dedicated construction workers, and the existing nuclear industry already lacks qualified and experienced staff. The global nuclear industry continues to lose much of the expertise that it does have to retirement, attrition, and death.

The Nuclear Energy Agency surveyed 16 nuclear member states of the Organisation for Economic Co-operation and Development (OECD), and concluded that some countries were "at risk" due to lack of educational capability for training in nuclear-related fields.[84] It documented declining university enrollment in nuclear engineering courses, an overall aging of the nuclear workforce, dilution of university course content related to nuclear physics, and changing expectations among young engineers that predisposed them away from working at nuclear power plants. As the study noted, "the nuclear industry does not attract the high numbers of good quality graduates and post graduates as it did when it was a fast developing and emerging industry a number of years ago. There are also problems with the retention of younger trained staff who are readily marketable to other sectors after a period in the nuclear industry."[85]

In the US, the Department of Energy (DOE) has warned that the lack of growth in the domestic nuclear industry has gradually eroded important infrastructural elements such as experienced personnel in nuclear energy operations, engineering, radiation protection, and other professional disciplines; qualified suppliers of nuclear equipment and components, including fabrication capability; and contractor, architect, and engineer organizations with personnel, skills, and experience in nuclear design, engineering, and construction.[86] Since all commercial American reactors are light water reactors, system operators have little experience with newer gas-cooled and other advanced reactor designs used throughout the world. Only two companies in the world, Japan Steel Works and Creusot Forge, currently have the heavy forging capability to create the largest reactor components.[87] In the 1970s, more than 400 suppliers of nuclear plant components existed, but the number dropped to 80 suppliers in 2008. Moreover, the Nuclear Energy Institute cautioned in 2005 that "half of the industry's employees are over 47 years old, and more than a quarter ... already are eligible to stop working," implying that the industry has far fewer available specialists with the requisite knowledge necessary to facilitate any rapid expansion of nuclear power.[88]

Another assessment in the UK warned that "the nuclear industry is facing a skills crisis."[89] As of 2007, fewer than 6% of the estimated 100,000 people who worked in the industry were under the age of 24; and at British Energy, which operates eight nuclear power stations and is the country's biggest electricity provider, 40% of the staff are set to retire within the next ten years. No British university offered a dedicated nuclear engineering course as of 2007 and a number of "vital occupations" remained unfilled. One nuclear consultant found it "amazing that so many people jumped on the bandwagon of this renaissance without ever looking at the industrial side of it." Another industry survey identified an "under-supply of qualified people" compared to the proportion of needed jobs in the nuclear power sector. It found a 20% deficit for high-level jobs, especially related to decommissioning, process and machine operators, and senior managers. The National Skills Academy for Nuclear in the UK estimated that as many as 16,500 new workers would be needed to operate existing facilities by 2015. The survey warned that "the sector needs to quadruple the number of apprentices over the next five years."[90]

Given these constraints in human capital, the fastest deployment of nuclear reactors for a single country has been France. France, which currently generates about three-quarters of its electricity from nuclear units, has the quickest record for deploying nuclear plants in history: 58 plants between 1977 and 1993, or an average of 3.4 reactors per year. The fastest the US ever deployed nuclear power plants was a peak in 1974 at 12 per year, and the greatest number of nuclear power plants being built at once globally was 28 in 1984. Yet to meet the target by 2030, slightly more than 1,900 new nuclear plants (sized 1,000 MW each) would need to be built — or a minimum of 86 plants per year every year for more than two decades, greater than three times the fastest historical rate on record.

Fuel Availability and Energy Payback

As a third and final technical impediment, almost all commercial nuclear reactors (even those that utilize reprocessed fuel) need fresh uranium ore to operate, something that lowers their overall energy payback — the amount of net energy produced from the overall nuclear fuel cycle. The IAEA classifies uranium broadly into two categories: "primary supply," including all newly mined and processed uranium; and "secondary supply," encompassing uranium from reprocessing inventories, including highly enriched uranium, enriched uranium inventories, mixed oxide fuel, reprocessed uranium, and depleted uranium tails. The IAEA, after collecting information on 582 uranium mines and deposits worldwide, expected primary supply to cover 42% of the demand for uranium in 2000, but acknowledged that the number will drop to between 4% and 6% of supply in 2025, as low-cost ores are expended and countries are forced to explore harder-to-reach, more expensive sites.[91] However, here lies a conundrum: the IAEA calculated that secondary supply can only contribute 8–11% of world demand. "As we look to the future, presently known resources fall short of demand," the IAEA stated in 2001, and "it will become necessary to rely on very high cost conventional or unconventional resources to meet demand as the lower cost known resources are exhausted."[92]

There simply will not be enough uranium to go around, even under current demand. Interestingly, though, the IAEA refused to state this obvious conclusion. While the IAEA recorded the total amount of uranium at around 3.6 Gg in 2001, the number inexplicably jumped to 4.7 Gg in 2006. The increase was not due to new discoveries or improved technologies, but rather because of a clever redefinition of what the IAEA counted as uranium. The IAEA included in its new estimate the category of uranium that costs US$80–$130 per kilogram. This class comprises uranium ores that are of relatively low grade and of greater depth so much harder to mine, and that require such longer transport that the IAEA historically has not even counted them as usable stocks of uranium at all.

Another October 2008 assessment reported that the world presently consumes 160 million pounds of uranium per year to fuel existing reactors, but only produces 100 million pounds.[93] The difference is made up from stored inventories of mined uranium, unused fuel from decommissioned plants, and diluted nuclear weapons, but these reserves are being exhausted.

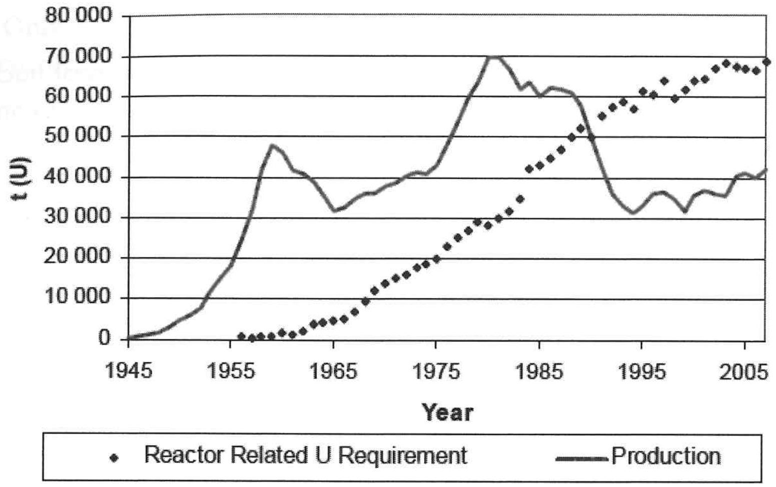

Figure 2: Global Annual Uranium Production and Reactor Fuel Requirements (in tons), 1945–2005[94]

As one example, the US produced 4.5 million pounds of uranium in 2007 but had to import 47 million pounds (or ten times as much) from other countries. The assessment concluded that enough high-grade uranium ore exists to supply the needs of the current fleet for 40–50 years, but warned that if the construction of new nuclear power plants were to accelerate, existing resources would not last more than ten years. Figure 2 clearly shows that a mismatch between uranium supply and demand is thus emerging, with dependence on secondary sources of uranium believed to run out by 2015.

One study from the Institute of Particle Physics of ETH Zurich and CERN (European Organization for Nuclear Research) cautioned that extraction from known mines and secondary resources during the coming 5–10 years appears to be much more difficult than generally believed, and almost no country that uses nuclear energy is self-sufficient in fuel production. Table 2, for example, shows that virtually every country producing uranium is now past its peak.[95] Germany and France have essentially stopped uranium mining; Japan, the UK, South Korea, and Sweden never had any substantial mining operations of their own; and production in the US is not even sufficient to satisfy 10% of national demand.

Table 2: Global Uranium Production and Use for Nuclear Reactors, 2008

Country	Nuclear Power Capacity (GWe)	Total Uranium Produced	Total Uranium Required	Peak Production (tons) and Year
United States	99	1,430	18,918	16,811 (1980/1981)
France	63.5	5	10,527	3,394 (1987/1988)
Japan	47.6	0	7,569	10 (1972/1973)
Russian Federation	21.7	3,521	3,365	16,000 (1987/1988)
Germany	20.3	0	3,332	7,090 (1965/1966)
South Korea	17.5	0	3,109	—
Ukraine	13.1	800	1,974	1,000 (1992/1993)
Canada	12.6	9,000	1,665	12,522 (2001/2002)
United Kingdom	11	0	2,199	—
Sweden	9	0	1,418	29 (1969)
South Africa/Namibia	1.8	5,021	303	10,188 (1980/1981)
Australia	0	8,430	0	9,512 (2004/2005)
Kazakhstan	0	8,521	0	8,521 (2008/2009)
Niger	0	3,032	0	4,363 (1981/1982)
World	**372**	**43,853**	**65,000**	**69,692 (1980/1981)**

Some Asian countries, such as China and India, have domestically available supplies of uranium, but these are extremely limited. The China National Nuclear Corporation expects the country's demand for uranium to rise from 1,000 tons per year in 2007 to 7,000 tons by 2020, by which time China will be more dependent on Australia for uranium imports. In fact, Chinese officials have already signed a deal with Australian firms to import 20,000 tons of uranium by 2020. Supplies of uranium ore are now recognized as "probably the biggest hurdle to expansion of the mainland's nuclear sector," and Chinese analysts expect the country to be dependent on foreign sources for 88% of its uranium ore by 2020.[96]

Geologists have estimated that India has about 61,000 tons of uranium reserves, but caution that most of it is stranded — far from existing mines and reactors where fuel is needed — and of very poor quality. Uranium mining companies have argued that Indian uranium ore concentrations hover around the 0.06% mark, compared to the minimum "economically exploitable" concentration of 0.1%. This dearth of recoverable Indian uranium has convinced many engineers to talk about shifting to thorium fuel cycles, but such advanced technology is at least a few decades away. Moreover, domestic Indian uranium supplies are already insufficient to supply existing nuclear power plants. Operators shut down five of the 17 nuclear power plants in the country at the end of 2007 and operated the remaining reactors at less than 50% capacity for want of fuel. Uranium fuel shortages have also forced the Nuclear Power Corporation of India to delay the commissioning of two new units at the Rajasthan Atomic Power Station and another new unit at Kaiga in Karnataka.[97]

To summarize, for the past 15 years only about two-thirds of global uranium requirements (between 31,000 and 44,000 tons) have been extracted from actual uranium mines, with the shortfall made up of civilian and military stocks of uranium and plutonium built up during the Cold War along with mixed oxide reprocessing. These secondary sources, however, are becoming rapidly exhausted, thus convincing the Nuclear Energy Agency and the IAEA to declare that "most secondary resources [of uranium] are now in decline and the gap will increasingly need to be closed by new production. Given the long lead time typically required to bring new resources into production, uranium supply shortfalls could develop."[98]

Even the reserves from existing mines are being rapidly depleted. One assessment from the IAEA, hardly an organization against nuclear power, concluded that enough high-grade uranium ore exists to supply the needs of the current fleet for only 40–50 years and warned that, if the construction of new nuclear power plants were to accelerate so that all coal plants were replaced, existing resources would not last more than ten years.[99] The most recent assessment of uranium deposits published by the IAEA noted that reasonably assured resources of uranium amounted to less than 3.4 million tons of uranium in 2009 (see Table 3) — enough to supply the existing reactor fleet for only 83 years, assuming annual production remained constant at 40,260 tons.[100] The US DOE has quietly acknowledged that domestic uranium production is currently at about 10% of its historical peak, and that most of the world's uranium reserves are becoming "stranded" and therefore much more difficult to extract.[101]

Such a bleak outlook was recently confirmed by a peer-reviewed study on available uranium resources at 93 deposits and fields located in Argentina, Australia, Brazil, Canada, Central African Republic, France, Kazakhstan, Malawi, Mongolia, Namibia, Niger, Russia, South Africa, the US, and Zambia.[102] The study reported that the quality of mined uranium peaked during the nuclear weapons programs of the 1940s and 1950s, when the highest-grade deposits were depleted. A long-term decline in the average uranium ore grade for almost all suppliers was documented. In the US, for example, the quality of uranium dropped from an average of 0.28% U_3O_8 in 1980 to 0.09% in 2005 — a decline of one third despite improvements in technology. No "world class" discoveries of uranium have occurred since the 1980s, and all increases in uranium mining and milling between 1988 and 2005 resulted from increased drilling and new assessments at known deposits. The study noted that uranium miners are having to go deeper and use more energy and water to extract uranium resources as the overall quality of ore declines.

Table 3: Reasonably Assured Resources of Uranium by Country (tons of uranium below US$130/kg U)

Country	Reasonably Assured Resources	%
Australia	725,000	22
Kazakhstan	378,000	11
United States	339,000	10
Canada	329,200	10
South Africa	284,400	8
Niger	243,100	7
Namibia	176,400	5
Russia	172,400	5
Brazil	157,400	5
Uzbekistan	72,400	2
India	48,900	1
China	48,800	1
Others	363,300	13
Total	**3,338,300**	**100**

To further complicate matters, finding and developing new deposits and fields requires large amounts of time and significant capital, as new mines and enrichment facilities take longer than a decade to bring online and can be delayed (like nuclear reactors) by unforeseen events. For example, a single cyclone stopped production of the Australian Ranger open-pit uranium mine in 2007 for more than a year, and the completion of the

Cigar Lake uranium mine in Canada was delayed for three years by a flash flood.[103]

Researchers at the Oxford Research Group suggest that declining ore grades will eventually yield a negative net energy loss before the end of this century.[104] They posit that the energy required to enrich ores of less than 0.02% U_3O_8 exceeds the total energy the uranium can produce. The global average for ore grade currently stands at 0.15%, though the range varies tremendously from high-grade locations like Canada's McArthur River (>21%)[105] to Australia's Lake Maitland (0.04%).[106] Although reserves today are comfortably above the 0.02% threshold, as high-grade reserves are exhausted, production will shift to low-grade sources at a higher cost. While technological advances may enable profitable access to these resources, doing so will inevitably need more energy and thus a larger carbon footprint.

The declining availability of high-quality uranium fuel, along with other factors, contributes to nuclear energy having a low energy payback. Even utilizing the richest ores available, a nuclear power plant must operate at ten full-load operating years before it has paid off its energy debts.[107] Based on this estimation, several known facts can modify the calculation: not all plants use the richest ores, plants operate at full capacity for an average of only 20 years, and most plants are decommissioned within 30 or 40 years. Accordingly, a plant using average-quality uranium and operating at full capacity for 20 years out of a 35-year life span will only generate twice as much energy as that consumed by the plant.

Other studies have documented how nuclear power plants generate 16% of global electricity, but provide only 6.3% of energy production and 2.6% of final energy consumption.[108] What accounts for this mismatch between generation, production, and consumption? Part of it stems from the poor consumption efficiency of electricity compared to other energy carriers as a whole (as electricity is relatively inefficient in energy terms compared to the use of oil). The other part relates to transmission losses associated with nuclear energy, usually situated far away from sources of demand, as well as the energy used by nuclear plants themselves (for cooling, management of spent fuel, operations, and refueling).

Utilizing a similar technique called an "energy payback ratio" (i.e. the ratio of total energy produced compared to the energy needed to build, maintain, operate, and fuel an energy system), Luc Gagnon found that nuclear power plants score unfavorably. He estimated that hydroelectric, wind, and biomass power plants are at least 1.5–20 times more efficient from an energy payback perspective than nuclear reactors.[109] Another meta-survey of hundreds of energy payback ratio studies found that hydroelectric facilities had the best performance (with ratios exceeding 170), and that biomass and wind power plants performed well (27–34) compared to ratios of below 16 for nuclear power plants and below 7 for fossil-fueled plants.[110] Figure 3 shows the energy payback ratios for a broad spectrum of technologies. Why do nuclear and fossil-fueled systems have such low energy payback ratios? As the best oil, gas, and uranium reserves get depleted, they tend to be replaced by wells and mines that require a higher energy investment (located in faraway regions). This leads to longer delivery distances and more energy needed for distribution. Other estimates have also confirmed nuclear's poor energy payback ratio compared to renewables such as wind and hydro.[111]

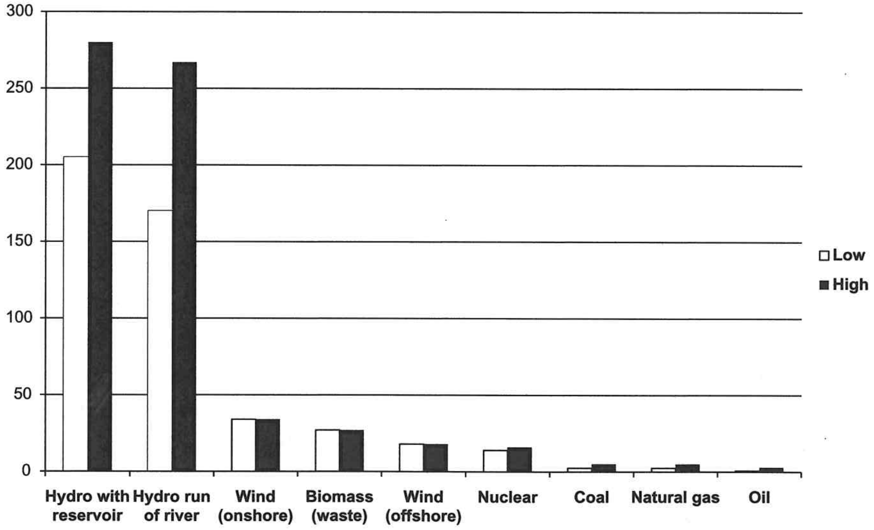

Figure 3: Energy Payback Ratios for Various Technologies and Systems

Note: A high ratio indicates good environmental performance. If a system has a payback ratio between 1 and 1.5, it consumes nearly as much energy as it generates.

These technical challenges alone — scores of incidents and accidents, a high probability of future accidents, reactor meltdowns, fuel cladding fires, an aging workforce and lack of skilled staff, and a declining energy payback ratio and uncertain reserves of fuel — might be sufficient to stop a nuclear renaissance on their own. Yet as the pages to follow will show, a nuclear renaissance must also overcome immense economic, environmental, and sociopolitical hurdles if it is to become a reality.

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