Nuclear Power: Economic, Safety, Health, and Environmental Issues of Near-Term Technologies

M.V. Ramana

Program in Science, Technology, and Environmental Policy and Program on Science and Global Security, Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, New Jersey 08542; email: ramana@princeton.edu

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accidents, climate change, costs, waste

Abstract

Nuclear power is confronted with a number of challenges in the near term. One major constraint is the economics of nuclear power, driven by both the high capital costs and financial uncertainties. The second is concern about catastrophic accidents; despite the development of newer reactor designs, the possibility of such an accident has not been completely eliminated. A third is to find a way of disposing nuclear waste that is technically feasible and politically acceptable to the public.

Contents

INTRODUCTION

After more than two decades of slow growth, or even decline in some countries, there is now talk of a revival of nuclear power. This has been driven by multiple factors, including concerns about climate change, desire for energy security, and volatility in the fossil fuel market, especially in natural gas prices.

There have been a number of recent studies that have looked at the future of nuclear power and the challenges to overcome to ensure sustainable growth; a key concern has been the economics of nuclear power. These studies have been conducted by academic institutions (1, 2), by government bodies or government-appointed panels (3–6), by the nuclear industry and related organizations (7, 8), by independent analysts and nongovernmental organizations (9, 10), and by agencies that study energy trends (11, 12). Most are focused on a specific country or countries.

LWR: light-water reactor

This article reviews some of the key issues relevant to the near-term future of nuclear power. Starting with an overview of the current status and future projections, some economic factors related to nuclear power and different perspectives on the safety of nuclear installations are discussed. This is followed by a brief examination of a few environmental and public health issues where there have been some new developments in recent years, including our understanding of the impacts of the Chernobyl accident, epidemiological studies of cancers in populations surrounding nuclear reactors, efforts to deal with nuclear waste, and the potential for nuclear power to be a solution to climate change. All of these issues can be explored at far greater depth, and this review provides only an overview.

CURRENT STATUS AND PROJECTIONS

Currently, the installed nuclear capacity around the world is 372 GW (gigawatts or 10^9 watts), comprising 439 nuclear reactors (13, p. 11). Five reactors are in long-term shutdown status, i.e., they have been shut down for an extended period (usually several years) without any firm recovery schedule, although these units are expected to eventually restart. Around the world, 33 reactors are under construction. These, and advanced designs presently under development, can be categorized into three types: water-cooled reactors, gas-cooled reactors, and fast reactors (14).

The most widespread nuclear reactor type today is the light-water reactor (LWR), a water-cooled reactor that is also moderated by water. There are two categories of LWRs, pressurized water reactors (PWR) and boiling water reactors (BWR); each come in multiple variations. Among operating power reactors, there are 265 PWRs and 94 BWRs. Other reactor types operating around the world include

44 pressurized heavy-water reactors (PHWRs), 18 gas-cooled, graphite-moderated reactors (GCRs), 16 light-water-cooled, graphite-moderated reactors (LWGR), and 2 fast breeder reactors (FBRs) (13, p. 61).

It is likely that the near-term future of nuclear power will be locked into light-water technology for historical and political reasons in addition to technical ones (15). This review therefore mostly focuses on this technology. Though differing in specificities, many of the issues that affect LWRs also affect the other reactor types currently in use. The only reactor type now in operation that is significantly different from LWR technology is the liquid-metal-cooled fast breeder reactor. Despite significant problems with breeders, several countries seem politically committed to continued pursuit of this technology, albeit at low levels of financial and institutional commitment.

The evolution in reactor technology has been often described as having generations. The latest generation of reactors was developed in the 1990s, following the Chernobyl accident, and includes passive safety features. The reactors expected to be built over the next 25 years will most likely be based on what are called Generation-III designs (12, p. 363). Some also talk about Generation-III+ reactors. However, there is no clear distinction between Generation-III and -III+ designs (16). There is also an ongoing international research effort to develop Generation-IV nuclear energy systems, including both the reactors and their fuel-cycle facilities. The aim is to provide significant improvements in economics, safety, sustainability, and proliferation resistance (17). However, these are intended for commercial deployment only by 2020–2030 and are not considered here.

Passive safety features: those based on natural forces, e.g., convection and gravity, rather than on active systems and components like pumps and valves

Most of the reactors currently on the market are typically over 1 GW of capacity. There is also an effort to build smaller reactors that might be better suited to smaller demand centers. Some of these are evolutions of older designs that were smaller to begin with, for example the 0.7 GW PHWR, which the Nuclear Power Corporation of India is planning to construct (18). There are numerous reactor designs that have been proposed for construction. **Table 1** lists a representative sample (19–22).

Table 1 Reactor types

Reactor[a]	Technology	Capacity (MW)	Reactor vendor
EPR	PWR	1600	Areva
ESBWR	BWR	1550	General Electric
ABWR	BWR	1370	General Electric, Hitachi, Toshiba
System 80+	PWR	1300	ABB Combustion Engineering Nuclear Power
VVER-1000	PWR	1000–1200	Atomenergoprom, Russia
AP1000	PWR	1120	Westinghouse
ACR	PHWR	700–1200	Atomic Energy of Canada
AP600	PWR	650	Westinghouse
PIUS	PWR	600	ABB-Atom, Sweden
VVER-500/600	PWR	635	Atomenergoprom, Russia
AC-600	PWR	600	China National Nuclear Corporation
IPHWR	PHWR	700	Nuclear Power Corporation of India
AHWR	PHWR	300	Department of Atomic Energy, India
PBMR	HTGR	180	Westinghouse and Eskom (South Africa)

[a]Abbreviations: ABWR, advanced boiling water reactor; ACR, advanced CANDU reactor; AHWR, advanced heavy-water reactor; AP600 and -1000, advance passive; BWR, boiling water reactor; EPR, evolutionary pressurized-water reactor; ESBWR, economic simplified boiling water reactor; HTGR, high-temperature gas-cooled reactor; IPHWR, Indian pressurized heavy-water reactors; PBMR, pebble bed modular reactor; PHWRs, pressurized heavy-water reactors; PIUS, process inherent ultimate safety; PWR, pressurized water reactor; VVER-500/600 and -1000, *vodo-vodyanoi energetichesky* reactor.

Levelized cost: the cost of electricity generation that is determined by equating the present value of all expenditures and revenues

Discount rate: the rate at which future costs are discounted to the present

OCC: overnight construction cost

Since the dawn of the nuclear age, a number of projections have been made of nuclear capacity in the future, especially by nuclear establishments in specific countries (Atomic Energy Commissions, usually) and the International Atomic Energy Agency (IAEA). Most of these have been well in excess of what actually materialized (23, p. 85). Nevertheless, projections do provide an indication of the nuclear industry's outlook and end up influencing policy makers and investors.

In the medium term, projections of nuclear energy largely fall into the range of 400–800 GW installed capacity in 2030. Illustrative of these are the low and high scenarios assumed by the IAEA in its 2008 projections of 473 and 748 GW (8, p. 17).[1] Expressed in terms of share of total electricity generation capacity, nuclear power goes from 8.4% in 2007 to 7.1% in the low scenario and to 9.1% in the high scenario. Just a year ago, the IAEA projected low and high capacities of 447 and 691 GW (24, p. 17). This variation suggests greater optimism but also underscores the uncertainties involved in such projections.

For the United States, the Department of Energy's *Annual Energy Outlook 2008* projects an increase from 100.2 GW in 2006 to 114.9 GW in 2030 (25, p. 11). Many countries that currently have no nuclear generating capacity have expressed an interest in building nuclear reactors, but it is unclear how many of them will actually undertake the necessary investment.

ECONOMICS

The economic cost of nuclear power has been a key barrier to the construction of new reactors around the world. As an influential interdisciplinary study conducted at the Massachusetts Institute of Technology some years back stated, "Today, nuclear power is not an economically competitive choice" (1, p. 3). The lack of competitiveness arises mainly from its capital intensity. The ongoing electricity sector restructuring process around the world, leading to a greater emphasis on economic competition, has accentuated this problem. Financial risks that were previously borne by consumers are increasingly seen as the responsibility of investors. Therefore, as the Organisation for Economic Co-operation and Development's (OECD's) Nuclear Energy Agency points out, because of the risks faced in competitive electricity markets, "investors tend to favor less capital intensive and more flexible technologies" (26, p. 16).

In comparing the economics of different technologies for generating electricity, the methodology that has become widely adopted is the use of levelized costs. This involves discounting all cash flows, both expenditures and revenues (from the expected sale of electricity), to some arbitrary but fixed reference date. The levelized cost of electricity is then determined by setting the sum of discounted costs equal to the sum of discounted revenues. For a review of the different ways of assessing the cost of electricity, see Reference 27.

The cost of generating electricity consists of three main components: the capital cost of constructing the generating facility, the annual fueling and operations and maintenance costs, and the waste management expenses. One other component in the case of nuclear power is that of decommissioning the reactors. Both decommissioning and dealing with radioactive wastes are expensive processes, but because much of the cost will be incurred many years into the future, their discounted costs, for any nonzero discount rate, will be small.

The three critical parameters that determine the economics of nuclear power are the overnight construction cost (OCC), i.e., not including interest during construction, the construction period, and the discount rate. Fixed costs of nuclear reactors are commonly discussed in units of dollars per kW of installed capacity. There is enormous uncertainty about both the OCC and the construction period, and

[1] In the low estimates, the IAEA assumes that present barriers to nuclear power development will prevail in most countries, whereas the high estimates are predicated on a moderate nuclear revival.

Table 2 Nuclear capital cost comparisons

Study (Reference)	Capital cost per kW	Included/excluded/assumptions	Construction (months)
Massachusetts Institute of Technology (1)	US$(2002) 2000	Includes 10% for contingency and 10% for optimism	60
University of Chicago (2)	US$(2003)1500	New design, does not include first-of-a-kind engineering (FOAKE)	84
International Energy Agency (12)	US$(2006)2000–2500	Reactors are built on existing sites	60
U.S. Congressional Budget Office (6)	US$(2006)2358	Does not include FOAKE costs; assumes favorable regulatory process	72
The Keystone Center (33)	US$(2007)3600–4000	Assumes cost escalation specific to construction industry; does not assume lowered costs from learning	60–72
Canadian Energy Research Insitute (34)	US$(2003)1689 (Twin ACR-700) & US$(2003)2140 (Twin Candu-6)	First-of-a-kind unit	72

there is also some debate about the appropriate choice of discount rate. Earlier, performance of nuclear reactors, as measured by indices such as outage rates and capacity factors, had a large influence on the cost of nuclear power, but in recent decades, reactor performances have improved markedly, and this issue is now only of secondary significance in cost calculations (28).

Construction Costs

Recent construction cost experience with light-water reactors is confined to a small number of plants completed in East Asia in the 1990s (29). There is also some data from constructing pressurized heavy-water reactors in India (30), but the relevance of this experience to future construction is uncertain. Some other reactors that have been commissioned in the past decade have been under construction for decades, including the Brazil's Angra-2 reactor and the Temelin-1 and -2 reactors in the Czech Republic; the costs involved in such instances cannot be generalized.

Despite the relatively small data set of recently constructed nuclear reactors, there is a profusion of estimates of construction costs that have been adopted by various studies that have come out in the last few years.[2] These figures span a large range for many reasons; broadly speaking, this is because they vary in what they include and what they do not include. For example, some include what are called first-of-a-kind engineering (FOAKE) costs, which refers to the expenses incurred in producing the engineering design specifications of a reactor of a particular kind before it has been built, while others do not. The OCC values used in some representative studies are listed in **Table 2**.

At an OCC of \$2000/kW and a discount rate of 6.7%, the International Energy Agency (IEA) calculates a total electricity generation

[2]The Nuclear Energy Agency of the OECD has also produced a series of studies, updated every few years, on the projected costs of electricity generation, including nuclear power (26, 31). These are based on projected cost data provided by OECD member countries and a few others in response to a questionnaire. Within each country, the data typically come from "official nuclear agencies. . .[and] are rarely if ever informed by the concrete, historical record of nuclear costs in the real world: instead they are always forecasts of future performance, where past problems are always solved and new problems will not emerge" (32). For example, in its 2005 update, the OCC of a nuclear reactor, to be commissioned in 2010, in Finland was taken to be \$1895/kW (26, p. 50). The OCC of the Olkiluoto-3 reactor that is being constructed in Finland is currently estimated at upward of \$4000/kW.

cost (levelized) of 4.9 cents/kWh, of which the construction cost contributes about 3.2 cents/kWh. At the same discount rate, if the OCC is assumed to be \$2500/kW, the levelized cost increases to 5.7 cents/kWh. For a higher discount rate of 9.6%, which may be more representative of market conditions in many countries in recent years, the levelized costs are 6.8 and 8.1 cents/kWh (12, pp. 367–68). Thus, at higher discount rates, an increase of \$500/kW translates to an increase of about 1.3 cents/kWh. At a discount rate of 9.6%, IEA estimates that thermal power from coal costs about 6 cents/kWh.

In the face of adverse economics, the U.S. Energy Policy Act of 2005 (EPACT) has offered various guarantees and incentives to promote nuclear reactor construction. Among the provisions of the Act that specifically apply to newly built nuclear reactors are funding for research and development, loan guarantees and insurance against regulatory delays, and a production tax credit (6, p. 1). Since its enactment, several utilities have announced their intention to construct new nuclear plants. Most of these are in states with regulated electricity generation; in these states, if the regulatory agency approves the construction of a plant, then the investor is guaranteed that electricity generated will be purchased at the price set by the regulator.

The costs of new nuclear reactor construction as estimated by these utilities have been much higher than the above-mentioned general studies have assumed. For example, in March 2008, Progress Energy, a Florida utility, filed a Certification of Need document, the first of the many state level regulatory steps, with the state's Public Service to construct two reactors, where it estimates OCCs of about \$5000/kW for the first unit and \$3300/kW for the second unit, with an average of about \$4200/kW (35). Utilities are weighing these high costs against a volatile fossil fuel market.

These estimates reflect the sharp increase in construction costs and cost estimates in recent years for power plants of all types, including coal, nuclear, natural gas, and wind (36). This increase has been attributed primarily to "dramatically increased raw material prices" and, to a lesser extent, "increased labor costs" (37).

Credit agencies, such as *Standard and Poor's*, believe that the provisions of the EPACT may not be substantial enough to sustain credit quality because nuclear generation still has "the highest overall business risk compared with other types of generation" (38). In May 2008, *Moody's* observed that a "utility that builds a new nuclear power plant may experience an approximately 25%–30% deterioration in cash-flow-related credit metrics" (39).

Many of these observations come from the United States. Much less is known about other countries; although given the globalized nature of the nuclear industry, there is reason to expect similar experiences. The 1600-MW Olkiluoto-3 plant constructed by Areva in Finland was estimated to cost 3 billion Euros, or about \$3000/kW, but it is now reported to have a 1.5-billion Euros cost overrun (40), raising its costs to the same range as estimated by U.S. utilities.

The problem posed by these high costs is compounded by uncertainty. Historical analyses of reactor construction and operation cost show significant variations among different reactors (41). Because these variations have to do with specific contingencies, it has been argued that assumptions about future nuclear costs should encompass not only the distribution in costs but also the uncertainty in the distribution (42).

Construction Time

The definition of construction time is not always clear in various studies as well as in reports of experiences. Some measure it from the first pour of concrete, whereas others start from the time of groundbreaking. What may be of most relevance, though, is the entire period over which capital is expended. Therefore, it is also important to include the preconstruction period during which various activities, such as ordering equipment, obtaining clearances, and site acquisition, are all conducted. In addition, it is possible that there is some expenditure on rehabilitation of those displaced from the area close to the reactor. One estimate of preconstruction cost is £250 million (or $470 million) (5).

Though most studies assume around 60 to 72 months as their construction time, actually achieved construction times of nuclear reactors may be significantly higher. **Table 3** shows construction times, measured from the first pour of concrete to the first grid connection of the unit, for reactors that were commissioned during the specified periods.

There are factors that might push construction times to the higher side in the near future. In particular, there are various supply bottlenecks, most notably, but not limited to, forging capacity for pressure vessels, steam generators, and pressurizers (29). Another problem has been the significant decline in numbers of supporting industries, especially in countries like the United States that have not had recent experience with reactor construction.

These are not fundamentally unsolvable problems, but there is a chicken-and-egg nature to them. Unless construction times are reduced in a cost-effective way and a number of other noneconomic challenges are overcome, there may not be a large-scale resumption of nuclear construction. And without a large-scale resumption, there is little motivation to build adequate capacity to overcome supply bottlenecks.

Table 3 Construction times for nuclear reactors[a]

Period[b]	Number of reactors	Average construction duration (months)
1976–1980	86	74
1981–1985	131	99
1986–1990	85	95
1991–1995	29	104
1996–2000	23	146
2001–2005	20	64
2006	2	77
2007	3	80

[a]Reference 13, p. 23.
[b]The figures for the period after 2000 are mainly those of reactors constructed in East Asia and do not appear to include figures for some reactors that were under construction for over 15 years.

Learning and Future Costs

Two primary sources of lowered costs in the future have been suggested by nuclear vendors: economies of scale and learning. Modularized factory construction has also been suggested as a way to lower costs, especially in the case of the pebble bed modular reactor (PBMR) (43), but there is not much experience with this factor in the case of nuclear construction to verify these claims.

Economies of scale might not be very useful for lowering the cost of nuclear power because the reactor size that underlies most economic discussions of nuclear power is over 1 GW, often constructed as twin units. A general rule of thumb is that a single power plant should not exceed 10% of the total grid size so as to avoid instability (44). Therefore, large nuclear power plants are not advisable in countries with small grid sizes. Furthermore, there is some evidence that if the actual capital cost, including interest during construction, is chosen as the relevant variable, there may not be significant economies of scale (45).

The second expectation is that future nuclear costs will be lower as a result of learning. Historically, however, nuclear construction costs have not reduced significantly with time (for the case of the United States, see **Table 4**). An increasing trend in cost, though not as dramatic as in the U.S. case, has also been reported in the series of reactors, with somewhat standardized design, that were commissioned in India in the 1990s (30, p. 849), although the reactors currently under construction are *estimated* to be cheaper. In the past, final cost figures for Indian reactors have been substantially higher than estimates (46, p. 1765).

At the same time, there is some evidence that when similar plants were built by the same organization, the follow-on plants cost less to build (47). To capture such effects, it is common to calculate a learning rate, usually defined as the percentage decrease in unit costs for each

Table 4 Historical U.S. construction costs in 2006 dollars[a]

Construction start	Number of plants	Estimated overnight	Actual overnight	Final cost to initial cost
1966–1967	11	$612/kW	$1279/kW	209%
1968–1969	26	$741/kW	$2180/kW	294%
1970–1971	12	$829/kW	$2889/kW	348%
1972–1973	7	$1220/kW	$3882/kW	318%
1974–1975	14	$1263/kW	$4817/kW	381%
1976–1977	5	$1630/kW	$4377/kW	269%

[a]Reference 6, p. 17.

doubling of experience (48). There are a range of estimates for learning rates, depending on their assumptions and data considered.

Most learning studies have focused on the United States. Many of the early studies done in the 1970s, which considered plants that were issued permits before 1975, came up with learning rates of 11% to 21.9%; but some of these relied on estimates of costs rather than final costs and hence may have overestimated learning rates (2, p. 4–8). Studies that were published in the 1980s come up with learning rates of 5% to 7%. One study even found no learning effects for construction firms but "some evidence" of learning effects for utilities that managed construction themselves (49). On the basis of these different studies and the empirical evidence they rely on, a study conducted by the University of Chicago on the economic future of nuclear power concludes that "a reasonable range for future learning rates in the United States nuclear industry is 3 to 10%" (2, p. 4–24). These estimates low compared to those of many other energy technologies. Because technology maturing costs and break-even capacities grow faster than exponentially with decreasing learning rates (48, p. 256), lower learning rates would require much greater levels of investment before the technology would become economical.

Various reasons have been put forward for the relatively low learning rate of nuclear power, including the relatively small reactor ordering rate after the 1970s, the interface between the complexity of nuclear power plant and the regulatory and political processes, and the variety of designs deployed (50). In addition, the relatively long lead times for construction and commissioning mean that improvements derived by feeding back information from operating and design experiences on the first units are necessarily slow.

Discount Rate and Financial Risks

The choice of discount rate greatly affects the levelized cost and therefore any comparisons of electricity generation costs. There is no consensus on what the discount rate should be because it is an expression of how planners wish to allocate resources and how they value future benefits in comparison with current sacrifices. In those cases where private markets finance the nuclear reactor, through either debt or equity, i.e., loaning money or taking ownership of a part of the project, the discount rate is the weighted average of the interest rate and the equity return rate. But these rates depend in part on the financial risk perception of nuclear technology on the part of investors.

The debate about the choice of discount rate is most intense when it comes to costs that are borne by future generations. Choosing a large discount rate would mean that future expenditures are given very little weight in economic calculations. Some economists have proposed that, in the interests of intergenerational equity, such activities should be valued at a zero or a very low discount rate (51). One approach that has been suggested to deal with this problem is to use two discount rates, one for near-term expenditures and a lower one for long-term expenditures (3).

The financial risk related to nuclear power arises from a variety of factors. The first and obvious factor has already been discussed: uncertainty in construction costs and time. A second factor is the division of costs into fixed and operating costs. Nuclear reactors have a higher share of fixed costs as compared to fossil fuel–based plants, which have higher operating costs; therefore, the former are subject to greater financial risk (52, 53). A third factor is the possibility of catastrophic accidents.[3] There is an extensive literature showing that the Three Mile Island (TMI) accident and Chernobyl resulted in negative, though transitory, price reactions among U.S. electric utilities, with the effect becoming greater with increasing nuclear share of the utility's holdings (55, 56). Economically, all these different financial risks translate primarily to a higher discount rate for nuclear power as compared to other forms of electricity generation.

Decommissioning Costs

There is limited experience with actually decommissioning commercial nuclear reactors and therefore an inadequate basis for final decommissioning costs. A typical assumption is that decommissioning would cost between 9% to 15% of the initial capital cost of a nuclear power plant (57). Assuming a capital cost of \$3000/kW, that translates to \$270–\$450/kW in current dollars. Cost estimates provided by some OECD countries and a few others to the Nuclear Energy Agency suggest that, on average, decommissioning PWRs, BWRs, and Canadian PHWRs cost \$320/kW, \$420/kW, and \$360/kW (2001 dollars), which are all somewhat higher than the previously mentioned range (58, pp. 59–61).

Going by estimates for the 1240-MW Superphenix (1985–1998) in France and the 14-MW demonstration fast reactor (DFR) (1959–1977) in the United Kingdom, decommissioning breeder reactors might cost significantly more; for example, decommissioning the DFR is estimated to cost £760 million (roughly \$100,000/kW) (59).

Spent Fuel Management

Spent fuel can either be reprocessed or directly disposed. Direct disposal starts with storing the spent fuel at an interim location, which is expected to be followed by its encapsulation and permanent storage in a geological repository. No country in the world has yet built an operational geological repository. Interim storage of spent fuel has been in pools or in dry casks, both at the reactor site and away from it (60).

Reprocessing involves the chemical processing of the spent fuel to separate out the plutonium and the (depleted) uranium. The plutonium is used to fabricate fuel for nuclear reactors or to make nuclear weapons. Reprocessing, therefore, provides both a service (that of dealing with the spent fuel) as well as a product (plutonium). Reprocessing also produces high-level radioactive waste, which is vitrified and put into long-term storage. As with direct disposal, the plan is to bury these in geological repositories. There are also intermediate and low-level radioactive wastes that are disposed of in other ways into the environment.

For decades now, there has been a debate over the economics of reprocessing versus direct disposal, in addition to debates over other factors such as lack of adequate storage space, safety, and environmental issues. As a purely waste management option, reprocessing is expensive in comparison to direct disposal of spent fuel because of its high capital costs (61). What could make it more attractive is if a credit can be attached to the recovered plutonium. However, the fabrication costs of the MOX (mixed oxide, a mixture of plutonium and uranium oxides) fuel are very high in comparison to the corresponding costs for uranium fuel.

[3]The concept underlying financial risk due to the possibility of accidents was essentially laid out by Peter Bradford, a former member of the U.S. Nuclear Regulatory Commission, who told the *New York Times*: "The abiding lesson that Three Mile Island taught Wall Street was that a group of NRC-licensed reactor operators, as good as any others, could turn a \$2 billion asset into a \$1 billion cleanup job in about 90 minutes" (54).

Therefore, even if the plutonium were assumed to be available at zero cost, unless the price of uranium were to increase severalfold, the cost of generating electricity using MOX fuel would be noncompetitive in LWRs (1, 62–64). The same is the case if the plutonium is used in fast-neutron breeder reactors (64, 65).

Because no country has to date constructed an operating geological repository, there are only rough estimates of the cost of final waste disposal. One country that has put out a projection of the cost of such a repository is Canada. Though this is intended to deal with spent PHWR fuel, it provides an indication of the costs involved. The Canadian Joint Waste Owners estimate that just the cost of constructing a deep geological repository is Cdn $12.9 billion (about $8.5 billion in 2002 U.S. dollars) for the disposal of 3.7 million fuel bundles, each weighing 20 kg, or about Cdn $175/kg (66). However, much of this expense is several years in the future, and when discounted using a rate of 3.25% (real), the present value comes down to about a third.

SAFETY

The likelihood and potential impact of nuclear accidents has been a topic of debate practically since the first reactors were constructed. It has also been a key factor in public concern about nuclear facilities. Numerous technical measures to reduce the risk of accidents or, should one occur, to minimize the amount of radioactivity released to the environment have been adopted. Despite the adoption of such measures, there have been many accidents with varying impacts as well near misses and incidents (67).[4] Two accidents that have had an enormous impact on nuclear safety studies are the ones at the TMI in 1979 and Chernobyl in 1986 (69). Such studies, in addition to earlier ideas, have resulted in different perspectives on nuclear safety. Broadly, these different perspectives vary in their emphasis on technological, human, and organizational factors. The latter classes of factors are not much discussed in the literature on the future of nuclear energy, which has focused primarily on whether it is technically possible to build and operate reactors with greater levels of safety. However, the question that is posed by some policy makers and the public in many countries is not whether nuclear facilities *can* be safer but *will* they in fact be safer? The answer to the latter question depends strongly on human and organizational factors.

Engineering Safety

The approach that characterizes much of the literature on nuclear safety is what might be called the engineering reliability view. According to this view, there are essentially two routes to making a system safe. The first is to design the reactor in such a way that even if one of many potential accidents occurs, the reactor recovers, and the damage does not spread, even if no protective action, automatic or deliberate, is taken. The second way is to incorporate protective systems, preferably with redundancies, that mitigate the effects of an accident.

In order to ensure what it considers adequate dependability of protection, the engineering reliability view relies on what it calls "defense in depth." The idea is to build in many levels of safety to cope with random potential failures. These defense mechanisms would all have to fail if there is to be a major mishap. The literature typically identifies three levels of safety. The first level is the design of the reactor and its components. The second level refers to protection measures to halt or deal with component failures. The third level includes mitigation measures to limit the consequences of accidents. Thus, the first level represents the former route of making the system safe identified above, whereas the second and third levels fall into the latter route.

Recent reactor designs, those that have tried to incorporate the lessons of TMI and

[4]Since the early 1980s, the Nuclear Energy Agency of the OECD and the IAEA have been operating an incident reporting system wherein about 30 countries report safety-related events every year. Over 25 years of operation, it has gathered more than 3250 reports (68, p. 9).

Chernobyl, have largely, if not exclusively, focused on the first level of safety, primarily through the adoption of passive measures or components. A passive component operates without any external input, for example operators or equipment, to activate the function (70, p. 662). Reliance on passive as opposed to active safety is expected to make reactors less prone to failures of components, and thus render it safer. An additional reason is economics: "active safety systems are expensive to build and operate" (71). Some reactors that have emphasized these aspects are the AP600 design put out by Westinghouse, the PBMR designed by Westinghouse and Eskom (South Africa), the process inherent ultimate safety (PIUS) design from ABB Atom in Sweden, and the advanced heavy-water reactor of India's Department of Atomic Energy.

The term inherently safe has often been used in connection with these designs. But this is problematic because, although one can design a reactor to be safe against specific accident modes, safety for specific modes cannot guarantee safety against all possible accident modes. The PBMR, for example, might be immune to loss of coolant accidents but is susceptible to graphite fires if there is ingress of water or air into the core (72).

In 1987, the IAEA initiated an effort to carefully define safety terms related to nuclear plants, and a technical committee meeting was held in 1988 (70, p. 667). The final report of this committee argued, "Potential inherent hazards in a nuclear power plant include radioactive fission products and their associated decay heat, excess reactivity and its associated potential for power excursions, and energy releases due to high temperatures, high pressures and energetic chemical reactions. Elimination of all these hazards is required to make a nuclear power plant inherently safe. For practical power reactor sizes this appears to be impossible. Therefore the unqualified use of 'inherently safe' should be avoided for an entire nuclear power plant or its reactor" (73, p. 9).

Though they may still have some residual hazards, it is widely accepted that many newer designs are safer than existing ones. However, reactor designs that incorporate high levels of passive safety may come with tight manufacturing requirements or operational problems. The PIUS design, for example, might be susceptible to frequent shutdowns owing to slight perturbations (74, p. 222). Because restarting the reactor might take long periods, this would lower capacity factors. High-temperature gas-cooled designs like the PBMR will need high reliability of fuel manufacture; the number of microspheres that would have to be manufactured to high degrees of precision is roughly three orders of magnitude greater than the number of uranium fuel pellets needed to supply an LWR of the same capacity (72). How these and other construction-related issues will affect the economics of electricity from these reactors is not well explored.

Theoretical research on safety within the engineering reliability view has mostly been within the framework of probabilistic safety analysis (PSA) or probabilistic risk assessment (PRA). The first prominent application of PRA methodology to nuclear safety was in the 1975 reactor safety study led by Norman Rasmussen (75). Following widespread criticism of the study, and especially its executive summary, the U.S. Nuclear Regulatory Commission (NRC) appointed an outside panel to examine the Rasmussen study, which eventually submitted its report in 1978 (76). This panel broadly endorsed the PRA methodology, although it was critical of several aspects of the Rasmussen study—in particular its uncertainty analysis. The PRA methodology was eventually adopted by the NRC, which issued a requirement in 1988 to nuclear reactor owners to undertake individual plant examinations of safety, encouraging them to use PRA techniques (77).

Though widely used, PSA/PRA techniques suffer from several limitations (9, pp. 202–23). These can be divided into two categories: those related to the modeling of human actions and structural limitations. Another category that could be added is problems that arise from the widespread use of computer software (78).

PSA: probabilistic safety analysis

PRA: probabilistic risk assessment

NAT: Normal Accident Theory

Interactive complexity: different subsystems interacting with each other in difficult to comprehend ways

Tight coupling: different components linked together in time-dependent ways

Structural limitations relate to the way that PSA/PRA conceives of an accident, as resulting from a series of failures. Such chain-of-events models, it has been argued, cannot account for the indirect, nonlinear, and feedback relationships common for accidents in complex systems (79). It has been difficult, for example, to model common-cause, common-mode, and dependent failures (80). This is partly because such failures occur infrequently, thereby resulting in sparse data, and because failure mechanisms are often plant specific (81, appendix C.2). Finally, the most important problem may be that it is "conceptually impossible to be complete in a mathematical sense in the construction of event-trees and fault-trees," and this "inherent limitation means that any calculation using this methodology is always subject to revision and to doubt as to its completeness" (76, p. ix).

The modeling of human actions and their impact on known, let alone unknown, failure modes is a major challenge to PRA/PSA techniques. This is particularly difficult during abnormal events, which could be hard to comprehend and stressful. The panel, which examined the Rasmussen report, pointed out that there is much uncertainty in how operators and other plant employees behave during an accident, and their behavior could make the situation much better or much worse, i.e., it could lead to uncertainties in the consequences of accidents (76, p. 31). More than a decade after that report, one study that looked at "how human performance influences the risk associated with nuclear power plant operations" found that in the case of many events with safety significance, "contributing human performance factors" were "not explicitly modeled in... the current generation of PRAs, including the individual plant examinations" (82, p. 18).

Human actions and choices are involved not just in operating the reactor but even in conducting PSA studies. This was illustrated by the PSAs for two nearly identical Swedish reactors, Forsmark 3 and Oskarshamn 3, which were carried out by two different power companies and analysis teams. Starting with similar overall goals, both PSAs chose similar initiating events, but analyzed these quite differently, treated common-cause initiators in different ways, used different human error events and their probabilities, and so on, all of which in combination resulted in significantly different results (83).

Structural Factors and Normal Accidents

One stream of safety studies that resulted from analyzing the TMI accident has focused on the structural elements, which include both the design and operations involved in nuclear technology, that make it prone to accidents. The most influential work in this stream was Perrow's conceptualization of what happened at TMI as a "normal accident" whose origins lay in the structural characteristics of the system (84). Since then, Perrow's work has spurred an enormous range of analyses on a variety of different systems (85).

Normal Accident Theory (NAT) identifies two characteristics, interactive complexity and tight coupling, that make nuclear reactors and similar technologies prone to catastrophic accidents. Interactive complexity pertains to the potential for hidden and unexpected interactions between different parts of the system, and tight coupling refers to the time dependency of the system and the presence of strictly prescribed steps and invariant sequences in operation that cannot be changed. According to Perrow, these are inherent features of nuclear reactors, and there is a limit to how far they can be reduced through engineering efforts.

From this perspective, there are significant limitations in the engineering reliability view. First, because of the complexity, the physical conditions that obtain during the operation of a reactor may never be fully comprehended, and the understanding of the reactor that designers or operators have would always be partial.[5]

[5] One illustration is the unforeseen appearance of the hydrogen bubble within the core of the TMI reactor. Once formed,

Second, because system components and phenomena could interact in unanticipated ways, it is not possible to predict all possible failure modes. Whether the reactor is safe against unanticipated failures cannot be predicted in advance. An obvious corollary is that numerical estimates of probabilities of catastrophic accidents are uncertain. Third, because of the complexity and short timescales involved, operator actions may not seem erroneous until postfacto analysis has been performed.

Finally, NAT has advanced a very important criticism of the engineering reliability view by pointing out that redundancy may have unexpected consequences (86, 87). According to NAT theorists, redundancy often, if not always, adds to interactive complexity and produces unanticipated problems. Thus, systems that are added to increase safety might well end up undermining safety in hidden ways. The classic example of this occurred at the Fermi fast breeder reactor in Lagoona Beach, Michigan, where pieces of zirconium added to the "core catcher," a safety system that is supposed to prevent molten fuel from burning through the reactor vessel, broke off and blocked the entry of liquid sodium into a couple of fuel assemblies. These melted and caused the reactor to shut down.

NAT has also been subjected to several criticisms. One is that NAT is not quantitative because "whether or not organizations are subject to normal accidents is not a qualitative yes or no. . .[but] a question of degree" (88). However, there have been some recent efforts at trying to quantitatively test NAT (89, 90). Another criticism has been that NAT focuses only on redundancy as a way of improving safety and ignores the many alternative designs that improve safety without increasing complexity, such as substituting nonhazardous materials for hazardous ones and using color coding and male/female adapters to reduce wiring errors (79).

Within the NAT framework, many of the newer designs that emphasize passive safety and fewer components would likely be less susceptible to catastrophic accidents. Westinghouse's AP1000, for example, is said to have reductions in the numbers of valves and pumps of 60% and 35%, respectively (91). Although this would be seen as enhancing safety, the NAT framework would also be sceptical of Westinghouse's estimates of 4.2E-7/year and 3.7E-8/year of core melt and large release frequencies, respectively.

Safety Culture and Human Factors

Another stream of safety research puts less emphasis on structural factors and focuses more on human agency. The literature on the subject is vast, so only a fraction of it is discussed here. Though all of this is based on existing reactor designs, it would be applicable to future reactor designs as well.

One relatively prevalent notion in discussions of nuclear safety is that of safety culture, inspired largely by the role of operators in causing the Chernobyl accident (92). There is considerable confusion about the concept, and the term has been defined in multiple ways (93, 94). However, there are many shared attributes, which include responsibilities at both the individual and management levels. The International Nuclear Safety Advisory Group, for example, defines the term as "the personal dedication and accountability of all individuals engaged in any activity which has a bearing on the safety of nuclear power plants" (95). Related insights come from the human factors literature, which looks at the way the engineered and human parts of the nuclear system interact. Some of the issues that are of concern to this way of safety analysis are standard ergonomic issues (such as design of individual control panels, visual displays and workstations) and studies of human body sizes, skills, cognitive capacity, decision making, and also information processing and error (96). The goal is "to design systems that use human capabilities in appropriate ways, that protect systems from

there was considerable confusion, despite the engagement of the foremost experts in the field, about if and when there would be sufficient oxygen to allow for an explosion.

human frailties, and that protect humans from hazards associated with the system" (97).

HRO: High Reliability Organization

A particularly influential perspective within the ambit of safety culture that focuses on organizational requirements for safe operations of reactors and other hazardous facilities has been advanced by the High Reliability Organization (HRO) school (98–101). Although not dismissing the challenges posed by the structural features identified by NAT, the HRO theorists tried to explain what allowed some organizations to operate such technological facilities with what they felt was "an extraordinary level of safety and productive capacity" (100, p. 60). In other words, their task was to identify the factors that allowed the management of risky technologies with a relative degree of safety. On the basis of detailed field studies in high-performing organizations, they found a broad range of strategies that organizations use to enhance reliability in operations. The HRO group maintains, however, that they have only uncovered "conditions that were *necessary* for relatively safe and productive management of technologies" but do not wish to imply that "these conditions were *sufficient*" (102).

The ideal organizations of the HRO theorists have formal structures and clear and consistent goals that ensure reliable operations. The common ingredients that go toward safe operation include political elites and organization leaders placing a high priority on safety in design and operations; flexibility in decision making; support for constrained improvisation in responses; sustained efforts to improve, including rewards for the discovery of incipient error; redundancy in technical operations and personnel management so that failure on the part of one person or instrument would be compensated by another; and continuous organizational learning via systematic gleaning of feedback (86, 100, 101). Many of these characteristics are similar to the requirements laid out in the safety culture and human factors literature (for example 95, pp. 12–15) but with the difference that in the HRO literature these characteristics are typically based on practices observed in some specific organizations, whereas the latter tend to be prescriptions.

The nuclear industry has tried to incorporate some of the insights from the research focused on human factors and safety culture through peer technical reviews of operations at various nuclear stations, with the aim of transferring experience and knowledge about successful industry practices. Such reviews have been mostly carried out within the aegis of the IAEA and the World Association of Nuclear Operators, a group formed after the Chernobyl accident whose approach parallels that of U.S. domestic nuclear power utilities in 1983 in the wake of TMI, when the Institute for Nuclear Power Operations was founded (103).

At the same time, there is some evidence that operational practices are not easy to change. Operators almost never follow instructions and written procedures exactly, and "the violation of rules appears to be quite rational, given the actual workload and timing constraints under which the operators must do their job" (78, p. 245). Many attempts to improve the safety of a system "were compensated by people adapting to the change in an unpredicted way" (104, p. 184).

HEALTH AND ENVIRONMENT

There is an extensive literature on the health and environmental impacts of nuclear energy generation and other sources of power (for example, References 105–112). Summarizing this vast and rich material is well beyond the scope of this paper, and the focus here will be on relatively recent developments.

These impacts could be radiological or nonradiological and could result from routine operations or accidents. Although the nonradiological impacts are similar in nature to other forms of electricity generation, the radiological impacts are largely unique to nuclear power.[6] The

[6]There is some literature on the release of uranium from the burning of coal and its radiological impacts, but the doses from this pathway appear to be small compared to

health impacts from nuclear power-related operations can accrue to workers or to the public.

Chernobyl

Our understanding of the environmental and health impacts of a nuclear accident has improved significantly following numerous recent evaluations of the consequences of the Chernobyl accident (112–119). Inasmuch as the likelihood of a catastrophic accident is not zero even in future designs, the Chernobyl experience remains relevant.

The best-documented, unambiguous health impact of the Chernobyl accident has been a dramatic increase in thyroid cancers. According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), "the number of thyroid cancers (about 1800) in individuals exposed in childhood, in particular in the severely contaminated areas of the three affected countries, is considerably greater than expected based on previous knowledge" (112, p. 514). These "form the largest number of cancers of one type, caused by a single event on one date, ever recorded" (115).

The other health impact that has been widely studied is leukemia, especially among children and rescue workers. Some of these have observed an increased rate of leukemia (119–121), whereas others are indefinite. Many have emphasized that it is still too early to draw definitive conclusions, and more impacts will likely manifest themselves over the coming years (119, 122)

There has also been an acrimonious, but unsettled, debate on the numbers of deaths attributable to the accident and consequent radiation exposure. This reflects in part the intrinsic technical difficulties in calculating the number of cancers and other stochastic health effects induced by low-level radiation exposure. Furthermore, the increase in cancers owing to Chernobyl will be overwhelmed by a much larger number of baseline cancers induced by both natural and anthropogenic (other than radiation from Chernobyl) causes. Therefore, it is difficult to determine if the excess of cancers is merely a statistical fluctuation of the background or if it is caused by radiation exposure from the accident. Finally, there are political reasons that propel individuals and groups to drive up or diminish the magnitude of the numbers of deaths attributed to the accident.

In 2003, because of the ongoing controversy surrounding the impact of the nuclear disaster, the IAEA and other international organizations convened the Chernobyl Forum to "generate 'authoritative consensual statements' on the environmental consequences and health effects attributable to radiation exposure arising from the accident as well as to provide advice on environmental remediation and special health care programmes, and to suggest areas where further research is required" (123, Foreword). In September 2005, the Forum concluded that "the total number of people that could have died or could die in the future due to Chernobyl originated exposure over the lifetime of emergency workers and residents of most contaminated areas is estimated to be around 4000" (116, p. 10). The reception of this conclusion was far from consensual (124).

The main problem with the Forum's report is their focus on just the most heavily exposed areas in Belarus, Ukraine, and the Russian Federation, which ignores the much larger populations in these countries themselves and the rest of the world, where people have been exposed to lower levels of radiation from Chernobyl. The effect of this narrow geographical focus can be estimated as follows. There is strong evidence that exposure to radiation, even at low levels, does result in a statistically increased number of health effects of various kinds, particularly cancers (112, 125). In 1993, UNSCEAR estimated that the collective radiation dose from Chernobyl to the entire world is 600,000 person Sieverts (109, p. 23).[7] The risk from

background levels of radiation as well as the potential doses from the nuclear fuel chain (108).

[7]More recent UNSCEAR volumes, including the 2000 volume, which focused on the Chernobyl accident, have not revisited this estimate (112).

radiation exposure as estimated by the U.S. National Academy of Sciences Committee on the Biological Effects of Ionizing Radiation (BEIR Committee) in 2006 is 0.057 cancer deaths per Sievert (125). Using this figure, the number of deaths can be estimated at about 34,000, albeit over a long period of time. This rough estimate is consistent with estimates of cancers in Europe in the long term (118), and much larger than the estimate of 4000 fatal cancers in Reference 116.

The noncancer problems that have arguably had the widest impact are the social and psychological traumas that the inhabitants of the large contaminated area surrounding the reactor are going through (112, Annex J). This is a result of the "complex web of events and long-term difficulties, such as massive relocation, loss of economic stability, and long-term threats to health in current and, possibly, future generations," unleashed by Chernobyl, "that resulted in an increased sense of anomie and diminished sense of physical and emotional balance" (117, p. 95).

Among the long-term environmental consequences, the main impact comes from the contamination of large areas of land with various radionuclides. Although "radioactive contamination of the ground was found to some extent in practically every country of the northern hemisphere," it is only those areas where the average cesium-137 deposition densities exceeded 37,000 becquerels per meter^2 (or 1 curie per kilometer^2) that is usually defined as contaminated (112, p. 458).[8] In the three most contaminated countries, Belarus, Russian Federation, and Ukraine, this area is over 146,110 km^2.

Health Impacts from Routine Operations

All countries with nuclear facilities have regulations that govern how much radiation can be released by these facilities, which are based on limiting the radiation dose that would accrue to any person living in the vicinity. In addition, they have rules limiting the nonradioactive pollutants discharged by the facilities. On the basis of the general current understanding of radiation and other pollutants, these regulations are expected to keep the risk of health impacts to a low level. For example, radiation limits are usually set to be 1 milliSievert per person per year, which is expected to lead to an increased cancer risk to the exposed individual of about 0.005% per year.

At the same time, there have been several epidemiological studies that claim to demonstrate increased risk of various diseases, especially cancers, among people who live near nuclear facilities. Among recent studies, a widely cited meta-analysis of 17 research papers covering 136 nuclear sites in the United Kingdom, Canada, France, United States, Germany, Japan, and Spain offered evidence of elevated leukemia rates among children living near nuclear facilities (126). Elevated leukemia rates among children were also found in a recent study that examined areas around all 16 major nuclear power plants in Germany (127). These are not consistent with many earlier studies that have tended not to show such associations (112, pp. 346–51). But no credible alternate explanations for the recent findings have so far emerged.

Nuclear Waste

Perhaps the environmental issue linked to nuclear power that has evoked the greatest public concern is that of long-lived radioactive waste. The political and social challenges that confront methods of dealing with nuclear waste have eclipsed the scientific and engineering ones and have been the primary focus of most recent efforts.

There is wide acceptance within the nuclear industry that geological disposal of long-lived high-level radioactive waste is "technically feasible" (128, p. 7).[9] However, as has been pointed

[8]Cesium-137 is chosen as a measure of ground contamination because of its substantial contribution to the lifetime effective dose, its long radioactive half-life of about 30 years, and its ease of measurement.

[9]There are concerns relating to other forms of nuclear waste, but high-level waste continues to be the most contentious issue.

out in the case of the United States, "technically tractable [does] not mean that it is necessarily politically tractable" (129, p. 252). Thus, even though the concept of a geological repository was proposed in the 1950s, and the U.S. Congress mandated in 1987 that a geological repository be built and licensed under Yucca Mountain, Nevada, by 1998, an application for a license was submitted only in 2008. This failure has been attributed to "technical difficulties, poor management, scientific uncertainties, cost overruns, equivocal political support, state opposition, and profound public distrust and antipathy" (130, p. 110). Some of the problems may be specific to the site, though, and it has been argued that "the disposal of high-level nuclear waste at Yucca Mountain is based on an unsound engineering strategy and poor use of [the] present understanding of the properties of spent nuclear fuel" (131, p. 660).

One recent technical effort to deal with the waste disposal problem in the United States is the U.S. Department of Energy's Global Nuclear Energy Partnership (GNEP) plan, which envisioned the construction of many fast-neutron reactors to fission the recovered plutonium and other transuranic elements. The goal is to lower the amount of material that would have to be stored in a geological repository. But even at the conceptual stage, GNEP's proposals have been widely criticized (for example, References 132–134); similar proposals in the past have also been found to be very expensive (63). Returning to such failed proposals suggests that the political challenge involved in setting up geological repositories is viewed as so great that it is better to postpone selecting a new site, even if the delay results in great expense.

The experience in the United States has prompted many other countries to go slower in their efforts to set up geological repositories. Not wanting to deal with a contentious issue before it is absolutely necessary, at least some countries appear to be waiting in the hope that the experience of constructing one or more successful repositories elsewhere could be used to deal with their domestic political and environmental opposition. Other countries have realized the importance of public acceptance and initiated site selection processes that include significant public stakeholder involvement (128).

In Canada, for example, the Environmental Assessment Agency, after a series of formal public hearings conducted in 1997, concluded that, although the waste disposal concept advocated by Atomic Energy Canada Limited (AECL) was technically sound, it did not have widespread public acceptability and "recommended that additional steps be taken, with an emphasis on comprehensive public participation within a framework of ethical and social assessment" (135, p. 215). As a result, various Canadian nuclear utilities set up the Nuclear Waste Management Organization (NWMO) in 2002. The NWMO asserts that it "is committed to developing and implementing a siting process collaboratively with potentially impacted communities of interest" and that "based on experience in Canada and other countries, the NWMO expects a voluntary siting process to be successful" (136). Six years later, as of December 2008, no site has been identified.

Although there is much expectation, as with the NWMO, that voluntary siting might provide a political solution to nuclear waste disposal, evidence for that expectation is limited. For example, the U.S. effort to store high-level waste in a temporary Monitored Retrievable Storage (MRS) facility on lands belonging to Native Americans encountered many problems, including issues of liability, intracommunity conflict, and lack of trust (137). The "most fundamental obstacle" identified was "a lack of interest in problem solving" because the host communities and the "vast majority of Americans do not feel a personal responsibility toward solving the high-level waste problem and see no compelling reason to host an MRS facility" (137, p. 257).

Climate Change

One environmental issue related to nuclear power that has witnessed intense debate in recent years is whether it can be a solution to climate change. Many have argued that an expansion of nuclear power would help combat climate change (138–140). Others have merely pointed out that it is one way to reduce emissions, but it comes with its own problems (141). A number of analysts have argued that an expansion of nuclear power would lead to unacceptable risks related to catastrophic accidents and the proliferation of nuclear weapons and nuclear terrorism, as well as to the challenges of more waste disposal (9, 10, 23). Others have argued that there are far better ways of dealing with climate change than investing in nuclear power, including the improved efficiency of energy use and greater reliance on decentralized and renewable energy sources (142).

At a different level, some have argued that nuclear power cannot be guaranteed to reduce emissions because the technology is an expensive source of energy services and can only attain economic viability in a society that relies on high levels of energy use (143). Nuclear power tends to require and promote supply-oriented energy policies and energy-intensive development paths, a paradigm that drives climate change. Societies organized in a fashion consistent with these demands will unavoidably increase fossil fuel use alongside the expanded use of nuclear power (143). As evidence, they point to large increases in carbon emissions in countries, such as Japan and South Korea, even as they increased their nuclear capacity rapidly. Others have likewise argued that it is not possible to simultaneously support centralized generation and expect the growth of a large-scale decentralized and renewable electricity generation system that many see as necessary to combat climate change (144).

On a more narrow, technical level, there has also been a debate on the quantity of greenhouse gas emissions from the complete nuclear fuel chain. Various studies have led to a large range of estimates. These studies include emissions attributed to uranium mining, enrichment, transport, and waste disposal as well as those from construction, operation, and decommissioning of reactors. The estimates vary by over two orders of magnitude, from 1.4 to 200 g CO_2/kWh (145, p. 2951). The range reflects multiple factors, including those considered and left out, assumptions are made about the energy inputs into different steps, and the kind of uranium that is mined.

Some of the low estimates were not comprehensive or used assumptions that were specific to particular countries. For example, a widely cited estimate from Vattenfall, a Swedish utility, assumed the use of almost fossil fuel–free electricity (51% hydroelectric plus 43% nuclear) in their estimates of emissions from upstream and downstream activities (146, p. 2553). The high estimates are usually associated with very poor quality (i.e., very low grades) of uranium ore. Neither of these extremes is likely to be the case everywhere in the near- to midterm future.

More recently, a few studies have compared different earlier estimates, sometimes with their own analyses of specific steps in the chain (147). These suggest life cycle emissions of somewhere between 16 to 70 g CO_2 per kWh, which will decrease significantly as centrifuge technology fully replaces gaseous diffusion for uranium enrichment, a likely prospect in the foreseeable future. In comparison, the life cycle emissions of coal, hydroelectric, and wind power are 790 to 1020, 17 to 22, and 4.2 to 11.1 g CO_2 per kWh, respectively (147).

CONCLUSIONS

Prospects for a global expansion of nuclear power are confronted with a number of challenges in the near term. Three key ones reviewed here are the costs of nuclear electricity generation, the risks of a catastrophic accident, and dealing with radioactive waste. One that we have not considered here is the association with nuclear weapons proliferation.

The economics of nuclear power continues to be a key constraint to its expansion. There is much uncertainty about how much it would cost and how long it may take to construct new nuclear reactors, but it is fairly clear that it will be expensive in the near term. The history of cost and time overruns with nuclear facilities continues with recent additions, such as the

Olkiluoto-3 reactor. Nuclear power also faces several types of financial risk, all of which are compounded by uncertainty in reactor construction costs and schedules. In many countries, these uncertainties have led to a situation where electric utilities and other agencies have not started on new nuclear construction, although they have continued to consider it as a potential option. There is relatively greater consensus on the economics of the back end of the fuel chain, and many studies have shown that reprocessing of spent nuclear fuel is more expensive compared to direct disposal.

A second concern is the safety of nuclear facilities. This has led to the development of several new reactor designs emphasizing passive safety, which are widely considered to have lower risks of accidents. Even for them, however, there is some likelihood of an accident. According to some theoretical perspectives on safety, this likelihood cannot be reliably estimated, and major accidents will continue to be a normal part of operations. Other perspectives have highlighted the many organizational steps and individual practices that could lower the risk of accidents owing to the actions of operators and other personnel associated with nuclear plants. The question that remains is how to ensure that such organization and individual practices are put in place everywhere.[10] The demanding nature of continuously ensuring safe operations even in just one facility has been highlighted by HRO theorists. On top of this, it is found that operating procedures vary even between identically designed plants, not to mention country to country. Thus, theoretical perspectives on safety and accidents suggest that ensuring an adequate safety culture all around the world is a highly daunting challenge.

The disposal of nuclear waste continues to face social and political difficulties everywhere. The countries that have made the most progress have typically started with public consultations and made voluntary siting a necessary condition. Although this consensus seeking mode is believed to have a greater chance of success than top-down modes of decision making, the process is necessarily slow, and there is inadequate experience around the world to know if it will succeed in all existing and aspiring nuclear nations.

SUMMARY POINTS

1. The economics of nuclear power, primarily determined by the construction costs of reactors, has been a key barrier. High construction costs are compounded by uncertainty and resultant financial risk.
2. Reprocessing of spent fuel is more expensive than direct disposal until uranium prices grow severalfold, even when the separated plutonium is used to fuel light-water or breeder reactors.
3. The use of passive safety mechanisms in nuclear reactors is expected to lower the risk of accidents, though residual hazards remain. Due to various structural characteristics of nuclear technology identified by Normal Accident theorists, the risk of catastrophic accidents will continue.
4. High Reliability Organization theorists have identified a number of demanding requirements that are necessary, though not sufficient, for nuclear facilities to be relatively safe. Getting organizations to adopt safer operating procedures will remain a challenge.

[10]The importance of doing so is emphasized in an old adage in the nuclear industry, "an accident anywhere is an accident everywhere."

5. The best documented health impact of the Chernobyl accident is a dramatic increase in thyroid cancers. The total number of deaths attributable to the accident continues to be debated.
6. Getting local communities to accept a geological repository for nuclear waste in their neighborhood remains a challenge.
7. There has been intense but unsettled debate in recent years about whether nuclear power could be a solution to climate change.

FUTURE ISSUES

1. There are reasons to expect both a reduction (for example, increased use of passive safety) and an increase (for example, increases in raw material prices) in the cost of construction of Generation-III and -III+ reactors. Construction experience could show which of these will dominate.
2. Though widely used, PSA/PRA techniques continue to face structural limitations and find the modeling of human actions difficult. The implications of the widespread use of computer software for safety remains to be explored in detail.
3. Studies of safety practices and culture in nuclear facilities, especially in countries other than the United States and Western Europe, are need to study questions such as how operators and managers have reacted to accidents and near misses, what acts of omission or commission have been undertaken prior to these accidents that may have played a role in triggering or furthering the accidents, and safety perspectives among different levels of the organization.
4. Many countries and organizations have promoted greater stakeholder participation to promote public acceptance of nuclear waste disposal sites. There is little research on whether such efforts do persuade reluctant members of the public to accept nuclear waste–related facilities near their homes.
5. The question of whether nuclear power will synergize with or inhibit other proposed solutions to climate change, such as increased use of decentralized, renewable sources of power or dramatic improvements in energy efficiency, has not been explored adequately.

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Annual Review of Environment and Resources

Volume 34, 2009

Contents

III. Management, Guidance, and Governance of Resources and Environment

Indexes

Errata

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