Questioning the Safety and Reliability of Nuclear Power. An Assessment of Nuclear Incidents and Accidents

ARTICLE *in* GAIA: OKOLOGISCHE PERSPEKTIVEN IN NATUR-, GEISTES- UND WIRTSCHAFTSWISSENSCHAFTEN · JANUARY 2011

Impact Factor: 1.35

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GAiA

ÖKOLOGISCHE PERSPEKTIVEN FÜR WISSENSCHAFT UND GESELLSCHAFT
ECOLOGICAL PERSPECTIVES FOR SCIENCE AND SOCIETY

2 | 2011

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oekom verlag

GAIA is available online at *www.ingentaconnect.com/content/oekom/gaia*
www.oekom.de | B 54649 | ISSN 0940-5550 |
GAIAEA 20/2, 73–144 (2011)

Questioning the Safety and Reliability of Nuclear Power

An Assessment of Nuclear Incidents and Accidents

Nuclear power is reputed to be one of the safest and cleanest sources of modern electricity. Yet in the wake of the Fukushima nuclear accident in Japan, many have begun to question the role of nuclear power in future energy production. A hard look at nuclear power accidents and incidents over the past six decades finds that the historical record gives rise to legitimate concern over the future likelihood of major nuclear disasters.

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GAIA 20/2 (2011): 95 – 103 | **Keywords:** energy security, nuclear energy, nuclear risk

The media frenzy surrounding the recent nuclear accident at the Fukushima Daiichi facility in Japan obscures one simple, and troubling, fact: incidents and accidents are a routine part of operations among the 440 nuclear reactors currently generating commercial electricity around the world. The International Atomic Energy Agency (IAEA) (2011), charged with managing a restricted database of "event reports" which record any incident of "safety significance" at nuclear power facilities, reports no less than 2,400 separate incidents since the organization began collecting data in the 1950s (though this database is not open access). Some of these incidents may seem trivial, if not for their seriousness, and include the following:

- a maintenance worker at a nuclear plant in Virginia cleaning the floor in an auxiliary building, catching 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 a Californian nuclear power plant who accidentally dropped it into the reactor, short-circuiting sensor arrays and leading to an increase in pressure that almost cracked the reactor vessel;
- a technician testing for air leaks with a candle who accidentally dropped it, causing a fire that burned 1.6 million electrical cables and forced a three-month shutdown in a nuclear plant in Alabama;
- a nest of field mice causing an electrical fire that shut down another nuclear facility in California for one week and
- a three-year shutdown of a nuclear power plant in Ohio after inspectors found excessive degradation of the pressure-vessel head of the reactor, but only after inspecting the wrong system by mistake.

Indeed, 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 so that they all provided the same wrong indication of liquid level within the cooling system of a reactor; and supposedly independent equipment 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 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 and shorted a circuit (Sovacool 2011, 2008). But just how serious is the risk of accidents and incidents at existing nuclear power facilities, especially given the improvements in safety culture after the well-known accidents at Three Mile Island in 1979, Chernobyl in 1986, and Fukushima in 2011? What types of damages, either to property or human life, have such events induced over the past six decades? How safe is nuclear energy compared to other sources? What lessons might we take away considering the nuclear renaissance?

Defining Nuclear Accidents, Incidents, and Events

Whenever anyone 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 In- >

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ternational Nuclear and Radiological Event Scale (INES) communicates the significance of a nuclear and radiological event through a logarithmic ranking system of eight levels: level 0 is "no safety significance", levels 1 to 3 are "incidents" whereas levels 4 to 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".

The Nuclear Regulatory Commission (NRC) in the U.S. 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. The Paul Scherrer Institute (Hirschberg et al. 1998) manages an Energy-Related Severe Accident Database (ENSAD) covering all accidents in the energy sector, not just nuclear ones, and it takes a slightly different approach. For the ENSAD, a severe accident is one which involves one of the following: at least five fatalities, at least ten injuries, 200 evacuees, 10,000 tons of hydrocarbons released, more than 25 square kilometers of cleanup, and/or more than five million US-Dollars in economic losses.

Under the classifications of accidents from the industry, the INES, 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 one million US-Dollars of property damage, a very different picture emerges. This definition seems more appropriate since loss of human life and damage to infrastructure and economic activity are the two most direct, and serious, consequences involved in generating electricity, though it does not include releases or accidents offsite from facilities or morbidity and mortality associated with downstream pollution.

A Troubling History

The author's own compilation meeting this definition, published previously in Sovacool (2008) and updated here, reveals 105 nuclear accidents totaling 176.9 billion US-Dollars in damages and 4,231 fatalities worldwide from 1952 to 2011. To be counted, an accident:

- must have occurred at a nuclear power plant and its associated infrastructure within its fuel cycle (uranium mine, enrichment facility, reactor, spent storage pool, etc.);
- must have resulted in at least one death (including latent fatalities) or cost above one million US-Dollars (in constant dollars that has not been normalized for growth in capital stock);
- had to be unintentional and in the commercial sector, meaning that military accidents and events during war and conflict are not covered, nor are intentional attacks nor those at defense installations;
- had to be verified by a published source.

The "cost" of the accident includes total economic losses such as destruction of property, emergency response, environmental remediation, evacuation, lost product, fines, court and insurance claims, and has been updated to 2010 US-Dollars. Whenever a range of costs or fatalities was reported, the table (pp. 97 to 102) provides the lowest number, so its results are likely conservative.

One might, after reading this list, get the impression that such accidents are exceptions rather than the norm. Though their specific definition of an accident, timeframe, and coverage differs, numerous other studies have documented mistakes, accidents, mishaps, and incidents at nuclear facilities. One of the first accident studies, conducted by the U.S. Atomic Energy Commission (1975), looked at the performance of early nuclear power 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[1] ("safe" levels are fiercely debated, but are generally less than ten rads). The study described 321 total fatalities, of which 184 occurred during construction, 212 during operations, 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.

Adato et al. (1987) referenced more than 200 accidents in commercial nuclear power plants from 1960 to 1980 in the U.S. 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 (Winter 2008). Still another study reported that, between the 1979 accident at Three Mile Island and 2009, there were more than 30,000 incidents at U.S. nuclear power plants alone, many with the potential to have caused meltdowns (Smith 2009).

It may seem like such accidents occur frequently in North America, due in part to reporting discipline, but researchers at American University (1996) calculated at least 124 "hazardous incidents" at nuclear units in India between 1993 and 1995. Greenpeace (2008, p. 10) also claims that the 200 nuclear facilities in France declare in total 700 to 800 serious incidents or significant safety events each year, though it is unclear which INES level these incidents were classified as. The lesson appears to be that complicated technological systems, like nuclear reactors, have unavoidable problems – making them prone to something Yale University sociologist Charles Perrow (1984) calls "normal accidents".

Worryingly, the above figures from Adato et al., Winter, and Smith tend to underestimate the risks associated with nuclear power, as they frequently do not include accidents and incidents at research reactors and other parts of the nuclear fuel chain. For example, accidents at the Savannah River reprocessing plant have

1 *rad* is a antiquated unit of absorbed radiation dose; the current unit is the *gray* (Gy). 100 rads are equal to 1 Gy.

TABLE: Major accidents and incidents at nuclear power facilities from 1952 to 2011 on a global scale (table to be continued).

date	location	description	fatalities	costs (mio. 2010 US-$)
12 Dec 1952	Chalk River, ON, CA	hydrogen explosion damage reactor interior, releasing 30 kilograms of uranium oxide particles	0	49
29 Sep 1957	Kyshtym, Chelyabinsk, USSR	heat exchangers fail at a liquid high-level nitrate storage tank at the Mayak Scientific-Production Association spent fuel rod storage facility, causing a chemical explosion that released 80 tons of radioactive waste which created a plume that extended for 900 square kilometers; 270,000 people are evacuated and large amounts of agricultural cropland are contaminated	103	1,620
8 Oct 1957	Windscale, UK	fire ignites plutonium piles, destroys surrounding dairy farms	33	84
24 May 1958	Chalk River, ON, CA	fuel rod catches fire and contaminates half of facility	0	72
26 Jul 1959	Simi Valley, CA, U.S.	partial core meltdown takes place at Santa Susana Field Laboratory's Sodium Reactor Experiment	0	35
3 Jan 1961	Idaho Falls, ID, U.S.	explosion at National Reactor Testing Station	3	24
5 Oct 1966	Monroe, MI, U.S.	sodium cooling system malfunctions at Enrico Fermi demonstration breeder reactor causing partial core meltdown	0	21
2 May 1967	Dumfries and Galloway, UK	fuel rod catches fire and causes partial meltdown at the Chaplecross Magnox nuclear power station	0	82
21 Jan 1969	Lucens, Canton of Vaud, CH	coolant system malfunctions at underground experimental reactor	0	24
1 May 1969	Stockholm, SE	malfunctioning valve causes flooding in Agesta pressurized heavy water nuclear reactor, short circuiting control functions	0	15
16 Jul 1971	Cordova, IL, U.S.	an electrician is electrocuted by a live cable at the Quad Cities Unit 1 reactor on the Mississippi river	1	1
11 Aug 1973	Palisades, MI, U.S.	steam generator leak causes manual shutdown of pressurized water reactor operated by the Consumers Power Company	0	11
22 Mar 1975	Browns Ferry, AL, U.S.	fire burns for seven hours and damages more than 1,600 control cables for three nuclear reactors, disabling core cooling systems	0	259
5 Nov 1975	Brownsville, NE, U.S.	hydrogen gas explosion damages the Cooper Nuclear Facility's Boiling Water Reactor and an auxiliary building	0	14
7 Dec 1975	Greifswald, GDR	electrical error causes fire in the main trough that destroys control lines and five main coolant pumps and almost induces meltdown	0	478
5 Jan 1976	Jaslovske Bohunice, CSR	leaking carbon dioxide from a KS 150's reactor coolant system at the Bohunice Nuclear Power Plant suffocates two workers to death	2	0
22 Feb 1977	Jaslovske Bohunice, CSR	mechanical failure during fuel loading at the same KS 150 reactor causes severe corrosion and release of radioactivity into the plant area, necessitating total decommission	0	1,836
10 Jun 1977	Waterford, CT, U.S.	hydrogen gas explosion damages three buildings and forces shutdown of Millstone-1 Pressurized Water Reactor	0	16
4 Feb 1979	Surry, VA, U.S.	Virginia Electric Power Company manually shuts down Surry Unit 2 in response to replace failed tube bundles in steam generators	0	13

already released ten times as much radioiodine than the accident at Three Mile Island; 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. 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 U.S. Almost 2,000 Navajo people, members of the second largest Native American tribe, were directly affected with undrinkable water, while sheep and livestock were heavily contaminated with lead-210, polonium-210, thorium-230, and radium-236 (Sovacool 2011).

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 square kilometers in Chelyabinsk and Sverdlovsk, causing the evacuation of 272,000 people. In September 1994, an explosion at the Serpong research reactor in Indo- >

TABLE: Major accidents and incidents at nuclear power facilities from 1952 to 2011 on a global scale (table to be continued).

date	location	description	fatalities	costs (mio. 2010 US-$)
28 Mar 1979	Middletown, PA, U.S.	equipment failures and operator error contribute to loss of coolant and partial core meltdown at Three Mile Island nuclear reactor	0	2,592
25 Jul 1979	Saclay, FR	radioactive fluids escape into drains designed for ordinary wastes, seeping into the local watershed at the Saclay BL3 Reactor	0	5
12 Sep 1979	Mihama, JP	fuel rods at the Mihama Nuclear Power Plant unexpectedly bow and damage the fuel supply system	0	12
13 Mar 1980	Loir-et-Cher, FR	a malfunctioning cooling system fuses fuel elements together at the Saint Laurent A2 reactor, ruining the fuel assembly, forcing an extended shutdown	0	24
22 Nov 1980	San Onofre, CA, U.S.	worker cleaning breaker cubicles at San Onofre Pressurized Water Reactor contacts an energized line, electrocuting him to death	1	0
11 Feb 1981	Florida City, FL, U.S.	Florida Light & Power manually shut down Turkey Point Unit 3 after steam generator tubes degrade and fail	0	2
8 Mar 1981	Tsuruga, JP	278 workers exposed to excessive levels of radiation during repairs of Tsuruga nuclear plant	0	3
26 Feb 1982	San Clemente, CA, U.S.	Southern California Company shuts down San Onofre Unit 1 out of concerns for earthquake	0	1
20 Mar 1982	Lycoming, NY, U.S.	recirculation system piping fails at Nine Mile Point Unit 1, forcing two-year shutdown	0	49
25 Mar 1982	Buchanan, NY, U.S.	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	60
18 Jun 1982	Senaca, SC, U.S.	feedwater heat extraction line fails at Oconee 2 Pressurized Water Reactor, damaging thermal cooling system	0	11
12 Feb 1983	Fork River, NJ, U.S.	Oyster Creek nuclear plant fails safety inspection, forced to shut down for repairs	0	35
26 Feb 1983	Pierce, FL, U.S.	workers discover damaged thermal shield and core barrel support at St. Lucie Unit 1, necessitating 13-month shutdown	0	58
7 Sep 1983	Athens, AL, U.S.	Tennessee Valley Authority discovers extensive damage to recirculation system pipeline, requiring extended shutdown	0	37
23 Sep 1983	Buenos Aires, AR	operator error during fuel plate reconfiguration cause meltdown in an experimental test reactor	1	70
10 Dec 1983	Plymouth, MA, U.S.	recirculation system piping cracks and forces Pilgrim nuclear reactor to shut down	0	4
14 Apr 1984	Bugey, FR	electrical cables fail at the command centre of the Bugey nuclear power plant and force a complete shutdown of one reactor	0	2
18 Apr 1984	Delta, PA, U.S.	Philadelphia Electric Company shuts down Peach Bottom Unit 2 due to extensive recirculation system and equipment damage	0	19

nesia 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.

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. Investigations identified poor quality assessment, not following procedures, and failure to document previous repairs to casks as the likely causes (Macfarlane 2001).

Onsite accidents at nuclear reactors and fuel facilities, unfortunately, are not the only cause of concern. The August 2003 blackout on the U.S. East Coast revealed that more than a dozen nuclear facilities in the U.S. 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 twelve 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

TABLE: Major accidents and incidents at nuclear power facilities from 1952 to 2011 on a global scale (table to be continued).

date	location	description	fatalities	costs (mio. 2010 US-$)
13 Jun 1984	Platteville, CO, U.S.	moisture intrusion causes six fuel rods to fail at Fort St. Vrain nuclear plant, requiring emergency shutdown from Public Service Company of Colorado	0	24
15 Sep 1984	Athens, AL, U.S.	safety violations, operator error, and design problems force six year outage at Browns Ferry Unit 2	0	119
9 Mar 1985	Athens, AL, U.S.	instrumentation systems malfunction during startup, convincing the Tennessee Valley Authority to suspend operations at all three Browns Ferry Units	0	1,976
9 Jun 1985	Oak Harbor, OH, U.S.	loss of feedwater provokes Toledo Edison Company to inspect Davis-Besse facility, where inspectors discover corroded reactor coolant pumps and shafts	0	25
22 Aug 1985	Soddy-Daisy, TN, U.S.	Tennessee Valley Authority Sequoyah Units 1 and 2 fail NRC inspection due to failed silicon rubber insulation, forcing three-year shutdown, followed by water circulation problems that expose workers to excessive levels of radiation	0	38
26 Dec 1985	Clay Station, CA, U.S.	safety and control systems unexpectedly fail at Rancho Seco nuclear reactor, ultimately leading to the premature closure of the plant	0	726
11 Apr 1986	Plymouth, MA, U.S.	recurring equipment problems with instrumentation, vacuum breakers, instrument air system, and main transformer force emergency shutdown of Boston Edison's Pilgrim nuclear facility	0	1,081
26 Apr 1986	Kiev, UA	mishandled reactor safety test at 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	7,236
4 May 1986	Hamm-Uentrop, DE	operator actions to dislodge damaged fuel rod at Experimental High Temperature Gas Reactor release excessive radiation to four square kilometers surrounding the facility	0	288
22 May 1986	Normandy, FR	a reprocessing plant at Le Hague malfunctions and exposes workers to unsafe levels of radiation and forces five to be hospitalized	0	5
31 Mar 1987	Delta, PA, U.S.	Philadelphia Electric Company shuts down Peach Bottom units 2 and 3 due to cooling malfunctions and unexplained equipment problems	0	432
12 Apr 1987	Triscastin, FR	Areva's Tricastin fast breeder reactor leaks coolant, sodium, and uranium hexachloride, injuring seven workers and contaminating water supplies	0	54
4 May 1987	Kalpakkam, IN	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 assembles, resulting in a two year shutdown	0	324
15 Jul 1987	Burlington, KS, U.S.	safety inspector dies from electrocution after contacting a mislabeled wire at the Wolf Creek Nuclear Power Plant	1	0
17 Dec 1987	Biblis, DE	stop valve fails at Biblis Nuclear Power plant and contaminates local area	0	14
19 Dec 1987	Lycoming, NY, U.S.	fuel rod, waste storage, and water pumping malfunctions force Niagara Mohawk Power Corporation to shut down Nine Mile Point Unit 1	0	162
29 Mar 1988	Burlington, KS, U.S.	a worker falls through an unmarked manhole and electrocutes himself when trying to escape	1	0

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 them, a complete shutdown of the plant was required; in four of them, 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, something also shown with the Fukushima accident. More worryingly, since many spent fuel ponds around the world do not receive backup power from emergency diesel generators, when offsite power goes down, pool water cannot be re-circulated to prevent boiling, evaporation, and exposure of fuel rods; the result is an increased risk of pool fires and explosions.

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 nu- >

TABLE: Major accidents and incidents at nuclear power facilities from 1952 to 2011 on a global scale (table to be continued).

date	location	description	fatalities	costs (mio. 2010 US-$)
10 Sep 1988	Surry, VA, U.S.	refueling cavity seal fails and destroys internal pipe system at Virginia Electric Power Company's Surry Unit 2, forcing twelve-month outage	0	10
5 Mar 1989	Tonopah, AZ, U.S.	atmospheric dump valves fail at Arizona Public Service Company's Palo Verde Unit 1, leading to main transformer fire and emergency shutdown	0	15
17 Mar 1989	Lusby, MD, U.S.	inspections at Baltimore Gas & Electric's Calvert Cliff Units 1 and 2 reveal cracks at pressurized heater sleeves, forcing extended shutdowns	0	130
10 Sep 1989	Tarapur, Maharashtra, IN	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 normal levels; repairs to the reactor take more than one year	0	84
2 Oct 1989	Vandellòs, ES	a fire at one of its turbines causes the malfunction of safety systems at the Vandellòs Nuclear Power Plant, forcing one of its 508 MWe units to permanently shut down	0	870
17 Nov 1991	Scriba, NY, U.S.	safety and fire problems force New York Power Authority to shut down the FitzPatrick nuclear reactor for 13 months	0	5
21 Apr 1992	Southport, NC, U.S.	NRC forces Carolina Power & Light Company to shut down Brunswick Units 1 and 2 after emergency diesel generators fail	0	2
13 May 1992	Tarapur, Maharashtra, IN	a malfunctioning tube causes the Tarapur nuclear reactor to release twelve curies of radioactivity	0	2
3 Feb 1993	Bay City, TX, U.S.	auxiliary feedwater pumps fail at South Texas Project Units 1 and 2, prompting rapid shutdown of both reactors	0	3
27 Feb 1993	Buchanan, NY, U.S.	New York Power Authority shut down Indian Point Unit 3 after AMSAC system fails	0	2
2 Mar 1993	Soddy-Daisy, TN, U.S.	equipment failures and broken pipes cause Tennessee Valley Authority to shut down Sequoyah Unit 1	0	3
31 Mar 1993	Bulandshahr, Uttar Pradesh, IN	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	238
25 Dec 1993	Newport, MI, U.S.	Detroit Edison Company prompted to shut down Fermi Unit 2 after main turbine experienced catastrophic failure due to improper maintenance	0	72
6 Apr 1994	Tomsk, RU	pressure build-up causes mechanical failure at Tomsk-7 Siberian Chemical Enterprise plutonium reprocessing facility, exploding a concrete bunker and exposing 160 onsite workers to excessive radiation	0	48
14 Jan 1995	Wiscasset, ME, U.S.	steam generator tubes unexpectedly crack at Maine Yankee nuclear reactor, forcing Maine Yankee Atomic Power Company to shut down the facility for one year	0	67
2 Feb 1995	Kota, Rajasthan, IN	the Rajasthan Atomic Power Station leaks radioactive helium and heavy water into the Rana Pratap Sagar River, necessitating a two-year shutdown for repairs	0	302
16 May 1995	Salem, NJ, U.S.	ventilation systems fail at Public Service Electric & Gas Company's Salem Units 1 and 2	0	37

merous criticality accidents at research reactors to date, including eleven loss-of-flow accidents, six loss-of-cooling accidents, 25 erroneous handlings or failures of equipment, and two special events that have so far resulted in 21 deaths spread across the U.S., the former Soviet Union, former Yugoslavia, Japan, and Argentina (Zafar 2008). The nonpartisan U.S. Government Accountability Office (GAO) (2008) also found that 31 research facilities with reactors or nuclear materials were operating in the U.S. for extended periods of time in noncompliance with nuclear safety licensing requirements. The GAO (2008, p. 3) concluded: "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". Such findings are scary, to say the least, as the national laboratories in the U.S. 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.

TABLE: Major accidents and incidents at nuclear power facilities from 1952 to 2011 on a global scale (table to be continued).

date	location	description	fatalities	costs (mio. 2010 US-$)
20 Feb 1996	Waterford, CT, U.S.	leaking valve forces Northeast Utilities Company to shut down Millstone Units 1 and 2, further inspection reveals multiple equipment failures	0	274
2 Sep 1996	Crystal River, FL, U.S.	balance-of-plant equipment malfunction forces Florida Power Corporation to shut down Crystal River Unit 3 and make extensive repairs	0	415
5 Sep 1996	Clinton, IL, U.S.	reactor recirculation pump fails, prompting Illinois Power Company to shut down Clinton boiling water reactor	0	41
20 Sep 1996	Senaca, IL, U.S.	service water system fails and prompts Commonwealth Edison to close LaSalle Units 1 and 2 for more than two years	0	77
9 Sep 1997	Bridgman, MI, U.S.	ice condenser containment systems fail at Indiana Michigan Power Company's D.C. Cook Units 1 and 2	0	12
25 May 1999	Waterford, CT, U.S.	steam leak in feedwater heater causes manual shutdown and damage to control board annunicator at the Millstone Nuclear Power Plant	0	8
18 Jun 1999	Shika, Ishikawa, JP	control rod malfunction set off uncontrolled nuclear reaction at Shika Nuclear Power Station's Unit-1	0	37
29 Sep 1999	Lower Alloways Creek, NJ, U.S.	major freon leak at Hope Creek Nuclear Facility causes ventilation train chiller to trip, releasing toxic gas and damaging the cooling system	0	2
30 Sep 1999	Ibaraki Prefecture, JP	workers at the Tokaimura uranium processing facility try to save time by mixing uranium in buckets, killing two and injuring 1,200	2	58
27 Dec 1999	Blayais, FR	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	59
21 Jan 2002	Manche, FR	control systems and safety valves fail after improper installation of condensers, forcing a two-month shutdown	0	110
16 Feb 2002	Oak Harbor, OH, U.S.	severe corrosion of control rod forces 24-month outage of Davis-Besse reactor	0	154
22 Oct 2002	Kalpakkam, IN	almost 100 kilograms of radioactive sodium at a fast breeder reactor leaks into a purification cabin, ruining a number of valves and operating systems	0	32
15 Jan 2003	Bridgman, MI, U.S.	a fault in the main transformer at the Donald C. Cook nuclear power plant causes a fire that damaged the main generator and backup turbines	0	11
10 Apr 2003	Paks, HU	damaged fuel rods hemorrhage spent fuel pellets, corroding heaver water reactor	0	40
9 Aug 2004	Fukui Prefecture, JP	steam explosion at Mihama Nuclear Power Plant kills five workers and injures dozens more	5	10
19 Apr 2005	Sellafield, UK	20 metric tons of uranium and 160 kilograms of plutonium leak from a cracked pipe at the Thorp nuclear fuel reprocessing plant	0	70
16 May 2005	Lorraine, FR	sub-standard electrical cables at the Cattenon-2 nuclear reactor cause a fire in an electricity funnel, damaging safety systems	0	13
16 Jun 2005	Braidwood, IL, U.S.	Exelon's Braidwood nuclear station leaks tritium and contaminates local water supplies	0	44

Conclusions and Implications

What might all of this mean when put into the context of a future nuclear renaissance, or even just continued reliance on existing nuclear power plants?

First, major nuclear accidents are an inevitable part of the future. The events at Chernobyl and Three Mile Island 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. Notwithstanding these reforms, the risk of future accidents is still significant, and current operators appear to have forgotten some of these lessons.

For instance, after conducting physical inspections of plant equipment and assessing indicators of plant performance, GAO (2006) found that a number of individual U.S. nuclear power plants were not performing within acceptable safety guidelines. The GAO identified 156 serious incidents which included a litany of problems, ranging from unplanned changes in reactor power and failures of emergency diesel generators to inadequate maintenance and human mismanagement. Another sample of U.S. >

TABLE: Major accidents and incidents at nuclear power facilities from 1952 to 2011 on a global scale.

date	location	description	fatalities	costs (mio. 2010 US-$)
4 Aug 2005	Indian Point, NY, U.S.	Entergy's Indian Point Nuclear Plant, located on the Hudson River, leaks tritium and strontium into underground lakes from 1974 to 2005	0	32
6 Mar 2006	Erwin, TN, U.S.	nuclear fuel services plant spills 35 litres of highly enriched uranium, necessitating seven-month shutdown	0	106
27 Jul 2006	Forsmark, SE	technician doing repair work with an electric arc shorts out a circuit and causes the Forsmark-1 reactor to shut down and disconnect from the grid, causing a three-week outage	0	11
24 Dec 2006	Jadugoda, IN	Tokyo Electric Power Company announces that their Kariwa nuclear plant leaks 1,192 litres of radioactive water into the Sea of Japan after being damaged by a 6.8-magnitude earthquake	0	27
18 Jul 2007	Kashiwazaki, JP	one of the pipes carrying radioactive waste from the Jadugoda uranium mill ruptures and distributes radioactive materials more than 100 square kilometers	0	2
4 Jun 2008	Ljubljana, SI	Slovenian regulators shut down the Krsko nuclear power plant after the primary cooling system malfunctions and coolant spills into the reactor core	0	11
14 Jun 2008	Fukushima Province, JP	a 7.2-magnitude earthquake cracks reactor cooling towers and spent fuel storage facilities, spilling 19 litres of radioactive wastewater and damaging the Tokyo Electric Power Company's No. 2 Kurihara Power Plant	0	49
4 Jul 2008	Ayrshire and Suffolk, UK	two British Energy nuclear reactors (the Largs and the Sizewell B facilities) shutdown unexpectedly after their cooling units simultaneously malfunction, damaging emergency systems and triggering blackouts	0	11
13 Jul 2008	Tricastin, FR	nuclear power operator Areva reports that dozens of liters of wastewater contaminated with uranium are accidentally poured on the ground and runoff into a nearby river	0	8
15 Mar 2009	Oskarshamn, SE	a maintenance worker repairing a shutdown reactor at the Oskarshamn dies after falling from the top of the turbine hall	1	0
4 Jul 2009	Hamburg, DE	a short circuit in a transformer causes fuel rod damage and an extended shutdown at Vattenfall's Krümmel nuclear plant	0	227
12 Aug 2009	Gravelines, FR	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
27 Aug 2009	St. Petersburg, RU	a cracked discharge accumulator and malfunctioning feed pump force the Leningrad Nuclear Power Plant reactor number 3 to close for extended repairs	0	119
1 Feb 2010	Vernon, VT, U.S.	operators report that deteriorating underground pipes from the Vermont Yankee nuclear power plant have been leaking radioactive tritium into groundwater supplies in Vermont, resulting in the eventual shutdown of the plant	0	756
11 Mar 2011	Fukushima Prefecture, JP	an earthquake and tsunami cause emergency backup generators to fail at the Fukushima Daiichi nuclear power plant. The pressure vessels at some of its reactors crack as a result, spent fuel pools at the facility have caught fire, fuel assemblies have melted down, and dangerous levels of radiation have been reported. More than 200,000 residents had been evacuated from a 30-kilometer safety zone	21 (estimated)	152,010 (estimated)

plants inspected from May 1999 to April 2004 revealed 25 serious incidents at 23 separate facilities (Cadwallader 2005). Yet another GAO study (2007) of U.S. 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". In July, 2008, government officials in the U.S. conducted surprise random inspections at ten reactors and found that many had yet to comply with safety regulations concerning fires issued way back in 1975 (Findlay 2011).

More recently Peter A. Bradford, a former regulator at the U.S. NRC, assessed nuclear power performance and warned that the technology has rushed "far ahead of its operating experience". He noted in a testimony before the Senate Committee on Environment and Public Works on March 24, 2009, that every state across the northern tier from Illinois to Maine has seen some combination of 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. 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 or, in the case of Fukushima, natural disasters.

Using some of the most advanced probabilistic risk assessment tools (PRA) available, an interdisciplinary team at the Massachusetts Institute of Technology (MIT) (2003) identified possible reactor failures and predicted that the best estimate of core damage frequency was around one every 10,000 reactor years. In terms of the expected global growth scenario for nuclear power from 2005 to 2055, the MIT team estimated that at least four serious core damage accidents (with a high probability of offsite releases) will occur worldwide and concluded that "both the historical and the PRA 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".

Second, the global nuclear industry needs to become more transparent about incidents, accidents, and events. A large proportion of the accidents listed in the table come from the U.S. not because its reactors are less safe, but because groups like the NRC and the GAO repeatedly assess, and publicly report, on nuclear performance. Such reporting requirements should become standardized around the world not only so the public can learn about nuclear safety, but also so that operators can learn from each other, and investors and insurers can better assess nuclear risks.

Third, nuclear power is less safe than alternatives. When overall fatalities from other energy sources are compared independent of the amount of energy they produce, nuclear power ranks as the second most fatal source of energy supply – after hydroelectric dams – and is responsible for more onsite deaths than oil, coal, and natural gas systems (Sovacool 2008).

Even the Paul Scherrer Institute's ENSAD, despite defining accidents differently, suggested that the latent effects of the Chernobyl disaster mean nuclear power is responsible for 41 times more fatalities per unit of energy delivered than equivalently sized coal, oil, natural gas, and hydroelectric projects. Indeed, when put into context of fatalities per unit of energy delivered – including Chernobyl but not Fukushima –, nuclear power results in almost 50 fatalities for every Gigawatt-year of electricity produced compared to less than two fatalities per Gigawatt-year for all other energy systems (though this number is the worldwide average independent of national or regional differences) (Hirschberg and Strupczweski 1999). Although only a few accidents globally involved fatalities, those that did collectively killed more people than have died in commercial U.S. airline accidents since 1982.

The point is not that systems fail – no technology is perfect – but that nuclear power plants present a unique suite of risks and costs. Better understanding these will be essential as we consider what future role, if any, nuclear power should play in our electricity supply.

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Submitted April 28, 2011; revised version accepted May 11, 2011.

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