Design and Siting Criteria for Nuclear Power Plants

in the 21st Century

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Abstract

The Canadian Nuclear Safety Commission (CNSC) has published draft documents providing guidance on the design and siting of new nuclear power plants. Those documents are reviewed here, together with analogous documents published by the International Atomic Energy Agency (IAEA). The IAEA documents provided templates for the CNSC documents. To provide a standard for assessing the CNSC and IAEA documents, this report discusses principles for the sustainability of engineered systems, and the application of those principles to commercial nuclear power. Review of the CNSC and IAEA documents shows that they reflect an obsolete paradigm of risk, deriving from fundamental weaknesses in the design of present nuclear power plants. The documents are not compatible with principles of sustainability that are widely recognized as imperatives for the 21st century, including the precautionary principle. As an alternative to the guidance set forth in the CNSC and IAEA documents, criteria for the design and siting of nuclear power plants are proposed here, focusing on the potential for an unplanned release of radioactive material. The proposed criteria provide a point of departure for public processes that could yield final criteria.

About the Institute for Resource and Security Studies

The Institute for Resource and Security Studies (IRSS) is an independent, nonprofit, Massachusetts corporation, founded in 1984. Its objective is to promote sustainable use of natural resources and global human security. In pursuit of that mission, IRSS conducts technical and policy analysis, public education, and field programs. IRSS projects always reflect a concern for practical solutions to resource and security problems.

About the Author

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Contents

Tables appear at the end of the report, as follows:

1. Introduction

This report has three purposes. First, it comments on two draft regulatory documents published by the Canadian Nuclear Safety Commission (CNSC), on the design and siting of new nuclear power plants.[1] Second, it comments on two analogous documents published by the International Atomic Energy Agency (IAEA). The IAEA documents provided templates for the CNSC documents. Third, it discusses principles for the sustainability of engineered systems, and the application of those principles to commercial nuclear power. These three purposes are inter-connected. The CNSC and IAEA documents reflect a shared paradigm. The principles of sustainability provide a basis to assess the adequacy of that paradigm.

The two CNSC draft documents are RD-337, *Design of New Nuclear Power Plants*, and RD-346, *Site Evaluation for New Nuclear Power Plants*.[2] The two IAEA documents are in the IAEA Safety Standards Series. They are NS-R-1, *Safety of Nuclear Power Plants: Design*, and NS-R-3, *Site Evaluation for Nuclear Installations*.[3]

Sustainability of engineered systems is a large subject.[4] Indeed, developing, refining and applying the principles of sustainability are likely to be major preoccupations of humanity throughout the 21st century. This report does not claim to provide a comprehensive discussion of the principles of sustainability. That task would require a much larger effort. Moreover, the principles of sustainability are evolving. There is no generally accepted, overall framework of sustainability principles, and no prospect of such a framework emerging soon. Yet, there is consensus among governments and international agencies that any new, large, long-lived engineered system should be designed according to sustainability principles. A new nuclear power plant would certainly be a large and long-lived system. The plant could require a decade to plan and build, and could then operate for five or more decades. Therefore, if construction of a nuclear power plant is to commence during the next decade, the plant's design must reflect the sustainability standards of the second and third quarters of the 21st century, to the extent that these can be predicted now.

The role of nuclear power in the 21st century is, like sustainability, a large subject. This report does not claim to provide a comprehensive discussion of the subject. Nevertheless, the CNSC and IAEA documents that are mentioned above cannot be properly reviewed without considering their context. These documents could have a major influence on the design of nuclear power plants constructed during the next few decades. Thus, in commenting on the CNSC and IAEA documents, this report necessarily provides a brief discussion of the overall compatibility of nuclear power with principles of sustainability.

SCENARIOS FOR FUTURE USE OF NUCLEAR POWER

Nuclear power is in a transitional phase. Annual, worldwide capacity additions peaked in 1985 and have been modest since 1990.[5] If construction of nuclear power plants does not resume, total capacity will decline as plants are retired. Observers view this situation in widely differing ways. Some call for a nuclear power «renaissance» in which nuclear generating capacity rises substantially. Others prefer or expect a scenario in which nuclear capacity declines, leading to eventual disappearance of the industry.

The most ambitious visions of the nuclear renaissance are exemplified by a «technology roadmap» issued under the auspices of the US Department of Energy in 2002.[6] The roadmap proposed the development and use of a range of «Generation IV» reactors that would push against engineering limits in a variety of respects. Some reactor types would produce hydrogen as well as electricity, thereby providing fuel for use in vehicles and other applications. Reactors would be deployed in such large numbers that uranium reserves would become depleted during the latter part of the 21st century. To prepare for that eventuality, large-scale reprocessing would begin during the next few decades, and breeder reactors would be deployed beginning in about 2030.

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[1] Throughout this report, the term «nuclear power plant» means a fission reactor and its associated equipment, including equipment to produce electricity, hydrogen, and/or process heat.

[2] CNSC, 2007a; CNSC, 2007b.

[3] IAEA, 2000; IAEA, 2003.

[4] The term «engineered system» is used in this report to describe a system that is deliberately created or assembled by humans to serve specified functions.

[5] IAEA, 2006a.

[6] NERAC/GIF, 2002.

A less extreme but still highly ambitious vision of the nuclear renaissance is contained in a study published under the auspices of Massachusetts Institute of Technology in 2003.[7] The authors saw no need for reprocessing or breeder reactors during at least the next 50 years. They offered an illustrative scenario for expansion of nuclear capacity using «Generation III» reactors whose designs would involve a comparatively small evolutionary step from the designs of present reactors. In the scenario, annual worldwide production of nuclear-generated electricity would rise by a factor of 4 to 6 between 2000 and 2050.

Many observers doubt the merits of nuclear power, and seek or expect a decline in its use. Some argue that nuclear power can and should be phased out, even during an effort to dramatically reduce greenhouse gas emissions from electricity generation.[8] Others argue that scenarios for expansion of nuclear capacity are fanciful, and that the commercial nuclear industry is in terminal decline.[9]

This report does not predict or recommend any scenario for the future use of nuclear power. Instead, it examines nuclear power through the lens of sustainability, and articulates nuclear power plant design criteria that are consistent with the principles of sustainability. Any new, large, long-lived engineered system should be designed according to universal principles of sustainability. Advocates of a nuclear renaissance must show that nuclear power can comply with that requirement. If nuclear power cannot comply, then it has no useful role.

SCOPE OF THIS REPORT

As discussed above, this report provides brief, limited discussion of two large subjects – the principles of sustainability, and the role of nuclear power in the 21st century. A thorough examination of both subjects, and their inter-connections, would involve two major tasks. First, a comprehensive framework of sustainability principles, indicators and criteria would be developed, to the point where it could be used to assess the sustainability of any proposed engineered system. Second, that framework would be used to assess a proposed program of nuclear power, examining the entire nuclear fuel cycle from uranium mining through to plant decommissioning and disposal of radioactive waste.

Those tasks are not undertaken here. As an indication of the scale of effort that those tasks could require, consider a research project that is being conducted in the UK. In September 2007, a team of researchers based at the University of Manchester began a three-year project funded by a grant of 2.1 million UK pounds from the Engineering and Physical Sciences Research Council, with the objective of performing an integrated assessment of the sustainability of nuclear power.[10] The project involves tasks similar to the two described above, although the sustainability framework to be developed at Manchester will be less comprehensive because it will apply to energy options rather than engineered systems in general. If the project is well run, it will produce interesting results. It will not, however, provide the final word on the complex subjects that it addresses. Research and debate on these subjects will continue for many years.

Here, a brief discussion of the sustainability of nuclear power provides a basis for reviewing the CNSC and IAEA documents on plant design and siting.[11] Those documents reflect a shared paradigm that gives no explicit recognition to principles of sustainability. Thus, one does not need a comprehensive framework of sustainability principles in order to assess the documents. After assessing the CNSC and IAEA documents, this report proposes some design and siting criteria that do reflect sustainability principles and could be used instead of the guidance set forth by CNSC and IAEA. Our proposed criteria focus on the potential for an unplanned release of radioactive material from a nuclear power plant. That is not the only sustainability issue related to plant design, but it is an issue with a high public profile, and it is the primary focus of the CNSC and IAEA documents. The criteria that are proposed here are intended to provide a point of departure for public processes that yield final criteria. Important features of such processes are described here.

STRUCTURE OF THIS REPORT

The remainder of this report has six sections. Section 2 discusses sustainability and nuclear power. Drawing upon that discussion, IAEA and CNSC documents are reviewed in Section 3. Then, Section 4 sets forth proposed criteria for design and siting of nuclear power plants. Section 5 discusses public processes for finalizing those criteria. Conclusions and recommendations appear in Section 6, and a bibliography is provided in Section 7. All documents cited in this report are listed in the bibliography. Tables, numbered according to the relevant section of the report, appear at the end of the report.

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[7] Ansolabehere et al, 2003.

[8] Makhijani, 2007; Greenpeace International, 2007.

[9] Schneider and Froggatt, 2007.

[10] EPSRC, 2007.

[11] CNSC, 2007a; CNSC, 2007b; IAEA, 2000; IAEA, 2003.

2. Sustainability and Nuclear Power

2.1 Imperatives and Principles of Sustainability

During recent decades, citizens and governments have increasingly recognized the need to organize human affairs within the context of a finite Earth. One manifestation of that need is human-induced, adverse change in the climate.[12] Other signs of stressed ecosystems are also evident. The Millennium Ecosystem Assessment determined that 15 out of the 24 ecosystem services that it examined «are being degraded or used unsustainably, including fresh water, capture fisheries, air and water purification, and the regulation of regional and local climate, natural hazards, and pests».[13] By abusing ecosystems in this manner, we deplete renewable resources that are essential to human life. Non-renewable resources are also being depleted. For example, a growing body of analysis predicts a peak in world oil production within the next few decades.[14]

In our well-populated, competitive world, limits to the availability of resources and ecosystem services have implications for peace and security. For example, analysts are considering the potential for climate change to promote, through its adverse impacts, social disorder and violence.[15] It is increasingly evident that nations must cooperate to protect and share the Earth's resources. International agreements such as the Framework Convention on Climate Change reflect that imperative. National policies on a range of issues – including energy, agriculture, forestry, transport, minerals, and urban planning – must be consistent with global needs.

Policy choices made now will determine the opportunities available to future generations. The future implications of current policy choices have been examined by analysts convened by the Stockholm Environment Institute (SEI).[16] These analysts identified six possible worldwide scenarios for human civilization over the coming century and beyond. In some scenarios, the world faces chronic, unresolved problems and conflicts. In others, the world descends into barbarism. The most attractive scenario, with the greatest opportunities for future generations, is one that the SEI analysts described as a New Sustainability Paradigm.

The concept of sustainability was brought to wide public attention by the World Commission on Environment and Development (WCED), in 1987. WCED discussed the concept in terms of «sustainable development», to emphasize that sustainability is compatible with improvement in the conditions of life for poorer societies. Since 1987, the concept of sustainability has been widely endorsed by governments and other entities. Yet, there has been comparatively little progress in making the concept operational at the level of specific policies and plans. In an effort to address that problem, the Organization for Economic Cooperation and Development (OECD) initiated a three-year project in 1998, seeking to identify sustainability principles and indicators that can be used in policy making. One product of the effort was a report by the OECD Nuclear Energy Agency (NEA), published in 2000, that discussed commercial nuclear power in the context of sustainable development.[17]

THE NEA VIEW OF SUSTAINABILITY

In discussing the concept of sustainability, the NEA report took as its starting point the WCED definition of sustainable development as «development that meets the needs of the present without compromising the ability of future generations to meet their own needs». The NEA report elaborated on that definition by suggesting that sustainability involves the passing on to future generations of a stock of capital assets, which could be human-made, natural, or human and social. Human-made assets include buildings, machinery, and infrastructure. Natural assets include the environment, and the renewable and non-renewable resources that it can supply. Human and social assets include education, health, scientific and technical knowledge, cultures, institutions, and social networks.

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[12] IPCC, 2007.
[13] MEA, 2005, page 1.
[14] GAO, 2007.
[15] Campbell et al, 2007.
[16] Raskin et al, 2002.
[17] NEA, 2000.

According to the NEA, «strong sustainability» involves the preservation of an asset in its present form. That approach is relevant, for example, to ecosystems that are essential and irreplaceable. Earth's atmosphere fits that category. An alternative approach is «weak sustainability», whereby the loss of one asset (e.g., an area of forested land) is offset by creation of another asset (e.g., development of a city on the formerly forested land). The weak-sustainability approach requires tradeoffs, which create the potential for conflicts within and between generations. The strong-sustainability approach is conceptually simpler, but is rarely encountered in its pure form. For example, human-induced emissions of CO_2 to the atmosphere cannot be eliminated instantly, but must be reduced over time. With the best of intentions, we cannot pass on to coming generations an atmosphere containing CO_2 at the present concentration.

The NEA report contained a general discussion of nuclear power from the perspective of sustainability. That discussion addressed many of the relevant issues, including emissions of CO_2 and other greenhouse gases. The NEA report did not, however, provide an analytic framework that could be used to assess the sustainability of a proposed program of nuclear power, or to compare the sustainability of that program and the sustainability of other strategies to meet energy needs.

The NEA report discussed the potential for a nuclear power plant to experience a large, unplanned release of radioactive material to the environment. Such a release would substantially degrade human-made, natural, human, and social assets in the affected locations. For example, contaminated land and buildings would be abandoned, and exposed populations would experience higher rates of cancers. Thus, the release could have significant, adverse effects on sustainability.

According to the NEA, the probability of a large, unplanned release is low. Thus, a conceptual and analytic framework is needed to assess the sustainability implications of potential events with large, adverse consequences and low probability. That issue is not unique to nuclear power. For example, capture and sequestration of CO_2 is an energy option that could allow use of fossil fuels without adverse effects on Earth's climate. If a proposed project involves CO_2 sequestration on a large scale, an assessment of the sustainability of the project should examine the probability and consequences of a large, unexpected release of sequestered CO_2 to the atmosphere.

Analysts in the nuclear industry and its regulatory bodies address the potential for high-consequence, low-probability events by defining an indicator called «risk». They define that indicator as the arithmetic product of a numerical indicator of consequences and a numerical indicator of probability.[18] They typically argue that equal levels of risk should be equally acceptable to citizens. That argument has been made so often that it has become dogma. Yet, the argument is not a scientific statement. It is, instead, a statement representing a particular set of values and interests.

The NEA report recognized that citizens may be more concerned about the potential for a high-consequence, low-probability event than about the potential for a low-consequence event with the same nominal level of risk. That concern can reflect a legitimate set of values and interests, skepticism about estimates of low probability, doubt that the complexity of consequences can be represented by simple indicators, and recognition that new phenomena can come into play when thresholds of consequence are exceeded.[19] The NEA report recommended that concerns of this type be heard, respected, and addressed by governments. Acceptance of that recommendation would require the abandonment of previous dogma about the acceptability of risk. Public-engagement processes and research could then be used to develop a new paradigm of risk and its acceptability.

2.2 Prudence, Uncertainty and the Precautionary Principle

A prudent citizen or public official will always give careful consideration to potential adverse outcomes of a proposed action. If the proposed action is the construction and operation of a nuclear power plant, two potential adverse outcomes will be particularly salient. One potential outcome, as mentioned above, would be a large, unplanned release of radioactive material from the plant to the environment. The second potential outcome would be the diversion of fissile or radioactive material from the plant by a national government or a sub-national group, for use in a nuclear or radiological weapon. The organizations that construct, operate and regulate nuclear power plants will implement measures intended to prevent these outcomes. Nevertheless, a prudent observer will consider the possibility that the preventive measures will fail. In view of the severe, adverse impacts that would be associated with these outcomes, it would be imprudent to ignore the possibility of their occurrence.

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[18] In this report, the term «risk» is used in a more general sense, to encompass a range of qualitative and quantitative information about the potential for an adverse outcome.

[19] There is evidence that the consequences of the 1986 Chernobyl reactor accident exceeded thresholds that brought new social and political phenomena into play. Many observers conclude that the accident undermined the legitimacy of the USSR government, contributing significantly to the breakup of the USSR. See, for example: Parsons, 2006.

ASSESSING THE POTENTIAL FOR AN UNPLANNED RELEASE

The potential for a large, unplanned release of radioactive material is typically regarded by the nuclear industry and its regulators as a «safety» issue. An analytic art, known as probabilistic risk assessment (PRA), has been developed to estimate the probabilities and consequences of potential releases. The first PRA for a nuclear power plant was known as the Reactor Safety Study, and was published by the US Nuclear Regulatory Commission (NRC) in 1975.[20] A PRA for a nuclear power plant considers a range of scenarios (event sequences) that involve damage to the reactor core. The initiating events are categorized as «internal» events (human error, equipment failure, etc.) or «external» events (earthquakes, fires, strong winds, etc.). The core-damage scenarios that arise from these events are termed «accidents». PRAs typically do not consider initiating events that involve deliberate acts of malice, although PRA techniques can be adapted to estimate the outcomes of such acts. The NRC adapted PRA techniques in developing its 1994 rule requiring protection of a nuclear power plant against attack using a vehicle bomb.[21]

A modern nuclear power plant has safety features – reactor shut-down systems, core cooling systems, etc. – with independent, redundant and diverse components. A core-damage accident at such a plant would typically involve a combination of independent failures that coincide, thereby overcoming the plant's safety features.[22] By contrast, during a deliberate attack on a nuclear power plant, the plant's safety features would be challenged by a common factor – the attackers' intellectual and practical capabilities. Attackers with the motivation and resources to mount a significant attack would be likely to plan the attack with the specific intention of overcoming the plant's safety features and causing a large radioactive release.

Attacks on buildings in New York and Washington in September 2001 demonstrated that an attack on a civilian facility by a skilled, highly-motivated and well-resourced sub-national group is a credible event. Many observers agree that a nuclear power plant is a potential target of a future attack of this kind. Faced with this threat, risk analysts, regulatory bodies and plant designers must modify their approach. The traditional safety paradigm is insufficient. To understand the threat, risk analysts must think like skilled attackers. Regulatory bodies must capture those insights in appropriate rules and guidance documents. Resistance to attack must become an explicit objective in the design of a nuclear power plant.

A large, unplanned release of radioactive material from a nuclear power plant would be a comparatively rare event. Any estimate of the probability of such an event will be highly uncertain.[23] Many PRAs for nuclear power plants have been performed, and the results are useful for various purposes. However, PRA estimates of the probabilities of accidental releases should not be regarded as definitive, scientific findings. Those estimates rely on numerous assumptions and judgments. There is no certainty that all of the relevant factors are captured by a PRA. The findings cannot be validated by direct statistical evidence.[24]

At present, there is no statistical basis for a quantitative estimate of the probability of a large release caused by a deliberate, malicious act. It does not follow, as some have suggested, that malicious acts should be ignored in risk analysis for nuclear power plants. In a policy or planning context, risk analysts could use judgment to assign minimum probabilities to postulated acts. That judgment could be combined with technical assessments of the vulnerability of plants to the postulated acts. Those assessments would rely, in part, on PRA techniques. For nuclear power plants now operating in the USA, it is reasonable to assume that the probability of a large, radioactive release arising from a deliberate attack during the next few decades is at least 1 per 10,000 plant-years.[25]

ASSESSING THE POTENTIAL FOR A DIVERSION OF MATERIAL

A second potential adverse outcome of operating a nuclear power plant, as mentioned above, is a diversion of fissile or radioactive material from the plant, for use in a nuclear or radiological weapon. That possibility is typically regarded by the nuclear industry and its regulators as a «safeguards» issue. Canada and many other countries have safeguards agreements with the IAEA. The purposes of these agreements include the prevention of diversion of fresh or spent fuel from nuclear power plants. If such diversion is successfully prevented, the fissile and radioactive material in the fuel will remain protected.

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[20] NRC, 1975.
[21] NRC, 1994.
[22] In some core-damage accidents, a common cause – such as a powerful earthquake – would simultaneously overcome a number of safety features.
[23] Hirsch et al, 1989.
[24] There have been two core-damage accidents involving unplanned releases of radioactive material from commercial nuclear power plants. Those accidents occurred at Three Mile Island in 1979 (involving a small release) and Chernobyl in 1986 (involving a large release).
[25] Thompson, 2007.

In the context of plant design, it is important to note that spent fuel could be diverted from some types of nuclear power plant with comparatively little technical effort. At such plants, prevention of diversion must rely primarily on administrative measures. CANDU plants, which employ on-line refueling, are in this category.[26]

A national government might, at some future date, break its safeguards agreement with the IAEA and extract fissile or radioactive material from the fresh or spent fuel of nuclear power plants under its control. Alternatively, a sub-national group might gain control of a quantity of fresh or spent fuel, and then extract fissile or radioactive material from that fuel. Either step could be the precursor to threatened or actual use of a nuclear or radiological weapon, which would be a severe, adverse outcome of the operation of nuclear power plants. There is no statistical basis for a quantitative estimate of the probability of that outcome. Nevertheless, a qualitative estimate of that probability is an inevitable component of an assessment of the sustainability of nuclear power. To ignore the issue would be to assume that the probability is zero.

THE PRECAUTIONARY PRINCIPLE

The preceding discussion addresses two potential adverse outcomes of constructing a nuclear power plant – an unplanned release of radioactive material, and a diversion of fissile or radioactive material. The probability of either outcome is highly uncertain. Yet, either outcome would be significant from the perspective of the sustainability of nuclear power. In a policy or planning context, citizens and policy makers must grapple with this conjunction of uncertainty and significance. The precautionary principle offers guidance in such situations. This principle has been much discussed, and is incorporated in laws and regulations in Canada and elsewhere. To date, however, it lacks an internationally-agreed definition and framework for implementation.

In the Canadian Environmental Assessment Act of 1992, the concept of precaution appears twice in the Purposes section.[27] First, at 4 (1) (a), the Act states that one of its purposes is «to ensure that projects are considered in a careful and precautionary manner before federal authorities take action with them, in order to ensure that such projects do not cause significant adverse environmental effects». Then, at 4 (2), the Act states that federal government entities shall, in administering the Act, «exercise their powers in a manner that protects the environment and human health and applies the precautionary principle».

The Act further states, at 4 (1) (b), that one of its purposes is «to encourage responsible authorities to take actions that promote sustainable development and thereby achieve or maintain a healthy environment and a healthy economy». Thus, the Act seeks to promote principles of sustainability and of precaution. That general commitment has been applied to specific cases by panels convened under the Act.[28]

In April 2007, the Canadian government issued the Cabinet Directive on Streamlining Regulation.[29] That directive sets forth six objectives for regulation by the federal government. The third of those objectives states that the government will:

«Make decisions based on evidence and the best available knowledge and science in Canada and worldwide, while recognizing that the application of precaution may be necessary when there is an absence of full scientific certainty and a risk of serious or irreversible harm».

One application of that objective would be to anthropogenic climate change. In that instance, the harm would be serious and irreversible if no action were taken to reduce emissions of greenhouse gases. Yet, there might not be full scientific certainty about the extent to which emissions should be reduced. The above-stated objective would call for early action, without waiting for full scientific certainty.

In the context of this report, serious and irreversible harm could arise from the taking of an action. The action would be the construction and operation of a nuclear power plant, if the design of the plant created a significant potential for an unplanned release of radioactive material, or for diversion of fissile or radioactive material. In this instance, the above-stated objective would favor the blocking of the plant's construction, even though the potential for harm could not be characterized with full scientific certainty as to consequences and probability.

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[26] Fischer and Szasz, 1985.
[27] Justice Department, 2007.
[28] Gibson, 2000.
[29] Government of Canada, 2007.

2.3 Efforts to Address Sustainability Issues in Designs for New Nuclear Power Plants

During the past four decades, there have been various efforts to address sustainability issues while developing designs for new nuclear power plants. Some of those efforts are summarized here. Persons involved in those efforts have adopted the language of sustainability only in the past decade. A conceptual progression over time is evident, but that progression has not yet arrived at designs that reflect a comprehensive framework of sustainability principles. Moreover, the design concepts discussed here are almost entirely theoretical. The present fleet of nuclear power plants, and the Generation III plants that are currently being offered, do not employ these concepts to any significant extent.

UNDERGROUND SITING

In the 1970s, there were several studies on constructing nuclear power plants underground. Those studies are exemplified by a report published in 1972 under the auspices of the California Institute of Technology (Caltech).[30] The report identified a number of advantages of underground siting. Those advantages included highly-effective confinement of radioactive material in the event of a core-damage accident, isolation from falling objects such as aircraft, and protection against acts of malice. Based on experience with underground testing of nuclear weapons, the report concluded that an appropriately designed plant would provide essentially complete containment of the radioactive material liberated from a reactor core during a core-damage event.

The Caltech report described a preliminary design study for underground construction of a light-water-reactor power plant with a capacity of 1,000 MWe. The minimum depth of the underground cavities containing the plant components would be 150 to 200 feet. The estimated cost penalty for underground siting would be less than 10 percent of the total plant cost.

In an appendix, the Caltech report described four underground nuclear reactors that had been constructed and operated in Europe. Three of those reactors supplied steam to turbo-generators, above or below ground. The largest of those reactors and its above-ground turbo-generator made up the Chooz plant in France, which had a capacity of 270 MWe. In describing the European reactors, the report noted:[31]

«The motivation for undergrounding the plant appears to be insurance of containment of accidentally released radioactivity and also physical protection from damage due to hostile military action.»

Since the 1970s, underground siting of nuclear power plants has been considered by various groups. For example, in 2002 a workshop was held under the auspices of the University of Illinois to discuss a proposed US-wide «supergrid». That grid would transmit electricity – via superconducting DC cables – and liquid hydrogen, which would provide cooling to the DC cables and be distributed as fuel. Much of the energy fed to the grid would be supplied by nuclear power plants, which could be constructed underground. Motives for placing those plants underground would include «reduced vulnerability to attack by nature, man or weather» and «real and perceived reduced public exposure to real or hypothetical accidents».[32]

THE PIUS REACTOR

In the 1980s the reactor vendor ASEA-Atom developed a preliminary design for an «intrinsically safe» commercial reactor known as the Process Inherent Ultimate Safety (PIUS) reactor. An ASEA-Atom official described the company's motives for developing the reactor as follows:[33]

«The basic designs of today's light water reactors evolved during the 1950s when there was much less emphasis on safety. Those basic designs held certain risks, and the control of those risks led to an increasing proliferation of add-on systems and equipment ending up in the present complex plant designs, the safety of which is nevertheless being questioned. Rather than to continue into this 'blind alley', it is now time to design a truly 'forgiving' light water reactor in which ultimate safety is embodied in the primary heat extraction process itself rather than achieved by add-on systems that have to be activated in emergencies. With such a design, system safety would be completely independent of operator actions and immune to malicious human intervention.»

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[30] Watson et al, 1972.
[31] Watson et al, 1972, Appendix I.
[32] Overbye et al, 2002.
[33] Hannerz, 1983, pp 1-2.

The central goal of the PIUS design was to preserve fuel integrity «under all conceivable conditions». That goal translated to a design specification of «complete protection against core melting or overheating in case of:

- → any credible equipment failures;
- → natural events, such as earthquakes and tornadoes;
- → reasonably credible operator mistakes; and
- → combinations of the above;

and against:

- → inside sabotage by plant personnel, completely knowledgeable of reactor design (this can be considered an envelope covering all possible mistakes);
- → terrorist attacks in collaboration with insiders;
- → military attack (e.g., by aircraft with 'off-the-shelf' non-nuclear weapons); and
- → abandonment of the plant by the operating personnel».[34]

To meet those requirements, ASEA-Atom designed a light-water reactor – the PIUS reactor – with novel features. The reactor pressure vessel would contain sufficient water to cool the core for at least one week after reactor shut-down. Most of that water would be borated, so that its entry into the core would inherently shut down the reactor. The borated water would not enter the core during normal operation, but would enter through inherent mechanisms during off-normal conditions. The reactor pressure vessel would be made of pre-stressed concrete with a thickness of 25 feet. That vessel could withstand an attack using 1,000-pound bombs. About two-thirds of the vessel would be below ground.

ASEA-Atom estimated that the construction cost of a four-unit PIUS station with a total capacity of 2,000 MWe would be about the same as the cost of a station equipped with two 1,000 MWe «conventional» light-water reactors. The PIUS station could be constructed more rapidly, which would offset its slightly lower thermal efficiency. Thus, the total generating cost would be about the same for the two stations. ASEA-Atom estimated (in 1983) that the first commercial PIUS plant could enter service in the early 1990s, if a market existed.[35] To date, no PIUS plant has been ordered.

PRIME REACTORS

In 1991, a study conducted at Oak Ridge National Laboratory examined various types of commercial nuclear reactor that were under development at the time.[36] Some types of reactor represented a comparatively small evolutionary step from existing reactors. Their safety systems tended to be simpler, and to rely more on passive mechanisms, than the safety systems of existing reactors. Other types of reactor were said to have PRIME characteristics. That acronym applied to designs with the features:

- → Passive safety systems;
- → Resilient safety systems;
- → Inherent safety characteristics (no need for safety systems);
- → Malevolence resistance; and
- → Extended safety (remaining in a safe state for an extended period after an accident or attack).

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[34] Hannerz, 1983, page 3.
[35] Hannerz, 1983, pp 73-76.
[36] Forsberg and Reich, 1991.

The Oak Ridge study identified several types of reactor as being in the PRIME category. Those reactors, which were in various stages of development, were: the PIUS reactor; the ISER reactor being developed in Japan; the Advanced CANDU Project; modular, high-temperature, gas-cooled reactors being developed in the USA and Germany; and a molten-salt reactor being developed jointly by the USSR and the USA. The Oak Ridge study did not set forth a framework of indicators and criteria that could be used to assess the comparative merits of those reactors, or to determine if a reactor belonged in the PRIME category.

GENERATION IV REACTORS AND FUEL CYCLES

During the past decade, proponents of a nuclear power renaissance have begun to use the language of sustainability, especially in connection with proposed Generation IV reactors and fuel cycles. Those proponents argue that use of fast-spectrum reactors and closed fuel cycles could extend the life of uranium reserves, allow the use of thorium as a fuel, and reduce the amount of radioactive waste that would be sent for disposal. The reactors could have passive-safety features and be refueled at long intervals by removing and replacing a «cassette» of fuel, thus avoiding onsite access to fuel. Fission heat could be used to produce electricity, hydrogen, process heat, or potable water.[37]

As stated in Section 1, above, the proposed Generation IV reactors would push against engineering limits in a variety of respects. Linking those reactors to a closed fuel cycle would add another level of technical difficulty. Costs are almost impossible to predict. The overall strategy assumes major technological advance across several fronts, an implementation plan that unfolds over a century or longer, strong centralized control by national governments and supra-national entities, and public acceptability of those actions. The feasibility of that strategy, and its contribution to sustainability, are highly questionable. Nevertheless, the European Commission's Directorate-General for Research offers that strategy as a long-term, sustainable future for nuclear power. Generation IV systems would be developed over the next several decades. During that period, Generation III reactors would be constructed as an interim source of electricity. The Directorate-General concedes that the Generation III reactors would not meet sustainability criteria.[38]

2.4 A Broader View of Sustainability

Since the World Commission on Environment and Development introduced the concept of sustainable development in 1987, research and practical experience have led to a deeper understanding of the imperatives and principles of sustainability. It is now recognized that sustainability involves a range of considerations, including the flexibility and resilience of engineered, natural, and social systems.[39] The precautionary principle has become part of the sustainability paradigm.

Engineers who seek to implement the sustainability paradigm in practical situations typically view the pursuit of sustainability as a multi-objective optimization problem.[40] To address such a problem, analysts must identify system boundaries, seek an understanding of the dynamic behaviors and interactions of the relevant systems, articulate a framework of indicators and criteria, and apply a process of optimization. Nuclear power has not yet been subjected to such an analysis. A group at the University of Manchester, as discussed in Section 1, above, recently began that task. According to their funding agency, «it is far from clear how sustainable the nuclear option is overall, compared to other generating options».[41]

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[37] See, for example: Wade, 2000.
[38] European Commission, 2007.
[39] Homer-Dixon, 2007.
[40] Sahely et al, 2005.
[41] EPSRC, 2007.

3.Review of IAEA and CNSC Design and Siting Documents

3.1 Scope of Review

IAEA and CNSC documents on the design and siting of new nuclear power plants are reviewed here. Those documents reflect a shared paradigm that gives no explicit recognition to principles of sustainability. Nevertheless, the documents are assessed here according to the sustainability principles discussed in Section 2, above. That is the appropriate standard for any large, long-lived engineered system in the 21st century.

A new nuclear power plant would be a component of a nuclear fuel cycle that extends from uranium mining through to plant decommissioning and disposal of radioactive waste, over a period that could exceed a century. Ideally, plans for the entire fuel cycle would be assessed using a comprehensive framework of sustainability principles, indicators and criteria. No such framework exists. Also, that assessment would require a much larger timeframe and budget than were available for preparation of this report. Thus, this review of the IAEA and CNSC documents focuses on their treatment of the potential for an unplanned release of radioactive material from a nuclear power plant. That potential is the primary focus of both sets of documents.

3.2 IAEA Design Document NS-R-1

IAEA document NS-R-1 was titled *Safety of Nuclear Power Plants: Design*.[42] That document was published in 2000, and reflected the consensus of IAEA Member States at the time. It was intended for application primarily to land-based, stationary nuclear power plants with water-cooled reactors. It established «design requirements for structures, systems and components important to safety». It addressed events that are «very unlikely», such as severe accidents that result in large releases of radioactive material, but it did not address «extremely unlikely» events such as the impact of a meteorite.[43]

NS-R-1 did not discuss malicious acts. That omission presumably reflects the consensus of Member States in 2000. The IAEA has considered malicious acts in documents published more recently, as discussed below.

«DESIGN-BASIS» AND «BEYOND-DESIGN-BASIS» ACCIDENTS

NS-R-1 articulated a set of safety objectives for new nuclear power plants. Those objectives are summarized in Table 3-1. A general objective was supported by specific objectives relating to radiation protection and technical safety. The technical safety objectives embraced a concept that is currently employed in the reactor-safety field worldwide. The concept is that certain potential accidents are taken into account in designing a nuclear power plant, while others are not. Accidents in the first category are known as «design-basis» accidents, and would not involve core damage if the plant functioned as designed. Accidents in the second category are known as «severe» accidents or «beyond-design-basis» accidents. Those terms are used interchangeably in NS-R-1. Accidents in the second category would involve core damage.

The practice of dividing potential reactor accidents into two categories has been so widely adopted that many persons now working in the nuclear industry and its regulators may be unaware of the practice's origins. Those origins date from the first two decades of the commercial nuclear power industry (roughly, 1953-1975), when the foundations of the industry were laid. The basic designs of the current fleet of nuclear power plants were established at that time.

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[42] IAEA, 2000.
[43] IAEA, 2000, pp 1-2.

Until 1975, the nuclear industry and its regulators, with some limited exceptions, equated design-basis accidents with credible accidents. It was assumed that accidents of greater severity, involving significant damage to a reactor core, were non-credible.[44] That assumption became untenable when the Reactor Safety Study was published in 1975.[45] The Three Mile Island accident of 1979 and the Chernobyl accident of 1986 demonstrated empirically that core-damage accidents are indeed credible. At that point, the industry could have gone back to the drawing board, and developed new, safer types of reactor. Indeed, ASEA-Atom took that step, developing and attempting to market the PIUS design in the early 1980s. The nuclear industry as a whole took a different path, and regulators participated in that decision. The formerly «non-credible» accidents became «beyond-design-basis» accidents. PRAs were performed to estimate the «risk» of a beyond-design-basis accident, and that risk was deemed «acceptable» if its estimated value was below some threshold. NS-R-1 reflected that paradigm.

PRAs have yielded useful, practical knowledge. They have identified deficiencies in the design, operation and maintenance of nuclear power plants. Some of those deficiencies have been corrected, thereby reducing the probability of a radioactive release. PRA findings have guided the development of capabilities for offsite emergency response. Nevertheless, it should not be forgotten that the need for PRAs derives from fundamental weaknesses in design. The present fleet of commercial reactors, and the proposed Generation III reactors, are unable to ride out a variety of credible events outside their design basis. If subjected to such an event, one of these reactors would experience core damage and, potentially, a release of radioactive material to the environment.

NS-R-1 did not specify any quantitative target for the risk of a beyond-design-basis accident. Instead, it specified qualitative targets. For example, as shown in Table 3-1, NS-R-1 called for a plant to be designed such that «the likelihood of accidents with serious radiological consequences is extremely low». NS-R-1 did not provide further guidance about implementing that objective.

RECOMMENDATIONS AND REQUIREMENTS REGARDING DESIGN FEATURES

NS-R-1 set forth general recommendations and specific requirements regarding the design features of nuclear power plants, from a safety perspective. The general recommendations are exemplified by Table 3-2, which shows a recommended hierarchy of preference in selecting a plant design feature. There was some merit in the hierarchy. It called for choosing an inherently safe design as the first preference, or a passively safe design as the second preference. That recommendation would move a plant design toward the PRIME category discussed in Section 2.3, above. However, the hierarchy in Table 3-2 was deficient in important respects. It ranked continuously-operating, active safety systems on the same level as passive safety features, which is a serious deficiency. It stated that a preference should be exercised if «that can reasonably be achieved», but provided no criterion for determining what is reasonable.

Two examples illustrate the specific design requirements that were set forth in NS-R-1. First, NS-R-1 stated that «Structures, systems and components important to safety shall generally not be shared between two or more reactors in nuclear power plants».[46] That requirement appears to rule out the plant designs used for CANDU stations in Ontario. At those stations, up to eight reactors share safety systems, including containment and core-cooling systems. The second example is the statement in NS-R-1 that «The means for shutting down the reactor shall consist of at least two different systems to provide diversity».[47]

The overall pattern of design recommendations and requirements in NS-R-1 was to set forth vague, elastic recommendations about plant performance, but precise, rigid requirements regarding particular aspects of plant design, such as the number of reactor shut-down systems. That approach is exactly opposite to the approach that would be taken if a regulator were seeking to maximize creativity in plant design. To maximize creativity and safety, a regulator would set forth precise, highly-demanding performance requirements, but would say comparatively little about design details.

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[44] Okrent, 1981.
[45] NRC, 1975.
[46] IAEA, 2000, page 24.
[47] IAEA, 2000, page 30.

STORAGE OF SPENT FUEL

NS-R-1 set forth requirements for the storage of spent (i.e., irradiated) fuel.[48] Those requirements addressed several specific design issues, such as the prevention of criticality. There was, however, no recognition of the potential for a large release of radioactive material as a result of an accident or an act of malice affecting a facility for storage of spent fuel.

At light-water nuclear power plants in the USA and elsewhere, large amounts of spent fuel are stored in pools adjacent to reactors. Those pools currently employ high-density racks, to maximize the amount of spent fuel that can be stored in each pool. Loss of water from one of the pools would lead to spontaneous ignition of the most recently discharged fuel, creating a fire that would spread across the pool. The fire would release a large amount of radioactive material to the atmosphere. Large areas of land downwind of the plant would be rendered unusable for decades. Loss of water could arise in various ways as a result of an accident or an act of malice.[49]

Measures are available for dramatically reducing the risk of a fire in a spent-fuel pool. Notably, pools could be re-equipped with low-density racks, as was intended when the plants were constructed. IAEA's failure to address the risk of a pool fire, and the measures available to reduce that risk, is a grave deficiency in NS-R-1. Analogous risks may arise from spent-fuel storage at plants other than light-water plants.

CONSIDERATION OF MALICIOUS ACTS

NS-R-1, which was published in 2000, did not discuss malicious acts. IAEA documents published more recently have discussed such acts. For example, in 2006, IAEA published a study on advanced nuclear power plant design options to cope with external events.[50] That study involved the participation of plant designers from a number of Member States. Design options considered in the study had, to varying extents, attributes in the PRIME category discussed in Section 2.3, above. Those attributes include the ability to resist malicious acts. The study did not yield specific design requirements for new nuclear power plants.

SUSTAINABILITY

NS-R-1 did not discuss sustainability. In 2006, IAEA published a document on nuclear power and sustainable development.[51] That document did not provide a framework that could be used to assess the sustainability of a proposed program of nuclear power. It did not provide any guidance on the design of a nuclear power plant according to sustainability principles.

SUMMARY

The design guidance in NS-R-1 reflected a paradigm in which potential accidents are in two categories – those within, and those beyond, the design basis. Accidents in the latter category are addressed probabilistically. That paradigm derives from fundamental weaknesses in the design of present nuclear power plants. NS-R-1 set forth vague, elastic recommendations about the safety performance of a plant. It did not address malicious acts or potential releases from stored spent fuel. Its guidance was not compatible with principles of sustainability.

3.3 IAEA Siting Document NS-R-3

IAEA document NS-R-3 was titled *Site Evaluation for Nuclear Installations*.[52] It was published in 2003. Its stated purpose was to «establish requirements for criteria» regarding the siting of all types of fixed nuclear installation except underground or offshore installations.

NS-R-3 stated that the main objective of site evaluation, in terms of nuclear safety, is «to protect the public and the environment from the radiological consequences of radioactive releases due to accidents».[53] At a later point, NS-R-3 discussed the implications for radiological risk of the site's features, the distribution of the surrounding population, and the characteristics of the nuclear installation. NS-R-3 stated that the combined effect of those factors should be such that:[54]

«The radiological risk to the population associated with accident conditions, including those that could lead to emergency measures being taken, is acceptably low.»

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[48] IAEA, 2000, page 45.
[49] Alvarez et al, 2003; National Research Council, 2006; Thompson, 2007.
[50] IAEA, 2006b.
[51] IAEA, 2006a.
[52] IAEA, 2003.
[53] IAEA, 2003, page 4.
[54] IAEA, 2003, page 9.

In that statement, and elsewhere, NS-R-3 explicitly adopted the nuclear industry's traditional definition of risk as the arithmetic product of a numerical indicator of consequences and a numerical indicator of probability.[55]

The above-quoted statement about radiological risk was the closest that NS-R-3 came to articulating criteria for assessing the merit of a site. The main function of NS-R-3 was to identify issues that should be addressed in site evaluation.

3.4 CNSC Design Document RD-337

CNSC draft document RD-337 was titled *Design of New Nuclear Power Plants*.[56] Its stated purpose was to «set out the expectations» of CNSC regarding the design of new plants. Thus, RD-337 can be regarded as a guidance document. One could reasonably expect RD-337 to be generally consistent with NS-R-1 and with design standards in leading industrialized countries. CNSC has encouraged that expectation by stating that its regulatory framework is aligned with «international standards and best practices», and that new nuclear power plants built in Canada «will meet the highest standards».[57]

Standards set forth in IAEA documents have been described as «lowest common denominator» standards that can be met in many Member States.[58] Thus, in comparing NS-R-1 and RD-337, one would expect the latter to have additional requirements and be generally more demanding. That is true in some respects, but not in all, as discussed below.

RD-337 shared with NS-R-1 the same basic paradigm, in which potential accidents are in two categories – those within, and those beyond, the design basis. Accidents in the former category are addressed deterministically, while those in the latter category are addressed probabilistically. That paradigm is linked with the nuclear industry's traditional definition of risk, and with the dogma that equal levels of risk are equally acceptable. The deficiencies of the two-tier accident paradigm are discussed in Section 3.2, above, and the deficiencies of the traditional approach to risk are discussed in Sections 2.1 and 2.2, above. Those deficiencies apply to RD-337, just as they apply to NS-R-1.

CONSIDERATION OF MALICIOUS ACTS

NS-R-1 did not consider malicious acts. By contrast, RD-337 did consider such acts, stating:[59]

«The design shall include provisions that promote security and robustness in response to malevolent acts, in accordance with applicable regulations and modern standards and codes.»

Having articulated that goal, RD-337 proceeded to introduce the concept of design-basis threats (DBTs) and beyond-design-basis threats (BDBTs), which are analogous to the two categories of accident mentioned above. DBTs were described as «credible malevolent acts», while BDBTs were described as «severe» DBTs. That terminology is reminiscent of pre-1975 practice regarding accidents, when design-basis accidents were equated with credible accidents.

RD-337 did not characterize either category of threat. A consultant to CNSC has examined the issue of designing nuclear power plants to resist malicious acts, and has offered recommendations intended to «facilitate the development of regulatory requirements».[60] The consultant postulated one type of DBT that is similar to aspects of the DBT employed in the USA by NRC, and a second type of DBT that could include «a common large commercial aircraft at speeds which can reasonably be achieved at low altitudes or an executive jet or a personal aircraft with a load of explosives taking off from an unregulated airfield». The consultant also provided examples of potential BDBTs, including «a large malevolent, explosive laden, vehicle or a LPG tanker gaining access past the physical protection barriers by stealth, deceit or force».[61]

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[55] In this report, the term «risk» is used in a more general sense, to encompass a range of qualitative and quantitative information about the potential for an adverse outcome.

[56] CNSC, 2007a.

[57] CNSC, 2006, page 3.

[58] Harvie, 2004, page 3.

[59] CNSC, 2007a, page 36.

[60] Asmis and Khosla, 2007, pp 66-67.

[61] Asmis and Khosla, 2007.

The consultant recommended that CNSC be the «prime developer» of the DBTs and BDBTs. Implementation of that recommendation would exclude citizens from participating in the determination of DBTs and BDBTs. Such exclusion would be antithetical to the principles of sustainability, and would be unnecessary. Citizens could be engaged in dialogue on this issue without broad dissemination of detailed technical information (e.g., computer models describing the response of a structure to blast) that might assist malicious persons in Canada or elsewhere.

QUANTITATIVE SAFETY GOALS

NS-R-1 did not set forth quantitative safety goals. By contrast, RD-337 set forth the quantitative safety goals shown in Table 3-3. In that table one will observe, for example, that the upper limit on the probability of core damage would be 1 per 100,000 plant-years, while the upper limit on the probability of a large release of radioactive material would be 1 per 1 million plant-years.

Core damage or a large release would be instances of a beyond-design-basis accident. RD-337 did not explain how the probability of a BDBT would relate to the quantitative safety goals. As discussed in Section 2.2, above, there is at present no statistical basis for a quantitative estimate of the probability of a postulated malicious act. Nevertheless, in a policy or planning context, judgment can be used to assign minimum probabilities to postulated acts. For nuclear power plants now operating in the USA, it is reasonable to assume that the probability of a large, radioactive release arising from a deliberate attack during the next few decades is at least 1 per 10,000 plant-years.[62]

Consideration of the potential for BDBTs could prevent CNSC from determining compliance with the quantitative safety goals in RD-337. If that potential were arbitrarily set aside, determining compliance could still be difficult or impossible. The determination would rely on PRAs, but PRA findings are highly uncertain.[63] Those findings cannot be directly validated by experience. For example, Table 3-3 shows a target probability of 1 per 1 million plant-years for core damage. Yet, worldwide operating experience of commercial nuclear power plants through 2007 is about 12,900 plant-years, and Canadian experience is about 560 plant-years.[64] Two core-damage events have occurred worldwide while that experience was accruing.

Practical experience in Canada casts doubt on PRA findings for CANDU plants.[65] For example, on one occasion designers of the Pickering 'A' station estimated the probability of a particular event sequence at 1 per 10 billion plant-years. An almost identical event occurred a few weeks later.[66] Also, Canada lacks a fully developed PRA culture. PRAs performed in Canada for CANDU reactors find extremely low probabilities for large releases. Based on those findings, the PRAs do not estimate the radiological impacts of large releases. Yet, the low probabilities are not credible.[67] The practice of ignoring large releases deprives citizens and policy makers of needed information. For example, in a recent analysis of the radiological risk of continued operation of the Pickering 'B' station, the largest release considered included 71 TBq of Cesium-137.[68] That is a comparatively small release, and is categorized as such in Table 3-3.

RECOMMENDATIONS AND REQUIREMENTS REGARDING DESIGN FEATURES

Like NS-R-1, RD-337 set forth general recommendations and specific requirements regarding the design features of nuclear power plants, from a safety perspective. NS-R-1, as shown in Table 3-2, set forth a recommended hierarchy of preference in selecting plant design features. By contrast, RD-337 described a similar set of design features, but did not place them in a hierarchy of preference. Instead, RD-337 stated that features should be adopted where «that can be reasonably achieved».[69] That approach was a significant retreat from the safety standard established by NS-R-1.

STORAGE OF SPENT FUEL

Like NS-R-1, RD-337 set forth requirements for the storage of spent (i.e., irradiated) fuel.[70] Those requirements addressed several specific design issues, such as the prevention of criticality. Like NS-R-1, RD-337 failed to recognize the potential for a large release of radioactive material as a result of an accident or an act of malice affecting a facility for storage of spent fuel.

[62] Thompson, 2007.
[63] Hirsch et al, 1989.
[64] Extrapolated from Table 1 of: IAEA, 2006a.
[65] Beare, 2005.
[66] Beare, 2005, page 33.
[67] Thompson, 2000; IRSS, 1992.
[68] SENES, 2007, Table B.5.3-1.
[69] CNSC, 2007a, page 13.
[70] CNSC, 2007a, pp 61-62.

SUMMARY

RD-337 was generally consistent with NS-R-1 and reflected the same paradigm. A notable difference between the two documents was that RD-337 considered malicious acts, while NS-R-1 did not. RD-337 introduced the concept of design-basis threats and beyond-design-basis threats, but did not characterize either category of threat. Also, RD-337 set forth quantitative safety goals, while NS-R-1 did not. However, CNSC's ability to determine compliance with the quantitative safety goals is questionable. RD-337 retreated from the safety standard established by NS-R-1 regarding preferences in selecting plant design features. RD-337 did not address potential releases from stored spent fuel.

3.5 CNSC Siting Document RD-346

CNSC draft document RD-346 was titled *Site Evaluation for New Nuclear Power Plants*.[71] Its stated purpose was to «set out the expectations» of CNSC regarding site evaluation for new plants. Thus, RD-346 can be regarded as a guidance document.

The guidance provided in RD-346 consisted primarily of an identification of issues that should be addressed in site evaluation. RD-346 offered some criteria regarding non-radiological impacts of a nuclear power plant on the local environment.[72] However, RD-346 offered no criteria for assessing the merit of a site from a safety perspective.

RD-346 stated that site evaluation should take into account «all phases of the NPP life cycle, from site preparation to abandonment». [73] That provision appropriately recognized that site features significant for safety, such as the population distribution in the surrounding region, could change over time. At a CNSC public meeting discussing RD-346 prior to its release, a participant suggested that the same provision should apply to existing nuclear power plants. The CNSC official chairing the meeting acknowledged that suggestion.[74] To date, CNSC has not acted on the suggestion. One could broaden the suggestion, to argue that existing plants should not be allowed to operate for an extended period if they cannot comply with the design and siting standards used for new plants.

From the perspective of sustainability, guidance on siting of a nuclear power plant should consider interactions between the plant and the built or natural environment surrounding it. For example, there may be opportunities to use waste heat from the plant as process heat in nearby industries, consistent with a broad strategy of energy efficiency. Also, if the reliability of the electrical grid connection is important to the safety of the plant, then the grid should be examined as part of site evaluation. Conversely, the plant's siting could affect the reliability of its supply of electricity to load centers. RD-346 did not address such issues.

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[71] CNSC, 2007b.
[72] CNSC, 2007b, Table 5.1.
[73] CNSC, 2007b, page 1.
[74] Comment by Shawn-Patrick Stensil and response by Chairperson, CNSC public meeting, Ottawa, 13 September 2007, transcript pp 156-158.

4. Proposed Criteria for Plant Design and Site Evaluation

As an alternative to the guidance set forth in the CNSC and IAEA documents reviewed above, criteria for the design and siting of nuclear power plants are proposed here. The proposed criteria focus on the potential for an unplanned release of radioactive material – i.e., on safety. That is not the only sustainability issue related to design and siting of a nuclear power plant, but it is the primary focus of the CNSC and IAEA documents.

Table 4-1 describes the proposed criteria. They are purely deterministic. All the events that they are intended to accommodate are within the plant's design basis. Thus, they offer a clear alternative to the paradigm employed by IAEA and CNSC, in which design-basis accidents are addressed deterministically and beyond-design-basis accidents are addressed probabilistically. The proposed criteria reject that two-tier paradigm, and also reject the nuclear industry's traditional concept of risk and its acceptability.

The criteria set forth in Table 4-1 are not definitive. At various points, they state that a parameter would be «specified», but they leave that specification open or suggest a tentative value for consideration. The intention is that the final parameters would be determined by public processes, as discussed in Section 5, below.

Table 4-1 provides design-basis criteria for a plant's safety performance under two conditions – reactor operation, and reactor refueling. The criteria for reactor operation are similar to those articulated by ASEA-Atom for the PIUS reactor. The criteria for reactor refueling reflect an expectation that the plant's containment would be somewhat compromised during refueling. The maximum release specified under the refueling criteria could be linked to the frequency of refueling for a particular plant design.

Both of these sets of criteria are performance-based. They would encourage creativity in plant design, providing an opportunity to move beyond the present designs, whose basic features were established in the 1950s and 1960s. Compliance with the criteria for reactor operation could be demonstrated, to a substantial extent, by testing of the actual plant prior to its entry into service. For example, the plant's ability to ride out a loss of power and normal heat sinks, and abandonment by operators, could be tested directly. Other aspects of compliance would be established through conservative modeling and analysis.

Table 4-1 provides deterministic siting criteria, expressed in terms of maximum radiological impacts from design-basis events. Those criteria would translate into permissible distributions of population and land use in regions surrounding a plant. Compliance would be established through conservative modeling and analysis.

5. Public Processes for Deciding on Final Criteria

The criteria set forth in Table 4-1 provide a point of departure for public processes that could yield final criteria for the design and siting of new nuclear power plants. That transition could occur in two steps. First, the general structure of the criteria would be debated, and modified as appropriate. Second, final specifications would be established for the various parameters that appear in Table 4-1, or the analogous parameters that would appear in a modified structure.

Suitable public processes would engage local and provincial governments, and a broad range of other groups of stakeholders, in dialogue about citizens' preferences regarding the safety and sustainability of nuclear power. That dialogue should be informed by technical analyses that respond to stakeholder questions. All aspects of the dialogue should occur openly, even when the dialogue addresses potential acts of malice. An essential feature of any sustainable energy system is that it should be robust against acts of malice by virtue of its inherent properties, and should not require protection through secrecy. Indeed, secrecy and related measures, such as surveillance of the population, are antithetical to sustainability.

The design of suitable public processes is a matter beyond the scope of this report. There is a body of relevant experience, in Canada and elsewhere, that could guide the design of suitable processes.

It can be presumed that the nuclear industry and other interested parties would provide analyses on the technical and economic feasibility of meeting proposed criteria. Public funding should be available to support the preparation of independent analyses. All analyses should respond to stakeholder questions.

Public processes might, or might not, yield criteria that the nuclear industry believes can be met within present technical and economic constraints. In the latter case, the criteria should not be relaxed. The fundamental objective should be to ensure that any energy system deployed in the 21st century satisfies the imperatives of sustainability.

6. Conclusions and Recommendations

Major conclusions of this report are as follows:

C1. Any new, large, long-lived engineered system should be designed according to sustainability principles, including the precautionary principle. That requirement would apply to any new nuclear power plant. To implement the requirement, a comprehensive framework of sustainability principles, indicators and criteria should be developed, to the point where it could be used to assess the sustainability of any proposed engineered system.

C2. When the new framework is used to assess the sustainability of a proposed program of nuclear power, it should examine the entire nuclear fuel cycle from uranium mining through to plant decommissioning and disposal of radioactive waste. No such assessment has been performed to date, and the necessary framework for the assessment is not yet available.

C3. One aspect of an assessment of the sustainability of a program of nuclear power would be an examination of the potential for unplanned, adverse outcomes of the construction and operation of a nuclear power plant. One such outcome would be a large, unplanned release of radioactive material from the plant to the environment. Another such outcome would be the diversion of fissile or radioactive material from the plant for use in a nuclear or radiological weapon.

C4. Analysts in the nuclear industry and its regulators have developed PRA techniques to estimate the consequences and probabilities of unplanned releases of radioactive material from nuclear power plants. Those analysts employ a concept called «risk», which they define as the arithmetic product of a numerical indicator of consequences and a numerical indicator of probability. They typically argue that equal levels of risk should be equally acceptable to citizens. That argument is not a scientific statement. It is, instead, dogma representing a particular set of values and interests.

C5. Citizens may be more concerned about the potential for a high-consequence, low-probability event than about the potential for a low-consequence event with the same nominal level of risk. That concern can reflect a legitimate set of values and interests, skepticism about estimates of low probability, doubt that the complexity of consequences can be represented by simple indicators, and recognition that new phenomena can come into play when thresholds of consequence are exceeded. A report by the OECD Nuclear Energy Agency recommended that concerns of this type be heard, respected, and addressed by governments.

C6. The nuclear industry and its regulators have embraced a paradigm in which potential accidents at a nuclear power plant are categorized as «design-basis» accidents that would not involve core damage if the plant functioned as designed, and «beyond-design-basis» accidents that would involve core damage. Accidents in the latter category are addressed using the concept of risk as described in conclusion C4, above. The paradigm reflects fundamental weaknesses in design. The present fleet of commercial reactors, and the proposed Generation III reactors, are unable to ride out a variety of credible events outside their design basis.

C7. IAEA document NS-R-1 provided guidance on the design of new nuclear power plants, from a safety perspective. That guidance reflected the paradigm described in conclusion C6, above. In articulating design recommendations and requirements, NS-R-1 set forth vague, elastic recommendations about the safety performance of a plant, but precise, rigid requirements regarding particular aspects of plant design. That approach is exactly opposite to the approach that would be taken if a regulator were seeking to maximize safety and creativity in plant design.

C8. IAEA document NS-R-3 provided guidance on site evaluation for new nuclear power plants and other nuclear facilities. The guidance consisted of an identification of issues that should be addressed in site evaluation. NS-R-3 offered no criterion for assessing the merit of a site.

C9. CNSC draft document RD-337 provided guidance on the design of new nuclear power plants, from a safety perspective. RD-337 was generally consistent with NS-R-1 and reflected the same paradigm. One notable difference between the two documents was that RD-337 considered malicious acts, while NS-R-1 did not. RD-337 introduced the concept of design-basis threats and beyond-design-basis threats, which are analogous to the two categories of accident described in conclusion C6, above. RD-337 did not characterize either category of threat. Another difference between the documents is that RD-337 set forth quantitative safety goals, while NS-R-1 did not. CNSC's ability to determine compliance with those quantitative safety goals is questionable. RD-337 retreated from the safety standard established by NS-R-1 regarding preferences in selecting plant design features.

C10. CNSC draft document RD-346 provided guidance on site evaluation for new nuclear power plants. The guidance consisted primarily of an identification of issues that should be addressed in site evaluation. RD-346 offered no criterion for assessing the merit of a site from a safety perspective.

C11. Documents NS-R-1 and RD-337 reflected an obsolete dogma of risk. Neither document is compatible with principles of sustainability that are increasingly recognized as imperatives for the 21st century, including the precautionary principle. Documents NS-R-3 and RD-346 did not provide criteria for assessing the merit of a site from a safety perspective.

C12. This report proposes some design and siting criteria that reflect sustainability principles and could replace the guidance set forth by CNSC and IAEA. The proposed criteria focus on the potential for an unplanned release of radioactive material. That is not the only sustainability issue related to design and siting of a nuclear power plant, but it is the primary focus of the CNSC and IAEA documents. The criteria that are proposed here would provide a point of departure for public processes that yield final criteria.

Based on the preceding conclusions, the following recommendations are offered:

R1. IAEA should work with Member States and other international agencies to develop a comprehensive framework of principles, indicators and criteria that could be used to assess the sustainability of any proposed program of nuclear power. Documents NS-R-1 and NS-R-3 should be withdrawn.

R2. The Canadian government should work with a range of partners, and should organize public processes, to develop a comprehensive framework of principles, indicators and criteria that could be used to assess the sustainability of any proposed engineered system.

R3. The Canadian government should work with a range of partners, and should organize public processes, to use an appropriate framework of principles, indicators and criteria to assess the sustainability of any proposed new program of nuclear power in Canada. In conjunction with that assessment, the Canadian government should review the charter and practices of the CNSC, to determine their compatibility with principles of sustainability.

R4. CNSC should withdraw the draft documents RD-346 and RD-337.

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Table 3-1

SAFETY OBJECTIVES FOR NEW NUCLEAR POWER PLANTS, AS SPECIFIED IN IAEA SAFETY STANDARDS SERIES DOCUMENT NS-R-1

OBJECTIVE	CHARACTERISTICS OF OBJECTIVE
GENERAL NUCLEAR SAFETY OBJECTIVE	Protect individuals, society and the environment from harm by establishing and maintaining effective defenses against radiological hazards
RADIATION PROTECTION OBJECTIVE	Ensure that, in all operational states, radiation exposure within the plant, or due to any planned release of radioactive material from the plant, is kept below prescribed limits and as low as reasonably achievable
	Ensure mitigation of the radiological consequences of any accident
TECHNICAL SAFETY OBJECTIVE	Take all reasonably practicable measures to prevent accidents and to mitigate their consequences should they occur
	Ensure, with a high level of confidence, that the radiological consequences of any accident taken into account in designing the plant would be minor and below prescribed limits
	Ensure that the likelihood of accidents with serious radiological consequences is extremely low

Source: nternational Atomic Energy Agency, *Safety of Nuclear Power Plants: Design, IAEA Safety Standards Series No. NS-R-1*, Vienna: IAEA, 2000, pp 3-4.

Table 3-2

HIERARCHY OF NUCLEAR POWER PLANT DESIGN CHARACTERISTICS RELEVANT TO SAFETY, AS SPECIFIED IN IAEA SAFETY STANDARDS SERIES DOCUMENT NS-R-1

PREFERENCE IN SELECTING A PLANT DESIGN FEATURE	DESIGN CHARACTERISTICS RELEVANT TO SAFETY
	THE EXPECTED PLANT RESPONSE TO ANY POSTULATED INITIATING EVENT SHALL BE THOSE OF THE FOLLOWING THAT CAN REASONABLY BE ACHIEVED ……
FIRST PREFERENCE	No significant safety-related effect, or a change toward a safe condition by virtue of inherent characteristics of the plant
SECOND PREFERENCE	The plant is rendered safe by passive safety features, or by the action of safety systems that are continuously operating
THIRD PREFERENCE	The plant is rendered safe by the action of safety systems that are brought into service in response to the initiating event
FOURTH PREFERENCE	The plant is rendered safe by specified procedural actions

Source: International Atomic Energy Agency, *Safety of Nuclear Power Plants: Design, IAEA Safety Standards Series No. NS-R-1*, Vienna: IAEA, 2000, page 11.

Table 3-3

SAFETY GOALS FOR A NEW NUCLEAR POWER PLANT, AS SPECIFIED IN CNSC DRAFT REGULATORY DOCUMENT RD-337

TYPE OF OUTCOME	SAFETY GOALS	
	SUM OF FREQUENCIES OF ALL EVENT SEQUENCES THAT CAN LEAD TO THIS OUTCOME ……..	
	SHOULD BE LESS THAN	SHALL NOT EXCEED
SMALL RELEASE TO THE ENVIRONMENT (MORE THAN 1,000 TBQ OF IODINE-131)	1 per 1 million plant-years	1 per 100,000 plant-years
LARGE RELEASE TO THE ENVIRONMENT (MORE THAN 100 TBQ OF CESIUM-137)	1 per 10 million plant-years	1 per 1 million plant-years
CORE DAMAGE (SIGNIFICANT CORE DEGRADATION)	1 per 1 million plant-years	1 per 100,000 plant-years

Source: Canadian Nuclear Safety Commission, *Design of New Nuclear Power Plants, RD-337, Draft*, Ottawa: CNSC, October 2007, page 5.

Table 4-1

PROPOSED SAFETY CRITERIA FOR DESIGN AND SITING OF A NEW NUCLEAR POWER PLANT

APPLICATION OF CRITERIA	CRITERIA
SAFETY PERFORMANCE OF THE PLANT DURING REACTOR OPERATION (design-basis criteria)	No significant damage of the reactor core or adjacent stored spent fuel in the event of: → Loss of all electrical power (AC & DC), compressed air, other power sources, and normal heat sinks for an extended period (e.g., 1 week); → Abandonment of the plant by operating personnel for an extended period (e.g., 1 week); → Takeover of the plant by hostile, knowledgeable persons who are equipped with specified explosive devices, for a specified period (e.g., 8 hours); → Military attack by specified means (e.g., 1,000-pound air-dropped bombs); → An extreme, specified earthquake; → Conceivable erroneous operator actions that could be accomplished in a specified period (e.g., 8 hours); or → Any combination of the above.
SAFETY PERFORMANCE OF THE PLANT DURING REACTOR REFUELING (design-basis criteria)	A specified maximum release of radioactive material to the accessible environment in the event of: → Loss of reactor coolant at a specified time after reactor shut-down, with replacement of the coolant by fluid (e.g., air, steam, or unborated water) creating the chemical and nuclear reactivity that would maximize the release of radioactive material, at a time when the plant's containment is most compromised; and → Any combination of the events specified above, in the context of reactor operation.
SITE SPECIFICATION (radiological-impact criteria)	In the event of the maximum release of radioactive material specified above, in the context of reactor refueling, radiological impacts would not exceed specified values regarding: → Individual dose; → Population dose; and → Land areas in various usage categories that would be contaminated above specified levels.

Note: The criteria in the first two rows of this table would apply to spent fuel stored adjacent to the reactor core. Separate criteria would apply to an independent facility for storing spent fuel, whether onsite or offsite.