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Nuclear power: Status report and future prospects

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HIGHLIGHTS

- Current status of nuclear reactor safety and security is judged to be adequate.
- Strong management and safety culture are vital to achieve adequate nuclear safety.
- Advanced reactor designs offer important safety advantages.
- Maintaining and strengthening international nuclear institutions is important.
- Achieving nuclear safety in "newcomer" countries requires a strong political culture.

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ABSTRACT

This article reviews the current status and future prospects of commercial nuclear electric power, with emphasis on issues of safety, physical security, proliferation, and economics. Discussions of these issues are presented separately for the current operating fleet, for new reactor designs similar in size to the current fleet, and for prospective new reactors of substantially smaller size. This article also discusses the issue of expansion of commercial nuclear power into new countries. The article concludes with recommendations, related both to technical issues and policy considerations. The major implications for policy are that although the level of safety and security achieved in today's operating reactor fleet worldwide is considered broadly acceptable, some advanced designs now under development potentially offer demonstrably safer performance, and may offer improved financial performance also. Management and safety culture are vital attributes for achieving adequate safety and security, as are a strong political culture that includes an absence of corruption, an independent regulatory authority, and a separation of nuclear operation from day-to-day politics. In some countries that are now considering a nuclear-power program for the first time, careful attention to these attributes will be essential for success.

1. Introduction

The scope of this article includes a review of the current status and future prospects of commercial nuclear electric power, with emphasis on issues of safety, physical security, proliferation, and economics. (Issues related to radioactive waste are outside of the scope here, because this article focuses on reactor safety. However, it is important to note that the challenges of safely handling and disposing radioactive waste strongly influence public opinion.)

Among the reasons why this review concentrating on nuclear-power safety is timely are the continuing public concerns about safety after the 2011 Fukushima accident in Japan, the potential for rapid growth in nuclear power in some countries that have not used nuclear power before, and the fact that nuclear power represents a low-carbon source of electricity.

Discussions of these issues are presented separately for the current operating fleet, for new reactor designs similar in size to the current fleet, and for prospective new reactors of substantially smaller size. This article also discusses the issue of expansion of commercial nuclear power into new countries. The article concludes with recommendations, related both to technical issues and policy considerations.

2. Reactor safety

The fundamental issue that makes nuclear power reactor installations different from other industrial undertakings is, of course, the possibility that a major accident could release large amounts of radioactivity into the environment, endangering offsite populations and contaminating offsite land and property, possibly

Abbreviations: HEU, Highly Enriched Uranium; IAEA, International Atomic Energy Agency; LWR, Light-Water Reactor; NEA, Nuclear Energy Agency; NPT, Non-Proliferation Treaty; SMR, Small Modular Reactor

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for a long time. As the world saw with the accident at Fukushima in Japan in 2011, this is a real possibility, even in the most advanced countries, and not merely a threat confined to countries with lesser technological prowess.

2.1. The likelihood of accidents

What do we know now about the likelihood of such accidents? The answer is that we know considerably more than was known two or three decades ago. We understand the origins of these accidents, we understand the variety of ways in which they might progress, and we can estimate the likelihood and the consequences of the many different accident scenarios (NRC, 1983). The advances in our analysis methods, and in the collection and use of the operating data needed to support them, have been remarkable world-wide in recent years (ASME-ANS, 2013).

We analyse "safety" by working out, in as realistic a way as we can, the likelihood per year that a large accident might occur. We now have methods that enable us to perform such an analysis, which is intrinsically probabilistic in character, and these analyses are now done routinely around the world (IAEA, 2001, 2010). The community has settled on two different figures-of-merit, one being the annual frequency that a reactor will suffer a core-damage accident, and the other the annual frequency of a so-called "large" release of radioactivity, defined as sufficient to cause prompt radiation-induced fatalities offsite.

Based on what we know today, the annual frequency of core damage of one of the reactors in the worldwide power-reactor operating fleet is estimated to be, on average, in the range of around a few times 10^{-5} per reactor-year (NRC, 1997). This is a typical value, mostly derived from studies of large light-water reactors (LWRs) but also thought to be applicable to the many non-LWR power reactors operating worldwide today. The value varies considerably from one to the next reactor even for similar or identical designs in the same country or operated by the same company, and it is known only within a factor of three or so, or even less well, depending on the analyst and the design. However, based on what we know, the worldwide average is believed to be in the range just cited (IAEA, 2001). The likelihood that any such accident will progress to a large release is small, perhaps in the range of a few percent to ten percent (NRC, 1990). This means that the frequency of a large release of radioactivity is likely in the range at or above $\sim 10^{-6}$ per reactor-year or so, as a worldwide average.

There is ample evidence, based on objective assessments of many different indicators, that the general safety performance of today's operating fleet has substantially improved over the last 15–20 years (NRC, 2015). This is a worldwide trend. The indicators include rates of initiating events that might cause an accident if not mitigated, failure rates of vital safety equipment, rates and severity of operator and maintenance errors, major improvements in fire protection, and changes in the designs to provide better safety-system backup and reliability. Another significant improvement has been the worldwide sharing of operating experience and a diligent effort worldwide to learn from that experience. Although the improvements vary from plant to plant, they have occurred worldwide (WANO, 2014).

Whether today's performance is adequately safe will not be addressed here. This is both an individual judgment that people make differently and a societal judgment made differently by different countries. Because the consequences of a major nuclear power-plant accident can be very large, especially in terms of contaminated land and property and disrupted economic activity, the societal judgment about acceptability is complicated, even though the likelihood of a large accident may be quite low. Thorough risk-based assessments, including assessing risks associated with alternative non-nuclear sources of energy, are to be encouraged.

2.2. The importance of management

There is a vital caveat that must be discussed, of course. Like any technology, nuclear-power technology can be mismanaged, and a major accident could occur at any time. (As an example taken from a different technology, consider the fact that for a passenger flying today on a commercial airliner, the safety performance is 30–100 times better on average than it was 40 years ago, and incontrovertibly so. But a plane crash could occur on any day. Yet if it did, even though it would a tragedy, it would not contravene the strong evidence that commercial flight is indeed much safer on average than it was decades ago.).

So it is too with nuclear power reactors: If the worldwide performance is in the range of a few times 10^{-5} per reactor-year, and if there are close to 450 reactors today, one such core-damaging event might occur on average every several decades. Yet one could occur tomorrow. Crucially, what worries the reactor safety community is that if a major error of some kind were made, as happened in Japan with the decision to place the Fukushima reactors at a tsunami-vulnerable site without adequate protection, the likelihood of an accident would be higher. Another concern (see below) is the deployment of reactors in countries, especially developing countries, that have never deployed nuclear power technology before. What to do?

It is important to note that we do know how to achieve a safety level like the above. A few vital attributes of the enterprise must all be present: (a) We must incorporate the appropriate safety features in all existing reactors, including improvements in equipment reliability and in the training of operators; (b) we must apply all lessons learned from operating experience worldwide; (c) we must emphasize safety culture everywhere; (d) we must remain attentive to aging issues, including equipment aging, staff aging, and institutional fossilization; (e) we must maintain the morale of staff, taking care to infuse the enterprise with a generational "mix" that includes both experience and youth; and (f) crucially, we must maintain and reinforce a vigorous and independent regulatory agency in every country, enhanced to the maximum extent possible by a strong international framework for establishing high safety standards, provision for technical assistance and peer reviews of design and operational safety, and sharing and disseminating lessons learned and best-practices experience.

If the above attributes are all present and attention is paid to maintaining each of them, the existing worldwide operating reactor fleet can continue to achieve the safety performance noted above. This is true not only for the light-water power reactors (LWRs) that comprise the bulk of today's operating fleet, but also for the others operating today: the heavy-water reactors, the gas reactors, and the Russian water-graphite reactors – but only if "operated well."

2.3. Limitations in today's operating LWR reactor designs

Why can't we achieve better safety performance with the existing large LWR reactors? Based on our understanding of the design of the existing large LWR reactors and of how they are operated, certain limitations seem to make it difficult to achieve, say, an order of magnitude better fleet average than the above. These limitations involve the way the designs call on safety equipment when in trouble, the reliability of the equipment, the way operators are relied on, and the interplay among these factors (NRC, 1990). These also apply broadly to the non-LWR power reactors operating worldwide today (WANO, 2014).