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ROBUST STORAGE OF SPENT NUCLEAR FUEL:
An Interim Report

by

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Abstract

The prevailing practice of storing most US spent nuclear fuel in high-density pools poses a very high risk. Knowledgeable attackers could induce a loss of water from a pool, causing a fire that would release to the atmosphere a huge amount of radioactive material. Nuclear reactors are also vulnerable to attack. Dry-storage modules used in independent spent fuel storage installations (ISFSIs) have safety advantages in comparison to pools and reactors, but are not designed to resist a determined attack. Thus, nuclear power plants and their spent fuel can be regarded as pre-deployed radiological weapons that await activation by an enemy. The US government and the Nuclear Regulatory Commission seem unaware of this threat.

This report sets forth a strategy for robust storage of US spent fuel. Such a strategy will be needed whether or not a repository is opened at Yucca Mountain. This strategy should be implemented as a major element of a defense-in-depth strategy for US civilian nuclear facilities. In turn, that defense-in-depth strategy should be a component of a homeland-security strategy that provides solid protection of our critical infrastructure.

The highest priority in a robust-storage strategy for spent fuel would be to re-equip spent-fuel pools with low-density, open-frame racks. As a further measure of risk reduction, ISFSIs would be re-designed to incorporate hardening and dispersal. Preliminary analysis suggests that a hardened, dispersed ISFSI could be designed to meet a two-tiered design-basis threat. The first tier would require high confidence that no more than a small release of radioactive material would occur in the event of a direct attack on the ISFSI by various non-nuclear instruments. The second tier would require reasonable confidence that no more than a specified release of radioactive material would occur in the event of attack using a 10-kilotonne nuclear weapon.

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1. Introduction

> "One fact dominates all homeland security threat assessments: terrorists are strategic actors. They choose their targets deliberately based on the weaknesses they observe in our defenses and our preparations. They can balance the difficulty in successfully executing a particular attack against the magnitude of loss it might cause."
>
> National Strategy for Homeland Security[1]

It is well known that nuclear power plants and their spent fuel contain massive quantities of radioactive material. (Note: Irradiated fuel discharged from a nuclear reactor is described as "spent" because it is no longer suitable for generating fission power.) Consequently, thoughout the history of the nuclear power industry, informed citizens have expressed concern that a substantial amount of this material could be released to the environment. One focus of concern has been the possibility of an accidental release caused by human error, equipment failure or natural forces (e.g., an earthquake). In response to citizens' demands and events such as the Three Mile Island reactor accident of 1979, the US Nuclear Regulatory Commission (NRC) has taken some actions that address this threat.

To date, citizens have been much less successful in forcing the NRC to address a related threat -- the possibility that a release of radioactive material will be caused by an act of malice or insanity. The citizens' failure is not for lack of effort. For many years, citizen groups have petitioned the NRC and engaged in licensing interventions, seeking to persuade the NRC to address this threat. Yet, the agency has responded slowly, reluctantly and in limited ways, even after the terrorist attacks of 11 September 2001. This strange response is not unique to the NRC. The US government in general seems unwilling to address the possibility that an enemy, domestic or foreign, will exploit a civilian nuclear facility as a radiological weapon.

The terrorist attacks of September 2001 demonstrated the vulnerability of our infrastructure to determined acts of malice, and cruelly validated long-neglected

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[1] Office of Homeland Security, 2002, page 7.

warnings by many analysts and concerned citizens. In response, the United States employed its military capabilities in Afghanistan and has signaled its willingness to use those capabilities in Iraq and elsewhere. Yet, nothing significant has been done to defend US nuclear power plants and their spent fuel against attack. There is much discussion in the media about "dirty bombs", but decision makers seem largely unaware that civilian nuclear facilities could be exploited as potent radiological weapons.

This report addresses robust storage of spent fuel from nuclear power plants. Here, the term "robust" means that a facility for storing spent fuel is made resistant to attack. Such resistance can be achieved in three ways. First, the facility can be made passively safe, so that spent fuel remains in a safe state without needing electrical power, cooling water or the presence of an operating crew. Second, the facility can be "hardened", so that the spent fuel and its containment structure are protected from damage by an instrument of attack (e.g., an anti-tank missile). For a facility at ground level, hardening involves the provision of layers of concrete, steel, gravel or other materials above and around the spent fuel. Third, the facility can be "dispersed", so that spent fuel is not concentrated at one location, but is spread more uniformly across the site. Dispersal can reduce the magnitude of the radioactive release that would arise from a given attack.

At present, all but a tiny fraction of US spent fuel is stored at the nation's nuclear power plants. Most of this fuel is stored at high density in water-filled pools that are adjacent to, but outside, the containments of the reactors. This mode of storage does not meet any of the above-stated three conditions for robustness. High-density spent-fuel pools are not passively safe. Indeed, if water is lost from such a pool, which could occur in various ways, the fuel will heat up, self-ignite and burn, releasing a large amount of radioactive material to the environment. Spent-fuel pools are not hardened against attack, and a pool concentrates a large amount of spent fuel in a small space, which is the antithesis of dispersal.

A growing fraction of US spent fuel, now about 6 percent of the total inventory, is stored in dry-storage facilities at nuclear power plants. The storage is "dry" in the sense that the spent fuel is surrounded by a gas such as helium, rather than by water. The NRC describes such a facility as an independent spent fuel storage installation (ISFSI).[2] All but two of the existing ISFSIs are at the sites of nuclear power plants, either operational plants or plants undergoing decommissioning.[3] Future ISFSIs could be built at nuclear-power-plant sites or at away-from-reactor sites. An application to build an ISFSI at an away-from-reactor site -- Skull Valley, Utah -- is awaiting decision by the NRC. It should be noted that the nuclear industry is building dry-storage ISFSIs not as an alternative to high-density pools, but to accommodate the growing inventory of spent fuel as pools become full.

Dry-storage ISFSIs meet one of the above-stated three conditions for robust storage of spent fuel. They are passively safe, because their cooling depends on the natural circulation of ambient air. However, none of the existing or proposed ISFSIs is hardened, and none of them is dispersed across its site.

This report describes the need for robust storage of all US spent fuel, whether in pools or dry-storage ISFSIs, and sets forth a strategy for meeting this need. A productive discussion of these issues must, however, occur within a broader context, and that context is addressed here. The provision of robust storage of spent fuel is part of a larger topic -- defending the nation's civilian nuclear industry, including all of the nuclear power plants and all of their spent fuel. That topic is itself a component of homeland security in general. Finally, homeland security is a key component of US strategy for national defense and international security.

The various levels of security, ranging from the security of nuclear facilities to the security of the nation and the international community, are linked in surprising ways. If our nuclear facilities and other parts of our infrastructure -- such as the airlines -- are poorly defended, we may feel compelled to use military force aggressively around the world, to punish or pre-empt attackers. Such action poses the risk of arousing hostility and promoting anarchy, leading to new attacks on our homeland. The potential exists for an escalating spiral of violence. If, however, our nuclear facilities and other critical items of infrastructure are strongly defended, we can gain a double benefit. First, the communities around

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[2] One wet-storage ISFSI exists in the USA, at Morris, Illinois. All other existing ISFSIs, and all planned ISFSIs, employ dry storage.

[3] The existing ISFSIs that are not at nuclear-power-plant sites are the small wet-storage facility at Morris and a facility in Idaho that stores fuel debris from Three Mile Island Unit 2.

each facility will receive direct protection. Second, we can take a more measured approach to national defense, with the prospect of detecting, deterring and apprehending potential attackers without undermining civil liberties or international security. Thus, a decision about the level of protection to be provided at a nuclear facility has wide-ranging implications.

This report's title describes it as an "interim report". That is because the investigation leading to this report has identified a number of issues that could not be resolved within the scope of the investigation. Issues of this kind are flagged in relevant parts of the report. Also, this report has a broad focus. It sets forth a strategy for providing robust storage of US spent fuel, and outlines a design approach for hardened, dispersed, dry storage. Additional analysis, supported by experiments, would be needed to test and refine this design approach and to determine the feasibility of implementing hardened, dispersed, dry storage at particular sites. That work would, in turn, set the stage for detailed, engineering-design studies that could lead to site-specific implementation. Moreover, a variety of governmental actions would be needed to support nationwide implementation of robust storage. For example, the NRC would need to develop new regulations and guidance. Also, the implementation program would require new financing arrangements, which would probably require new legislation.

An attack on a nuclear facility could be assisted by detailed information about the facility's vulnerability and the measures taken to defend the facility. Thus, certain categories of information about a facility are not appropriate for general distribution. However, experience shows that secrecy breeds incompetence, complacency and conflicts of interest within the organizations that are shielded from public view.[4] Thus, in the context of defending nuclear facilities, protection of the public interest requires that secrecy be limited in two respects. Firstly, the only information that should be withheld from the public is detailed technical information that would directly assist an attacker. Second, stakeholder groups should be fully engaged in the development and implementation of measures for defending nuclear facilities, through processes that allow debate but protect sensitive information.[5] It should be noted that this report does not contain sensitive information and is suitable for general distribution.

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[4] Thompson, 2002, Section X.

[5] Thompson, 2002a, Sections IX and X.

The remainder of this report begins, in Section 2, with the provision of some basic information about US nuclear power plants and their spent fuel. Then, Section 3 discusses the potential for attacks on nuclear facilities, describes the US government's response to this threat, and outlines a balanced response. Section 4 addresses the vulnerability of nuclear facilities to attack, describes the potential consequences of an attack, outlines a defense-in-depth strategy for a nuclear facility, and sets forth a national strategy for robust storage of spent fuel. Elaborating upon this proposed strategy for robust storage, Section 5 discusses the various factors that must be considered in planning hardened, dispersed, dry storage of spent fuel. Section 6 offers a design approach that accounts for these factors. A set of requirements for nationwide implementation of robust storage is described in Section 7. Conclusions are set forth in Section 8, and a bibliography is provided in Section 9. Documents cited in this report are, unless indicated otherwise, drawn from this bibliography.

2. Nuclear Power Plants and Spent Fuel in the USA

2.1 Status and Trends of Nuclear Power Plants and Spent Fuel

There are 103 commercial nuclear reactors operating in the USA at 65 sites in 31 states.[6] Of these 103 reactors, 69 are pressurized-water reactors (PWRs), 9 with ice-condenser containments and 60 with dry containments. The remaining 34 reactors are boiling-water reactors (BWRs), 22 with Mark I containments, 8 with Mark II containments and 4 with Mark III containments. In addition there are 27 previously-operating commercial reactors in various stages of storage or decommissioning. As of December 2000, all but 2 of the 103 operating reactors had been in service for at least 9 years, and 55 reactors had been in service for at least 19 years.[7] Thus, the reactor fleet is aging. The nominal duration of a reactor operating license is 40 years.

Four of the 103 operating reactors have design features intended to resist aircraft impact. The Limerick Unit 1, Limerick Unit 2 and Seabrook reactors were designed to withstand the impact of an aircraft weighing 6 tonnes, while the

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[6] In addition, Browns Ferry Unit 1, a BWR with a Mark I containment, is nominally operational. However, it is defueled and not in service.

[7] Data from the NRC website (www.nrc.gov), 24 April 2002.

Three Mile Island Unit 1 reactor was designed to withstand the impact of an aircraft weighing 90 tonnes. No other US reactor was designed to withstand aircraft impact.[8]

The core of a commercial nuclear reactor consists of several hundred fuel assemblies.[9] Each fuel assembly contains thousands of cylindrical, uranium-oxide pellets stacked inside long, thin-walled tubes made of zirconium alloy. These tubes are often described as the "cladding" of the fuel. After several years of use inside an operating reactor, a fuel assembly becomes "spent" in the sense that it is no longer suitable for generating fission power. Then, the fuel is discharged from the reactor and placed in a water-filled pool adjacent to the reactor but outside the reactor containment. This fuel, although spent, contains numerous radioactive isotopes whose decay generates ionizing radiation and heat.

After a period of storage in a pool, the thermal power produced by a fuel assembly declines to a level such that the assembly can be transferred to a dry-storage ISFSI. Current practice is to allow a minimum cooling period of 5 years before transfer to dry storage. However, this cooling period reflects an economic and safety tradeoff rather than a fundamental physical limit. Fuel cooled for a shorter period than 5 years could be transferred to dry storage, but in that case fewer assemblies could be placed in each dry-storage container. Alternatively, older and younger spent fuel (counting age from the date of discharge from the reactor) could be co-located in a dry-storage container. The major physical limit to placement of spent fuel in dry storage is the maximum temperature of the cladding, which the NRC now sets at 400 degrees C. This temperature limit constrains the allowable heat output of the fuel, which in turn constrains the cooling period.

At present, there are 20 ISFSIs in the USA, of which 15 are at sites where commercial reactors are in operation.[10] More ISFSIs will be needed, because the spent fuel pools at operating reactors are filling up. Analysis by Allison Macfarlane of MIT shows that, by 2005, almost two-thirds of reactor licensees

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[8] Markey, 2002, page 73.

[9] The number of fuel assemblies in a reactor core ranges from 121 (in some PWRs) to 764 (in some BWRs).

[10] Data from the NRC website (www.nrc.gov), 24 April 2002.

will face the need to acquire onsite dry-storage capacity, even if shipment of spent fuel away from the reactor sites begins in 2005.[11] NAC International, a consulting firm and vendor of dry-storage technology, reaches similar conclusions. NAC estimates that, at the end of 2000, about 6 percent of the US inventory of commercial spent fuel was stored in ISFSIs at reactor sites, whereas about 30 percent of the inventory will be stored in ISFSIs by 2010.[12] New ISFSIs entering operation by 2010 will generally be at reactor sites, although some might be at new sites. At present, only one proposed ISFSI at a new site -- Skull Valley, Utah -- seems to be a plausible candidate for operation by 2010.

If spent fuel is shipped away from a reactor site, the fuel could have three possible destinations. First, fuel could be shipped to another reactor site, which Carolina Power and Light Co. is now doing, shipping fuel from its Brunswick and Robinson reactors to its Harris site.[13] Second, fuel could be shipped to an ISFSI at an away-from-reactor site, such as Skull Valley. Third, fuel could be shipped to a repository at Yucca Mountain, Nevada. At Yucca Mountain, the fuel would be emplaced in underground tunnels. Under some scenarios for the operation of Yucca Mountain, emplacement would be preceded by a period of interim storage at the surface.

There seems to be no current planning for shipment of spent fuel to any reactor site other than Harris. Also, there are factors that argue against shipping fuel to an away-from-reactor ISFSI. First, such shipment would increase the overall transport risk, because fuel would be shipped twice, first from the reactor site to the ISFSI, and then from the ISFSI to the ultimate repository. Second, an away-from-reactor ISFSI would hold a comparatively large inventory of spent fuel, creating a potentially attractive target for an enemy.[14] Third, shipment to an away-from-reactor ISFSI would not free most reactor licensees from the

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[11] Macfarlane, 2001a.

[12] NAC, 2001. NAC estimates that the end-2000 US inventory of spent fuel was 42,900 tonnes, of which 2,430 tonnes was in ISFSIs. Also, NAC estimates that the 2010 US inventory will be 64,300 tonnes, of which 19,450 tonnes will be in ISFSIs.

[13] The Harris site features one reactor and four spent-fuel pools, and thus has more pool-storage capacity than other reactor sites. Spent fuel that is shipped to Harris is placed in a pool, and there is no current plan to build an ISFSI at Harris.

[14] The proposed Skull Valley ISFSI could hold 40,000 tonnes of spent fuel, according to the Private Fuel Storage website (www.privatefuelstorage.com), 4 October 2002.

obligation to build some ISFSI capacity at each reactor site.[15] Fourth, there is a risk that a large, away-from-reactor ISFSI would become, by default, a permanent repository, despite having no long-term containment capability. Finally, storage of spent fuel in reactor-site ISFSIs would be cheaper than shipping fuel to away-from-reactor ISFSIs.[16] Time will reveal the extent to which these factors affect the development of away-from-reactor ISFSIs at Skull Valley or elsewhere.

The Yucca Mountain repository project will not free reactor licensees from the obligation to develop ISFSI capacity, for three reasons. <u>First</u>, the Yucca Mountain repository may never open. This project is politically driven, does not have a sound scientific basis, and is going forward only because previously-specified technical criteria for a repository have been abandoned.[17] These deficiencies add weight to the determined opposition to this project by the state of Nevada and other entities. That opposition will also be fueled by concern about the risk of transporting fuel to Yucca Mountain. <u>Second</u>, decades will pass before fuel can be emplaced in a repository at Yucca Mountain. The US Department of Energy (DOE) claims that it can open the repository in 2010, but the US General Accounting Office has determined that several factors, including budget limitations, could extend this date to 2015 or later.[18] DOE envisions that, after the repository is opened, emplacement of fuel will occur over a period of at least 24 years and potentially 50 years.[19] This vision may prove to be optimistic. <u>Third</u>, under present federal law the Yucca Mountain repository will hold no more than 63,000 tonnes of commercial spent fuel.[20] Yet, the cumulative amount of commercial spent fuel to be generated during the lifetimes of the 103

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[15] Macfarlane, 2001a.

[16] Macfarlane, 2001b.

[17] Ewing and Macfarlane, 2002.

[18] Jones, 2002b.

[19] DOE, 2002. DOE contemplates the construction of a surface facility for interim storage of spent fuel at Yucca Mountain, especially if emplacement of fuel occurs over a period of 50 years. However, given the cost of this surface facility, a more likely alternative is that fuel will remain in ISFSIs until it is emplaced in the repository.

[20] DOE, 2002. The Nuclear Waste Policy Act limits the total amount of waste that can be placed in a first repository to 70,000 tonnes until a second repository is in operation. DOE plans to use 63,000 tonnes of this capacity for commercial spent fuel. DOE has studied the possible expansion of Yucca Mountain's capacity to include 105,000 tonnes of commercial spent fuel together with other wastes.

currently-licensed reactors is likely to exceed 80,000 tonnes.[21] Reactor licensees have shown strong interest in obtaining license extensions which, if granted, would lead to the production of a substantial additional amount of spent fuel.

To summarize the preceding paragraphs, it is clear that thousands of tonnes of spent fuel will be stored at reactor sites for several decades to come, in pools and/or ISFSIs. Similar amounts of fuel might be stored at away-from-reactor ISFSIs. Moreover, it is entirely possible that the Yucca Mountain repository will not open, with the result that the entire national inventory of spent fuel will be stored for decades, perhaps for 100 years or more, at reactor sites (in pools and/or ISFSIs) and/or at away-from-reactor ISFSIs. It is therefore imperative that each ISFSI is planned to allow for its possible extended use. The NRC has begun to recognize this need, by performing research to determine if dry storage of spent fuel can safely continue for a period of up to 100 years.[22]

2.2 Present Practice for Storing Spent Fuel

The technology that is currently used for storing spent fuel was developed without any consideration of the possibility of an attack. Nor was there any consideration of the possibility that spent fuel would be stored for many decades. Instead, the technology has been adapted to changing circumstances. Throughout this process, cost minimization has been a top priority.

When the present generation of nuclear power plants was designed, the nuclear industry and the US government both assumed that spent nuclear fuel would be reprocessed. Thus, spent-fuel pools were designed to hold only the amount of spent fuel that a reactor would discharge over a period of a few years. This was accomplished by equipping the pools with low-density, open-frame racks. However, in the mid-1970s the US government banned reprocessing, and the industry faced the prospect of an accumulating inventory of spent fuel.

Industry's response was to re-rack the pools at progressively higher densities, so that more fuel could be stored in a given pool. Now, pools across the nation are equipped with high-density, closed-frame racks that, in many instances, fill the floor area of the pool from wall to wall. The NRC has allowed this transition to

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[21] Macfarlane, 2001a.

[22] "Radioactive Waste Safety Research", from NRC website (www.nrc.gov), 23 September 2002.

occur despite the fact that a loss of water from a pool equipped with high-density racks can cause the zirconium cladding of the spent fuel to heat up, spontaneously ignite and burn, releasing a large amount of radioactive material to the atmosphere. This hazard is discussed further in Section 4.2.

Consistent with its focus on cost minimization, the nuclear industry has turned to alternative methods of fuel storage only when pools have begun to fill up. Preventing a pool fire has not been a consideration. Thus, dry-storage ISFSIs have not been introduced as an alternative to pool storage. Instead, standard industry practice is to fill a pool to nearly its maximum capacity, then to establish an onsite ISFSI into which spent fuel is transferred at a rate sufficient to open up space in the pool for fuel discharged from the reactor.[23] As a part of this strategy, ISFSIs have a modular design, and consist of an array of identical fuel-storage containers. These containers can be purchased and installed as needed, so that the ISFSI grows incrementally. There is nothing intrinsically wrong with this modular approach. Indeed, it has many advantages. The problem is that ISFSI capacity is expanding too slowly. Pools remain packed with fuel at high density, and can therefore be readily exploited as radiological weapons. Moreover, the ISFSIs themselves are not designed to resist attack.

The NRC has approved 14 different designs of dry-storage module for general use in ISFSIs.[24] In each of these designs, the central component of the module is a cylindrical, metal container whose interior is equipped with a metal basket structure into which spent fuel assemblies can be inserted. This container is filled with spent fuel while immersed in a spent fuel pool. Then, the container lid is attached, the container is removed from the pool and sealed, its interior is dried and filled with an inert gas (typically helium), and it is transferred to the ISFSI.

Available designs of dry-storage modules for ISFSIs fall into two basic categories. In one category, the metal container has a thick wall, and no enclosing structure is provided. This type of container can be described as a monolithic cask. Such a cask is placed in an ISFSI so that its axis is vertical. In the second category, the

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[23] In standard practice, the maximum storage capacity of a spent-fuel pool is less than the number of fuel-assembly slots in the pool, to allow for the possibility of offloading a full reactor core.

[24] "Dry Spent Fuel Storage Designs: NRC Approved for General Use", from NRC website (www.nrc.gov), 20 September 2002.

metal container is stored within an enclosing structure that is made primarily of concrete. For one variant of the second category -- the NUHOMS design -- the enclosing structure is a rectangular box and the axis of the metal container is horizontal. For other designs in the second category, the enclosing structure is a vertical cylinder.

One example of a monolithic cask is the CASTOR V/21, which was approved by the NRC in 1990 for general use and is employed at the Surrey ISFSI. This cask is about 4.9 meters high and 2.4 meters in diameter, and can hold 21 PWR fuel assemblies. The cask body is made of ductile cast iron with a wall thickness of about 38 cm. Circumferential fins on the outside of the cask body facilitate cooling by natural circulation of ambient air. Fully loaded, this cask weighs about 98 tonnes.[25] The NRC has approved this cask for storage but not for transport, although CASTOR casks are widely used in Europe for both purposes. CASTOR casks have not been popular in the US market.

The NUHOMS design was approved for general use in 1995. In this design, the metal container that holds the spent fuel is about 4.7 meters long and 1.7 meters in diameter, and has a wall thickness of 1.6 cm. This container, which is placed horizontally inside its enclosing structure, is made of stainless steel and can hold 24 PWR fuel assemblies or 52 BWR fuel assemblies. The enclosing structure is a reinforced-concrete box about 6.1 meters long, 4.6 meters high and 2.7 meters wide, with walls and roof 91 cm thick.[26] Ambient air passes into and out of this structure through vents, and cools the metal container by natural convection. NUHOMS modules are in use at the Davis-Besse site and some other reactor sites.

A module design that is increasingly popular in the USA is one in which the metal container that holds the fuel is stored vertically within a cylindrical structure -- called an "overpack" -- that is made primarily of concrete. One example of this type of module is the NAC-UMS, which the NRC approved for general use in 2000. In this instance, the metal container is about 4.7 meters high and 1.7 meters in diameter, and has a wall thickness of 1.6 cm. This container, which is made of stainless steel, can hold 24 PWR fuel assemblies or 56 BWR fuel assemblies. The overpack is a reinforced-concrete cylinder about 5.5 meters high

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[25] Raddatz and Waters, 1996.

[26] Ibid.

and 3.5 meters in diameter. The wall of this overpack consists of a steel liner 6.4 cm thick and a layer of concrete 72 cm thick. Ambient air passes into and out of the overpack through vents, and cools the metal container by natural convection. At the Maine Yankee nuclear plant, which is being decommissioned, sixty NAC-UMS modules are being installed. Most of the modules will be used to store spent fuel discharged from the plant. Some modules will store pieces of the reactor core shroud, which is classified as greater-than-Class C (GTCC) waste.[27]

These descriptions show that there are two distinct approaches to designing a dry-storage module. In one approach -- the monolithic cask -- the fuel is contained within a thick-walled metal cylinder that is comparatively robust.[28] In the second approach, the fuel is contained within a thin-walled metal container that has a limited capability to withstand an accident or an attack. During storage in an ISFSI, the metal container is surrounded by a concrete structure. During the initial transfer of fuel from the spent-fuel pool to the ISFSI, the metal container is surrounded by a transfer cask. If fuel is eventually shipped away from the site, the metal container would be placed inside a transport cask.

The second approach employs concrete -- a cheap material -- as the primary constituent of the storage overpack. Also, this approach allows transfer casks and transport casks to be used multiple times. Thus, this approach can be substantially cheaper -- about half as expensive, according to some reports -- than using monolithic casks.

At ISFSIs in the USA, dry-storage modules are placed on concrete pads in the open air. This approach contrasts with German practice, where dry-storage modules -- usually CASTOR casks -- are placed inside buildings. These ISFSI buildings are designed to have some resistance to attack from outside using anti-tank weapons. This aspect of their design has been informed by tests conducted in the period 1979-1980. At one German reactor site -- Neckarwestheim -- the ISFSI is inside a tunnel built into the side of a hill.[29]

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[27] Stone and Webster, 1999.

[28] The vendor of the CASTOR cask has developed a cheaper type of monolithic cask that is made as a steel-concrete-steel sandwich. This cask, known as CONSTOR, was developed for storage and transport of spent fuel from Russian reactors. The vendor states that the CONSTOR cask could be used in the USA. See: Peters et al, 1999.

[29] Janberg, 2002.

Another feature of the US approach to ISFSI design, consistent with the high priority that the nuclear industry assigns to cost minimization, is that dry-storage modules are packed closely together in large numbers. In illustration, consider the ISFSI that is proposed for the Diablo Canyon site in California. This facility would hold up to 140 of Holtec's HI-STORM 100 dry-storage modules, whose design is similar to the NAC-UMS system described above. These modules would sit on concrete pads, 20 casks per pad in a 4 by 5 array. Initially, two pads would be built. Ultimately, as the ISFSI expanded, seven pads would be positioned side by side, covering an area about 150 meters by 32 meters. Each module would be a vertical-axis cylinder about 3.7 meters in diameter and 5.9 meters high. The center-to-center spacing of modules would be about 5.5 meters, leaving a gap of 1.8 meters between modules. A security fence would surround the area needed for this array, at a distance of about 15 meters from the outermost modules. That fence would in turn be surrounded by a second fence, at a distance of about 30 meters from the outermost modules.[30]

2.3 Present Security Arrangements

The defense strategy for a nuclear site should be a component of the national strategy for homeland security, which should itself be a component of the overall national strategy for defense and security. At the site level, security should rely upon a defense-in-depth strategy, as discussed in Section 4.4 of this report. Logical planning of this kind may eventually occur. However, at present, the security arrangements for US nuclear facilities are riddled with inadequacies.

For two decades or more it has been clear to many people that nuclear power plants and other nuclear facilities are potential targets of acts of malice or insanity, including highly destructive acts. The NRC has repeatedly rebuffed citizens' requests that this threat be given the depth of analysis that would be expected, for example, in an environmental impact statement (EIS). This history is illustrated by a September 1982 ruling by the Atomic Safety and Licensing Board (ASLB) in the operating license proceeding for the Harris plant. The intervenor, Wells Eddleman, had proffered a contention alleging, in part, that the plant's safety analysis was deficient because it did not consider the

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[30] PG&E, 2001a.

"consequences of terrorists commandeering a very large airplane.....and diving it into the containment." In rejecting this contention the ASLB stated:[31]

> "This part of the contention is barred by 10 CFR 50.13. This rule must be read *in pari materia* with 10 CFR 73.1(a)(1), which describes the "design basis threat" against which commercial power reactors *are* required to be protected. Under that provision, a plant's security plan must be designed to cope with a violent external assault by "several persons," equipped with light, portable weapons, such as hand-held automatic weapons, explosives, incapacitating agents, and the like. Read in the light of section 73.1, the principal thrust of section 50.13 is that military style attacks with heavier weapons are not a part of the design basis threat for commercial reactors. Reactors could not be effectively protected against such attacks without turning them into virtually impregnable fortresses at much higher cost. Thus Applicants are not required to design against such things as artillery bombardments, missiles with nuclear warheads, or kamikaze dives by large airplanes, despite the fact that such attacks would damage and may well destroy a commercial reactor."

In this statement, the ASLB correctly described the design basis for US nuclear power plants. However, other design bases are possible. In the early 1980s the reactor vendor ASEA-Atom developed a preliminary design for a commercial reactor known as the PIUS reactor. The design basis for the PIUS reactor included events such as equipment failures, operator errors and earthquakes, but also included: (i) takeover of the plant for one operating shift by knowledgeable saboteurs equipped with large amounts of explosives; (ii) aerial bombardment with 1,000-pound bombs; and (iii) abandonment of the plant by the operators for one week.[32] It seems likely that this design basis would also provide protection against the impact of a large, fuel-laden aircraft. Clearly, ASEA-Atom foresaw a world in which acts of malice could pose a significant threat to nuclear facilities. The NRC has never exercised an equivalent degree of foresight.

For decades, the NRC has held the position that its licensees need not design or operate nuclear facilities to resist enemy attack. However, events have forced the NRC to progressively modify that position, so as to require greater protection

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[31] ASLB, 1982.

[32] Hannerz, 1983.

against acts of malice or insanity. A series of incidents, including the 1993 bombing of the World Trade Center, eventually forced the NRC to introduce, in 1994, regulations requiring licensees to defend nuclear power plants against vehicle bombs. The terrorist events of 11 September 2001 forced the NRC to require additional, interim measures by licensees to protect nuclear facilities, and are also forcing the NRC to consider strengthening its regulations in this area. Nevertheless, present NRC regulations require only a light defense of nuclear facilities.

Present NRC regulations for the defense of nuclear facilities are focused on site security. As described in Section 4.4, below, site security is one of four types of measure that, taken together, could provide defense in depth against acts of malice or insanity. The other three types of measure are, with some limited exceptions, ignored in present NRC regulations and requirements.[33]

At a nuclear power plant or an ISFSI, the NRC requires the licensee to implement a set of physical protection measures. According to the NRC, these measures provide defense in depth by taking effect within defined areas with increasing levels of security. In fact, these measures provide only a fraction of the protection that could be provided by a comprehensive defense-in-depth strategy. Within the outermost physical protection area, known as the Exclusion Area, the licensee is expected to control the area but is not required to employ fences and guard posts for this purpose. Within the Exclusion area is a Protected Area encompassed by physical barriers including one or more fences, together with gates and barriers at points of entry. Authorization for unescorted access within the Protected Area is based on background and behavioral checks. Within the Protected Area are Vital Areas and Material Access Areas that are protected by additional barriers and alarms; unescorted access to these locations requires additional authorization.

Associated with the physical protection areas are measures for detection and assessment of an intrusion, and for armed response to an intrusion. Measures for intrusion detection include guards and instruments whose role is to detect a potential intrusion and notify the site security force. Then, security personnel

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[33] For information about the NRC's present regulations and requirements for nuclear-facility defense, see: the NRC website (www.nrc.gov) under the heading "Nuclear Security and Safeguards", 2 September 2002; Markey, 2002; Meserve, 2002; and NRC, 2002.

seek additional information through means such as direct observation and closed-circuit TV cameras, to assess the nature of the intrusion. If judged appropriate, an armed response to the intrusion is then mounted by the site security force, potentially backed up by local law enforcement agencies and the FBI.

The design of physical protection areas and their associated barriers, together with the design of measures for intrusion detection, intrusion assessment and armed response, is required to accommodate a "design basis threat" (DBT) that is specified by the NRC in 10 CFR 73.1. The DBT for an ISFSI is less demanding than that for a nuclear power plant. At a nuclear power plant, the dominant sources of hazard are the reactor and the spent-fuel pool(s). In theory, both of these items receive the same level of protection, but in practice the reactor has been the main focus of attention. At present, the DBT for a nuclear power plant has the following features:[34]

> "(i) A determined violent external assault, attack by stealth, or deceptive actions, of several persons with the following attributes, assistance and equipment: (A) Well-trained (including military training and skills) and dedicated individuals, (B) inside assistance which may include a knowledgeable individual who attempts to participate in a passive role (e.g., provide information), an active role (e.g., facilitate entrance and exit, disable alarms and communications, participate in violent attack), or both, (C) suitable weapons, up to and including hand-held automatic weapons, equipped with silencers and having effective long range accuracy, (D) hand-carried equipment, including incapacitating agents and explosives for use as tools of entry or for otherwise destroying reactor, facility, transporter, or container integrity or features of the safeguards system, and (E) a four-wheel drive land vehicle used for transporting personnel and their hand-carried equipment to the proximity of vital areas, and
>
> (ii) An internal threat of an insider, including an employee (in any position), and
>
> (iii) A four-wheel drive land vehicle bomb."

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[34] 10 CFR 73.1, Purpose and Scope, from the NRC web site (www.nrc.gov), 2 September 2002.

For an ISFSI, the DBT is the same as for a nuclear power plant except that it does not include the use of a four-wheel drive land vehicle, either for transport of personnel and equipment or for use as a vehicle bomb. This is true whether the ISFSI is at a new site or a reactor site. Thus, an ISFSI at a reactor site will be less protected than the reactor(s) and spent-fuel pool(s) at that site. At a reactor site or a new site, an ISFSI will be vulnerable to attack by a vehicle bomb.

After the events of 11 September 2001, the NRC concluded that its requirements for nuclear power plant security were inadequate. Accordingly, the NRC issued an order to licensees of operating plants in February 2002, and a similar order to licensees of decommissioning plants in May 2002, requiring "certain compensatory measures", also described as "prudent, interim measures", whose purpose is to "provide the Commission with reasonable assurance that the public health and safety and common defense and security continue to be adequately protected in the current generalized high-level threat environment".[35] The additional measures required by these orders have not been publicly disclosed, but the NRC Chairman has stated that they include:[36]

(i) increased patrols;
(ii) augmented security forces and capabilities;
(iii) additional security posts;
(iv) vehicle checks at greater stand-off distances;
(v) enhanced coordination with law enforcement and military authorities;
(vi) additional restrictions on unescorted access authorizations;
(vii) plans to respond to plant damage from explosions or fires; and
(viii) assured presence of Emergency Plan staff and resources.

In addition to requiring these additional security measures, the NRC has established a Threat Advisory System that warns of a possible attack on a nuclear facility. This system uses five color-coded threat conditions ranging from green (low risk of attack) to red (severe risk of attack). These threat conditions conform with those used by the Office of Homeland Security. Also, the NRC is undertaking what it describes as a "top-to-bottom review" of its security

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[35] The quoted language is from page 2 of the NRC's order of 25 February 2002 to all operating power reactor licensees. Almost-identical language appears at page 2 of the NRC's order of 23 May 2002 to all decommissioning power reactor licensees.

[36] Meserve, 2002.

requirements. The NRC has stated that it expects that this review will lead to revision of the present DBT. The review is not proceeding on any specific schedule.

A cursory examination of the present DBT reveals significant limitations. For example, this threat does not include aircraft bombs (e.g., fuel-laden commercial aircraft, light aircraft packed with high explosive) or boat bombs.[37] This threat does not include lethal chemical weapons as instruments for disabling security personnel. This threat allows for one vehicle bomb, but not for a subsequent vehicle bomb that gains access to a vital area after the first bomb has breached a security barrier. Also, this threat envisions a small attacking force equipped with light weapons, rather than a larger force (e.g., 20 persons) equipped with heavier weapons such as anti-tank missiles. In sum, the present DBT is inadequate in light of the present threat environment. The compensatory measures required by the NRC's recent orders do not correct this deficiency.[38]

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[37] An NRC Fact Sheet (NRC, 2002) mentions new measures "against water-borne attacks", but it does not appear that these measures provide significant protection against boat bombs.

[38] POGO, 2002.

3. The Potential for Attacks on Nuclear Facilities

3.1 A Brief History

There is a rich history of events which show that acts of malice or insanity pose a significant threat to nuclear facilities around the world.[39] Consider some examples. Nuclear power plants under construction in Iran were repeatedly bombed from the air by Iraq in the period 1984-1987. Yugoslav Air Force fighters made a threatening overpass of the Krsko nuclear plant in Slovenia -- which was operating at the time -- a few days after Slovenia declared independence in 1991. So-called research reactors in Iraq were destroyed by aerial bombing by Israel in 1981 and by the United States in 1991. In 1987, Iranian radio threatened an attack by unspecified means on US nuclear plants if the United States attacked launch sites for Iran's Silkworm anti-ship missiles. Bombs damaged reactors under construction in Spain in 1977 and in South Africa in 1982. Anti-tank missiles struck a nuclear plant under construction in France in 1982. North Korean commandos were killed while attempting to come ashore near a South Korean plant in 1985. These and other events illustrate the "external" threat to nuclear plants. Numerous crimes and acts of sabotage by plant personnel illustrate the "internal" threat.

The threat posed to nuclear facilities by vehicle bombs became clearly apparent from an October 1983 attack on a US Marine barracks in Beirut. In a suicide mission, a truck was driven at high speed past a guard post and into the barracks. A gas-boosted bomb on the truck was detonated with a yield equivalent to about 5 tonnes of TNT, destroying the building and killing 241 Marines. In April 1984 a study by Sandia National Laboratories titled "Analysis of Truck Bomb Threats at Nuclear Facilities" was presented to the NRC. According to an NRC summary:[40] "The results show that unacceptable damage to vital reactor systems could occur from a relatively small charge at close distances and also from larger but still reasonable size charges at large setback distances (greater than the protected area for most plants)." Eventually, in 1994, the NRC introduced regulations that require reactor licensees to install defenses (gates, barriers, etc.) against vehicle bombs. The NRC was spurred into taking

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[39] Thompson, 1996.

[40] Rehm, 1984.

this action by two incidents in February 1993. In one incident, a vehicle bomb was detonated in a parking garage under the World Trade Center in New York. In the other incident, a man recently released from a mental hospital crashed his station wagon through the security gate of the Three Mile Island nuclear plant and rammed the vehicle under a partly-opened door in the turbine building.

The threat of suicidal aircraft attack on symbolic or high-value targets became clearly apparent from three incidents in 1994.[41] In April 1994 a Federal Express flight engineer who was facing a disciplinary hearing was travelling as a passenger on a company DC-10. He stormed the cockpit, severely wounded all three members of the crew with a hammer, and tried to gain control of the aircraft. The crew regained control with great difficulty. Federal Express employees said that the flight engineer was planning to crash into a company building. In September 1994 a lone pilot crashed a stolen single-engine Cessna into the grounds of the White House, just short of the President's living quarters. In December 1994 four Algerians hijacked an Air France Airbus 300, carrying 20 sticks of dynamite. The aircraft landed in Marseille, where the hijackers demanded that it be given a large fuel load -- three times more than necessary for the journey -- before flying to Paris. Troops killed the hijackers before this plan could be implemented. French authorities determined that the hijackers planned to explode the aircraft over Paris or crash it into the Eiffel Tower.

The incident involving the Federal Express flight engineer illustrates the vulnerability of industrial systems, including nuclear plants, to "internal" threats. That vulnerability is further illustrated by a number of incidents. In December 2000, Michael McDermott killed seven co-workers in a shooting rampage at an office building in Massachusetts. He had worked at the Maine Yankee nuclear plant from 1982 to 1988 as an auxiliary operator and operator before being terminated for exhibiting unstable behavior.[42] In 1997, Carl Drega of New Hampshire stockpiled weapons and killed four people -- including two state troopers and a judge -- on a suicide mission. He had passed security clearances at three nuclear plants in the 1990s.[43] In October 2000 a former US Army sergeant pleaded guilty to assisting Osama bin Laden in planning the bombing

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[41] Wald, 2001.

[42] Barnard and Kerber, 2001.

[43] Ibid.

of the US embassy in Nairobi, which occurred in 1998.[44] In June 1999, a security guard at the Bradwell nuclear plant in Britain hacked into the plant's computer system and wiped out records. It emerged that he had never been vetted and had two undisclosed criminal convictions.[45] These and other incidents demonstrate clearly that it is foolish to ignore or downplay the "internal" threat of acts of malice or insanity at nuclear plants.

The events mentioned in the preceding paragraphs occurred against a background of numerous acts of terrorism around the world. Many of these acts have been highly destructive. US facilities have been targets on many occasions, as illustrated by the bombing of the US embassy in Beirut in 1983, the embassies in Nairobi and Dar es Salaam in 1998, and the USS Cole in 2000. There have been repeated warnings that the threat of terrorism is growing and could involve the US homeland. For example, in 1998 three authors with high-level government experience wrote:[46]

> "Long part of the Hollywood and Tom Clancy repertory of nightmarish scenarios, catastrophic terrorism has moved from far-fetched horror to a contingency that could happen next month. Although the United States still takes conventional terrorism seriously, as demonstrated by the response to the attacks on its embassies in Kenya and Tanzania in August, it is not yet prepared for the new threat of catastrophic terrorism."

Some years ago the US Department of Defense established an advisory commission on national security in the 21st century. This commission -- often known as the Hart-Rudman commission because it was co-chaired by former Senators Gary Hart and Warren Rudman -- issued reports in September 1999, April 2000 and March 2001. The findings in the September 1999 report included the following:[47]

> "America will become increasingly vulnerable to hostile attack on our homeland, and our military superiority will not entirely protect us..............States, terrorists and other disaffected groups will acquire

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[44] Goldman, 2000.

[45] Maguire, 2001.

[46] Carter et al, 1998.

[47] Commission on National Security, 1999.

> weapons of mass destruction and mass disruption, and some will use them. Americans will likely die on American soil, possibly in large numbers."

It is clear that the potential for acts of malice or insanity at nuclear facilities -- including highly destructive acts -- has been foreseeable for many years, and has been foreseen. However, the terrorist attacks on the World Trade Center and the Pentagon on 11 September 2001 provided significant new information. These attacks conclusively demonstrated that the threat of highly-destructive acts of malice or insanity is a clear and present danger, and that no reasonable person can regard this threat as remote or speculative. According to press reports, US authorities have obtained information suggesting that the hijackers of United Airlines flight 93, which crashed in Pennsylvania on 11 September 2001, were planning to hit a nuclear plant.[48] This may be true or false, or the truth may never be known. Whatever the truth is, it would be foolish to regard nuclear plants as immune from attack.

The NRC has a longstanding policy of dismissing citizens' concerns about nuclear-facility accidents if the probability of such accidents is, in the agency's judgement, low. A body of analytic techniques known as probabilistic risk assessment (PRA) has been developed to support such judgements.[49] However, the NRC Staff has conceded that it cannot provide a quantitative assessment of the probability of an act of malice at a nuclear facility. In a memo to the NRC Commissioners, the Staff has stated:[50]

> "The staff, as a result of its ongoing work with the Federal national security agencies, has determined that the ability to quantify the likelihood of sabotage events at nuclear power plants is not currently supported by the state-of-the-art in PRA methods and data. The staff also believes that both the NRC and the other government stakeholders would need to conduct additional research and expend significant time and resources before it could even attempt to quantify the likelihood of sabotage events. In addition, the national security agencies, Intelligence

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[48] Rufford et al, 2001.

[49] The state of the art of PRA can be illustrated by: NRC, 1990. For a critique of PRA, see: Hirsch et al, 1989.

[50] Travers, 2001.

> Community, and Law Enforcement Agencies do not currently quantitatively assess the likelihood of terrorist, criminal, or other malevolent acts."

To date, there has been no determined attack on a US civilian nuclear facility. At present, we cannot quantitatively estimate the probability of such an attack in the future. However, from a qualitative perspective, it is clear that the probability is significant.

3.2 The Strategic Context

In considering the need to defend civilian nuclear facilities, one is obliged to take a broad view of the security environment. An ISFSI, for example, may remain in service for 100 years or more. During that period the level of risk will vary but the cumulative risk will continue to grow. Thus, the ISFSI's designer should take a conservative position in specifying a DBT. That position should be informed by a sober assessment of the range of threats that may be manifested over coming decades.

A number of strategic analysts have warned that world affairs may become more turbulent over the coming decades. Analysts have pointed to destabilizing factors that include economic inequality, poverty, political grievances, nationalism, environmental degradation and the weakening of international institutions. For example, a 1995 RAND study for the US Department of Defense contains the statement:[51]

> "If the worst does transpire, the world could combine the negative features of nineteenth-century geopolitics, twentieth-century political passions, and twenty-first century technology: a chronically turbulent world of unstable multi-polarity, atavistic nationalism, and modern armaments."

As another example, the Stockholm Environment Institute (SEI) has identified a range of scenarios for the future of the world over the coming decades, and has

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[51] Kugler, 1995, page xv.

studied the policies and actions that will tend to make each scenario come true. In summarizing this work, SEI states:[52]

> "In the critical years ahead, if destabilizing social, political and environmental stresses are addressed, the dream of a culturally rich, inclusive and sustainable world civilization becomes plausible. If they are not, the nightmare of an impoverished, mean and destructive future looms. The rapidity of the planetary transition increases the urgency for vision and action lest we cross thresholds that irreversibly reduce options -- a climate discontinuity, locking-in to unsustainable technological choices, and the loss of cultural and biological diversity."

SEI has specifically considered the implications of the September 2001 terrorist attacks, concluding:[53]

> "Certainly the world will not be the same after 9/11, but the ultimate implications are indeterminate. One possibility is hopeful: new strategic alliances could be a platform for new multinational engagement on a wide range of political, social and environmental problems. Heightened awareness of global inequities and dangers could support a push for a more equitable form of global development as both a moral and a security imperative. Popular values could eventually shift toward a strong desire for participation, cooperation and global understanding. Another possibility is ominous: an escalating spiral of violence and reaction could amplify cultural and political schisms; the new military and security priorities could weaken democratic institutions, civil liberties and economic opportunity; and people could grow more fearful, intolerant and xenophobic as elites withdraw to their fortresses."

In view of the range of possibilities for world order or turbulence over the coming decades, it would be prudent to assume that any US civilian nuclear facility could be the subject of a determined attack. Moreover, civilian nuclear facilities may be especially prime targets because of their symbolic connection with nuclear weapons. The US government flaunts its superiority in nuclear weapons and rejects any constraint on these weapons through international

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[52] Raskin et al, 2002, page 11.

[53] Ibid.

law.[54] At the same time, the government has signaled its willingness to attack Iraq because that country might acquire a nuclear weapon. It would be prudent to assume that this situation will motivate terrorist groups to search for ways to attack US nuclear facilities. For example, a terrorist group possessing a crude nuclear weapon might choose to use that weapon on a US civilian nuclear facility, because the target would be symbolic and the radioactive fallout from the weapon would be greatly amplified.

There is a natural tendency to look outside the country for sources of threat. However, an attack on a nuclear facility could also originate within the United States. The national strategy for homeland security contains the statement:[55]

> "Terrorist groups also include domestic organizations. The 1995 bombing of the Murrah Federal Building in Oklahoma City highlights the threat of domestic terrorist acts designed to achieve mass casualties. The US government averted seven planned terrorist acts in 1999 -- two were potentially large-scale, high-casualty attacks being organized by domestic extremist groups."

3.3 The US Government's Response to this Threat

The preceding discussion shows that there is a significant potential for a determined attack on a US civilian nuclear facility. Such an attack could employ a level of sophistication and violence that is characteristic of military operations. However, in most attack scenarios the attacking group would have a negligible capability for direct confrontation with US military forces. Thus, it is appropriate to think of an attack of this kind as a form of asymmetric warfare. The attacking group, be it domestic or foreign, will have a set of political objectives. For symbolic and practical reasons, the attackers will prefer to obtain their weapons and logistical resources inside the USA.

The White House has recently articulated a national security strategy for the United States.[56] This strategy rests primarily on the use of military force outside the country, to deter, disrupt or punish potential attackers. In support of this

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[54] Deller, 2002.

[55] Office of Homeland Security, 2002, page 10.

[56] White House, 2002.

concept, the strategy asserts the right to conduct unilateral, pre-emptive attacks around the world, and repudiates the International Criminal Court. Homeland security is regarded as a secondary form of defense, as illustrated by the statement:[57]

> "While we recognize that our best defense is a good offense, we are also strengthening America's homeland security to protect against and deter attack."

A strategy for homeland security has been articulated by the White House.[58] This document contains a section titled "Defending against Catastrophic Threats", and that section begins with an aerial photograph of a nuclear power plant. Yet, the section does not mention civilian nuclear facilities or the NRC. Thus, at the highest levels of strategic planning, the US government has nothing to say about the potential for an attack on a nuclear facility, or about the measures that could be taken to defend against such attacks. In fact, the US government seems largely unaware of this threat, and has delegated its responsibility to the NRC. As described in Section 2.3 of this report, the NRC's response to the threat has been limited and ineffectual.

This situation is symptomatic of a larger imbalance in national security and defense planning. As another example of imbalance, consider the threat of attack on the United States by inter-continental ballistic missiles (ICBMs). Large expenditures are devoted to the development of technologies that might, ultimately, allow missile warheads to be intercepted. Yet, in considering the respective risks of attack by missiles or other means, the US National Intelligence Council has stated:[59]

> "Nonmissile means of delivering weapons of mass destruction [WMD] do not provide the same prestige or degree of deterrence and coercive diplomacy associated with ICBMs. Nevertheless, concern remains about options for delivering WMD to the United States without missiles by state and nonstate actors. Ships, trucks, airplanes, and other means may be used. In fact, the Intelligence Community judges that US territory is

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[57] Ibid, page 6.

[58] Office of Homeland Security, 2002.

[59] National Intelligence Council, 2001, page 18.

> more likely to be attacked with WMD using nonmissile means, primarily because such means:
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> - Are less expensive than developing and producing ICBMs.
> - Can be covertly developed and employed; the source of the weapon could be masked in an attempt to evade retaliation.
> - Probably would be more reliable than ICBMs that have not completed rigorous testing and validation programs.
> - Probably would be much more accurate than emerging ICBMs over the next 15 years.
> - Probably would be more effective for disseminating biological warfare agent than a ballistic missile.
> - Would avoid missile defenses."

Using a similar line of argument, it is clear that US civilian nuclear facilities are candidates for attack under conditions of asymmetric warfare. They are large, fixed targets that are, at present, lightly defended. In the eyes of an enemy, they can be regarded as pre-deployed radiological weapons. They can be attacked using comparatively low levels of technology. Yet, the US government has largely ignored this threat.

At present, US policy for national security assigns a higher priority to offensive actions worldwide than to defensive actions within the homeland. This is a tradition of many years' standing. However, in the contemporary era of asymmetric warfare, this policy should be reconsidered. If our vulnerable infrastructure -- including nuclear facilities, the airlines, etc. -- is poorly defended, we may feel compelled to use military force aggressively around the world, in order to pre-empt or punish attackers. Such action poses the risk of arousing hostility and promoting anarchy, leading to new attacks on our homeland. The potential exists for an escalating spiral of violence. Strategic analysts have warned of this danger, both before and after the terrorist events of September 2001.[60]

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[60] See, for example: Sloan, 1995; Martin, 2002 (see especially the chapter by Conrad Crane in this volume); Mathews, 2002; and Conetta, 2002.

3.4 A Balanced Response to the Threat

The United States needs a balanced, mature strategy for national defense and international security. Within that strategy, it needs a balanced strategy for homeland security. Finally, as a part of homeland security, the nation needs a defense-in-depth strategy to protect its civilian nuclear facilities. At present, all three levels of strategy are deficient. However, articulation of a balanced strategy at all three levels is a task beyond the scope of this report.

This report does articulate, in Sections 4.4 and 4.5 respectively, a defense-in-depth strategy for nuclear facilities and a national strategy for robust storage of spent fuel. As an illustration of how these measures might be subsumed within a higher-level strategy, consider Carl Conetta's suggestion of a four-pronged campaign against the terrorist group al-Qaeda. The four prongs would be:[61]

> "(i) squeeze the blood flow of the organization -- its financial support system;
> (ii) throw more light on the organization's members and components through intelligence gathering activities;
> (iii) impede the movement of the organization by increasing the sensitivity of screening procedures at critical gateways -- borders, financial exchanges, arms markets, and transportation portals; and
> (iv) improve the protection of high-value targets."

4. Defending Nuclear Power Plants and Spent Fuel

4.1 Potential Modes and Instruments of Attack

It is not appropriate to publish a detailed discussion of scenarios whereby a nuclear power plant or a spent-fuel storage facility might be successfully attacked. However, it must be assumed that attackers are technically sophisticated and possess considerable knowledge about individual nuclear facilities. For decades, engineering drawings, photographs and technical analyses have been openly available for every civilian nuclear facility in the USA. This material is archived at many locations around the world. Thus, a public

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[61] Conetta, 2002, page 3.

discussion, in general terms, of potential modes and instruments of attack will not assist attackers. Indeed, such a discussion is needed to ensure that appropriate defensive actions are taken.

The safe operation of a US commercial reactor or a spent-fuel pool depends upon the fuel in the reactor or the pool being immersed in water. Moreover, that water must be continually cooled to remove fission heat or radioactive decay heat generated in the fuel. A variety of systems are used to ensure that water is available and is cooled, and that other safety-related functions -- such as shutdown of the fission reaction when needed -- are performed. Some of the relevant systems -- such as the switchyard -- are highly vulnerable to attack. Other systems are located inside reinforced-concrete structures -- such as the reactor auxiliary building -- that provide some degree of protection against attack. The reactor itself is inside a containment structure. At some plants, but not all, the reactor containment is a concrete structure that is highly reinforced and comparatively robust. Spent-fuel pools have thick concrete walls but are typically covered by lightweight structures.

A group of attackers equipped with highly-destructive instruments could take a brute-force approach to attacking a reactor or a spent-fuel pool. Such an approach would aim to directly breach the reactor containment and primary cooling circuit, or to breach the wall or floor of a spent-fuel pool. Alternatively, the attacking group could take an indirect approach, and many such approaches will readily suggest themselves to technically-informed attackers. Insiders, or outsiders who have taken over the plant, could obtain a release of radioactive material without necessarily employing destructive instruments. Some attack scenarios will involve the disabling of plant personnel, which could be accomplished by armed attack, use of lethal chemical weapons, or radioactive contamination of the site by an initial release of radioactive material.

Dry-storage ISFSIs differ from reactors and spent-fuel pools in that their operation is entirely passive. Thus, each dry-storage module in an ISFSI must be attacked directly. To obtain a release of radioactive material, the wall of the fuel container must be penetrated from the outside, or the container must be heated by an external fire to such an extent that the containment envelope fails. The attack could also exploit stored chemical energy in the zirconium cladding of spent fuel inside the module. Combustion of this cladding in air, if initiated, would generate heat that could liberate radioactive material from the fuel to the outside environment. A knowledgeable attacker could combine penetration of the fuel container with the initiation of combustion.

In some attack scenarios that involve the use of destructive instruments, the attackers may need to carry these instruments, by hand or in a vehicle, to the point of application. Such an action would require the overcoming of site-security barriers. In other scenarios, the instruments could be launched from a position outside some or all of these barriers.

One instrument that an attacking group will consider is a fuel-laden commercial aircraft. As indicators of the forces that could accompany the impact of such an aircraft, consider the weights and fuel capacities of some typical jetliners.[62] The Boeing 737-300 has a maximum takeoff weight of 56-63 tonnes and a fuel capacity of 20-24 thousand liters. The Boeing 747-400 has a maximum takeoff weight of 363-395 tonnes and a fuel capacity of 204-217 thousand liters. The Boeing 757 has a maximum takeoff weight of 104-116 tonnes and a fuel capacity of 43 thousand liters. The Boeing 767 has a maximum takeoff weight of 136-181 tonnes and a fuel capacity of 63-91 thousand liters.

Commercial jet fuel typically has a heat of combustion of about 38 MJ per liter. For comparison, 1 kilogram of TNT will yield 4.2 MJ of energy. Thus, complete combustion of 1 liter of jet fuel will yield energy equivalent to that from 9 kilograms of TNT. Complete combustion of 100 thousand liters of jet fuel -- about half the fuel capacity of a Boeing 747-400 -- will yield energy equivalent to that from 900 tonnes of TNT. Thus, the impact of a fuel-laden aircraft could lead to a violent fuel-air explosion. Fuel-air munitions have been developed that yield more than 5 times the energy of their equivalent weight in TNT, and create a blast overpressure exceeding 1,000 pounds per square inch.[63] A fuel-air explosion arising from an aircraft impact will be less efficient than a munition in converting combustion energy into blast, but could generate a highly-destructive blast if fuel vapor accumulates in a confined space before igniting.

The attacking group might choose to use an explosive-laden, general-aviation aircraft as an instrument of attack. Such an aircraft could be much easier to obtain than a large commercial aircraft. In 1999, about 219,000 general-aviation

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[62] Jackson, 1996.

[63] Gervasi, 1977.

aircraft were in use in the USA.[64] Of these, about 172,000 had piston engines, 5,700 were turboprops, 7,100 were turbojets and 7,400 were helicopters.[65] In the piston-engine category, about 21,000 aircraft had two engines, the remainder having one engine. The general-aviation fleet in 2002 must be similar to that in 1999.

It is clear that terrorist groups can readily obtain and use explosive materials. Such use is a tragic accompaniment to political disputes around the world. Moreover, explosives are easily obtainable within the USA. In 2001, about 2.4 million tonnes of explosives were sold in the USA. Most of this material consisted of blasting agents and oxidizers used for mining, quarrying and construction. Much of the blasting material consisted of mixtures of ammonium nitrate and fuel oil, which are readily-available materials. It is also noteworthy that current law in many US states allows high explosives to be purchased without a permit or a background check.[66]

Another instrument of attack that could be used is an anti-tank missile. Large numbers of these missiles exist around the world, and they can be obtained by many terrorist groups. As an example, consider the tube-launched, optically-tracked, wire-guided (TOW) anti-tank missile system, which is now marketed by Raytheon.[67] This system is said to be the most successful anti-tank missile system in the world. It first entered service with the US Army in 1970 and is currently in use by more than 40 military forces. As of 1991, more than 460,000 TOW missiles had been produced, and the cumulative production up to 2002 must be substantially higher. The TOW missile has a maintenance-free storage life of 20 years, and all versions of the missile can be fired from any TOW launcher. TOW systems have been sold to countries such as Colombia, Iran, Lebanon, Pakistan, Somalia, Yugoslavia and South Yemen, so it must be presumed that they can be obtained by terrorist groups. There is no indication from available literature that the TOW missile or launcher is self-disabling if it

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[64] Data from the website of the General Aviation Manufacturers Association (www.generalaviation.org), 30 September 2002.

[65] The remainder of the fleet consisted of gliders, balloons/blimps and experimental aircraft.

[66] Information from the website of the Institute of Makers of Explosives (www.ime.org), 30 September 2002.

[67] Information from: Hogg, 1991; Gervasi, 1977; Raytheon website (www.raytheon.com), 26 September 2002; US Marine Corps website (www.hqmc.usmc.mil), 26 September 2002; and Canadian Army website (www.army.forces.gc.ca), 27 September 2002.

passes into inappropriate hands. In connection with the availability of systems of this kind, it is interesting to note that, in August 2002, federal agents seized more than 2,300 unregistered armor-piercing missiles from a private, counter-terrorism training school in New Mexico.[68]

Modern anti-tank missiles are reliable, accurate and easy to use. They are capable of penetrating considerable thicknesses of armor plate using a shaped-charge warhead that is designed for this purpose. Some types of missile can also be equipped with a general-purpose warhead that would be used for attacking targets such as fortified bunkers and gun emplacements. All types can be set up and reloaded comparatively quickly. Consider the TOW missile system as an example. The launcher can be mounted on a light vehicle or carried a short distance and mounted on the ground on a tripod. A late-model TOW launcher weighs about 93 kilograms, the guidance set about 24 kilograms and each missile about 22 kilograms. A rate of fire of about two rounds per minute can be sustained, and the missile has a range in excess of 3,000 meters. It is reported that an early-model TOW missile can blow a hole as much as two feet in diameter in the armor of a Soviet T-62 tank, or cut through three feet of concrete. Later-model TOW missiles are more capable.[69]

A nuclear weapon could be used to attack a civilian nuclear facility. This possibility was a source of concern during the Cold War, and there is a body of technical and policy literature on this subject.[70] Russia retains the capability to attack US nuclear facilities using ICBMs with thermonuclear warheads, and might be motivated at some future date to threaten or implement such an attack. A greater concern in the current period is that a sub-national group, with or without the assistance of a government, might use a comparatively low-yield fission weapon -- perhaps one with an explosive yield in the vicinity of 10 kilotonnes of TNT equivalent -- to attack a US nuclear facility. The means of delivery might be a land vehicle or a general-aviation aircraft. Such a weapon would not be easy to obtain, but many knowledgeable experts have warned that the fissionable material for a simple nuclear weapon could be diverted from

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[68] Reuters, 2002.

[69] Information from: Hogg, 1991; Gervasi, 1977; Raytheon website (www.raytheon.com), 26 September 2002; US Marine Corps website (www.hqmc.usmc.mil), 26 September 2002; and Canadian Army website (www.army.forces.gc.ca), 27 September 2002.

[70] See, for example: Fetter, 1982; Fetter and Tsipis, 1980; and SIPRI, 1981.

poorly-secured stocks in Russia and elsewhere.[71] There is even the possibility that a complete nuclear weapon will be diverted. A high-level group advising the US government has examined the security of nuclear weapons and fissile material in Russia, concluding:[72]

> "The most urgent unmet national security threat to the United States today is the danger that weapons of mass destruction or weapons-usable material in Russia could be stolen and sold to terrorists or hostile nation states and used against American troops abroad or citizens at home. This threat is a clear and present danger to the international community as well as to American lives and liberties."

4.2 Vulnerability to Attack

The preceding section of this report describes, in deliberately general terms, the potential modes and instruments of attack on a nuclear power plant or an ISFSI. In discussing the vulnerability of nuclear facilities to such attacks, one must be similarly careful to avoid disclosing sensitive information. In this context, the word "vulnerability" refers to the potential for an act of malice or insanity to cause a release of radioactive material to the environment. At the site of a nuclear power plant or an ISFSI, most of the radioactive material at the site is in the reactor(s), the spent-fuel pool(s) and the ISFSI modules.

Every US commercial reactor has been subjected to a PRA-type study by the licensee. This study addressed the reactor's potential to experience accidents, but did not consider acts of malice or insanity. No spent-fuel pool or ISFSI has been subjected to a PRA-type study or a study of its vulnerability to acts of malice or insanity. Indeed, there has never been a comprehensive, published study of the vulnerability of any US nuclear facility to acts of malice or insanity. Spurred by the terrorist events of September 2001, the NRC has sponsored secret, ongoing studies on the vulnerability of nuclear facilities to impact by a large commercial aircraft. Available information suggests that these studies are narrow in scope and will provide limited guidance regarding the overall vulnerability of nuclear facilities.

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[71] See, for example: Baker, Cutler et al, 2001; Bunn et al, 2002; and Sokolski and Riisager, 2002.

[72] Baker, Cutler et al, 2001, first page of Executive Summary.

A comprehensive study of a facility's vulnerability would begin by identifying a range of potential attacks on the facility. The probability of each potential attack would be qualitatively estimated, with consideration of the factors (e.g., international events, changing availability of instruments of attack) that could alter the probability over time. Site-specific factors affecting the feasibility and probability of attack scenarios include local terrain and the proximity of coastlines, airports, population centers and national symbols. A variety of modes and instruments of attack would be considered, of the kind discussed in Section 4.1.

After identifying a range of potential attacks, a comprehensive study would examine the vulnerability of the subject facility to those attacks. This could be done by adapting and extending known techniques of PRA, with an emphasis on the logical structure of PRA rather than the numerical probabilities of events. The analysis would consider the potential for interactions among facilities at a site. For example, a potentially important interaction could be the prevention of personnel access at one facility (e.g., a spent-fuel pool) due to a release of radioactive material at another facility (e.g., a reactor). Attention would be given to the potential for "cascading" scenarios in which attacks at some parts of a nuclear-power-plant site (e.g., control room, switchyard, diesel generators) lead to releases from reactors and/or spent fuel pools that were not directly attacked.

In the absence of any comprehensive study of vulnerability, one is obliged to rely upon partial information. Also, one must contend with misleading information disseminated by the nuclear industry. An egregious example is a recent paper in Science, a journal that is usually sound.[73] Two points illustrate the remarkably low scientific quality of this paper. First, the paper cites an experiment performed at Sandia National Laboratories as proof that an aircraft cannot penetrate the concrete wall of a reactor containment. In response, Sandia officials have stated that the test has no relevance to the structural behavior of a containment wall, a fact that is readily evident from the nature of the test.[74] Second, the paper states, in connection with the vulnerability of spent-fuel shipping casks, that "there is virtually nothing one could do to these shipping casks that would cause a significant public hazard".[75] A report prepared by

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[73] Chapin et al, 2002.

[74] Jones, 2002a.

[75] Chapin et al, 2002, page 1997.

Sandia for the NRC is cited in support of this statement.[76] Yet, examination of the Sandia report reveals that it considers only the effects on a shipping cask of impact and fire pursuant to a truck or train accident. The Sandia report does not address the effects of, for example, attack by a TOW missile, a vehicle bomb, or a manually-placed charge.

A rough indication of the vulnerability of a nuclear power plant to aircraft impact can be obtained from the PRA for the Seabrook reactor. This reactor is a 4-loop Westinghouse PWR with a large, dry containment, and is one of only four US reactors that were specifically designed to resist impact by an aircraft, a 6-tonne aircraft in the case of Seabrook.[77] The Seabrook PRA finds that any direct impact on the containment by an aircraft weighing more than 37 tonnes will lead to penetration of the containment and a breach in the reactor coolant circuit. Also, the Seabrook PRA finds that a similar impact on the control building or auxiliary building will inevitably lead to a core melt.[78] All of the typical, commercial aircraft mentioned in Section 4.1 of this report weigh considerably more than 37 tonnes. Moreover, the Seabrook PRA does not consider the effects of a fuel-air explosion and/or fire as an accompaniment to an aircraft impact. Finally, this PRA, like other PRAs, does not consider malicious acts such as an attack on the reactor by an explosive-laden general-aviation aircraft.

Analytic techniques are available for estimating the effects that aircraft impact will have on the structures and equipment of a nuclear facility. However, those techniques focus on the kinetic energy of the impacting aircraft. The effects of an accompanying fuel-air explosion and/or fire are given, at best, a crude analysis. A 1982 review by Argonne National Laboratory of the state of the art for aircraft impact analysis stated:[79]

> "Based on the review of past licensing experience, it appears that fire and explosion hazards have been treated with much less care than the direct aircraft impact and the resulting structural response. Therefore, the claim that these fire/explosion effects do not represent a threat to nuclear power plants has not been clearly demonstrated."

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[76] Sprung et al, 2000.

[77] Markey, 2002, page 73.

[78] PLG, 1983, pp 9.3-10 to 9.3-11.

[79] Kot et al, 1982, page 78.

Examination of PRAs and related studies for nuclear facilities shows that the Argonne statement remains valid today. Indeed, in view of the large amount of energy that can be liberated in a fuel-air fire or explosion, previous analyses of aircraft impacts may have grossly underestimated the vulnerability of nuclear facilities to such impacts.

The vulnerability of spent-fuel pools deserves special attention because these pools contain large amounts of long-lived radioactive material that could be liberally released to the atmosphere during a fire.[80] The potential for such a fire exists because the pools have been equipped with high-density racks. In the 1970s, the spent-fuel pools of US nuclear power plants were typically equipped with low-density, open-frame racks. If water were partially or totally lost from such a pool, air or steam could circulate freely throughout the racks, providing cooling to the spent fuel. By contrast, the high-density racks that are used today have a closed structure. To suppress criticality, each fuel assembly is surrounded by solid, neutron-absorbing panels, and there is little or no gap between the panels of adjacent cells. This configuration allows only one mode of circulation of air and steam around a fuel assembly -- vertically upward within the confines of the neutron-absorbing panels.

If water is totally lost from a high-density pool, air will pass downward through available gaps such as the gap between the pool wall and the outer faces of the racks, will travel horizontally across the base of the pool, will enter each rack cell through a hole in its base, and will rise upward within the cell, providing cooling to the spent fuel assembly in that cell. If the fuel has been discharged from the reactor comparatively recently, the flow of air may be insufficient to remove all of the fuel's decay heat. In that case, the temperature of the fuel cladding may rise to the point where a self-sustaining, exothermic oxidation reaction with air will begin. In simple terms, the fuel cladding -- which is made of zirconium alloy -- will begin to burn. The zirconium-alloy cladding can also enter into a self-sustaining, exothermic oxidation reaction with steam. Other exothermic oxidation reactions can also occur. For simplicity, the occurrence of one or more of the possible reactions can be referred to as a pool fire.

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[80] The NRC has published a variety of technical documents that address spent-fuel-pool fires. The most recent of these documents is: Collins et al, 2000.

In many scenarios for loss of water from a pool, the flow of air that is described in the preceding paragraph will be blocked. For example, a falling object (e.g., a fuel-transfer cask) might distort rack structures, thereby blocking air flow. As another example, an attack might cause debris (e.g., from the roof of the fuel handling building) to fall into the pool and block air flow. The presence of residual water in the bottom of the pool would also block air flow. In most scenarios for loss of water, residual water will be present for significant periods of time. Blockage of air flow, for whatever reason, will lead to ignition of fuel that has been discharged from a reactor for long periods -- potentially 10 years or longer.[81] The NRC Staff failed to understand this point for more than two decades.[82]

Partial or total loss of water from a spent fuel pool could occur through leakage, evaporation, siphoning, pumping, displacement by objects falling into the pool, or overturning of the pool. These modes of loss of water could arise, directly or indirectly, through a variety of attack scenarios. As a simple example, consider leakage as a direct result of aircraft impact on the wall of a pool. An NRC Staff study includes a crude, generic analysis of the conditional probability that aircraft impact will cause a loss of water from a spent fuel pool.[83] The pool is assumed to have a 5-ft-thick reinforced concrete wall. Impacting aircraft are divided into the categories "large" (weight more than 5.4 tonnes) and "small" (weight less than 5.4 tonnes). The Staff estimates that the conditional probability of penetration of the pool wall by a large aircraft is 0.45, and that 50 percent of penetration incidents involve a loss of water which exposes fuel to air. Thus, the Staff estimates that, for impact of a large aircraft, the conditional probability of a loss of water sufficient to initiate a pool fire is 0.23 (23 percent).

An earlier paragraph in Section 4.2 of this report mentions the potential for interactions among facilities on a site, and points out that a potentially important interaction could be the prevention of personnel access at one facility (e.g., a spent-fuel pool) due to a release of radioactive material at another facility (e.g., a reactor). This type of interaction was partially addressed during a licensing proceeding for the Harris nuclear power plant. In that proceeding, the NRC Staff

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[81] The role of residual water in promoting ignition of old fuel is discussed in: Thompson, 1999, Appendix D.

[82] Thompson, 2002a, Section II.

[83] Collins et al, 2000, page 3-23 and Appendix 2D.

conceded that a fire in one spent-fuel pool would preclude the provision of cooling and makeup to nearby pools, thereby leading to evaporation of water from the nearby pools followed by fires in those pools.[84] This situation would arise mostly because the initial fire would contaminate the site with radioactive material, generating high radiation fields that preclude personnel access. An analogous situation could arise in which the release of radioactive material from a damaged reactor precludes the provision of cooling and makeup to nearby pools. For example, an attack on a reactor could lead to a rapid-onset core melt with an open containment, accompanied by a raging fire. That event would create high radiation fields across the site, potentially precluding any access to the site by personnel. One can envision a variety of "cascading" scenarios, in which there might eventually be fires in all of the pools at a site, accompanied by core-melt events at all of the reactors.

A pool fire could begin comparatively soon after water is lost from a pool. For example, suppose that most of the length of the fuel assemblies is exposed to air, but the flow of air to the base of the racks is precluded by residual water or a collapsed structure. In that event, fuel heatup would be approximately adiabatic. Fuel discharged for 1 month would ignite in less than 2 hours, and fuel discharged for 3 months would ignite in about 3 hours. The fire would then spread to older fuel. Once a fire has begun, it could be impossible to extinguish. Spraying water on the fire would feed an exothermic zirconium-steam reaction that would generate flammable hydrogen. High radiation fields could preclude the approach of firefighters.

The dry-storage modules used at ISFSIs are passively safe, as discussed in Section 4.1 of this report. Thus, an attacking group that seeks to obtain a radioactive release from an ISFSI must attack each module directly. To obtain a release of radioactive material, the wall of the fuel container must be penetrated from the outside, or the container must be heated by an external fire to such an extent that the containment envelope fails. In addition, a technically-informed and appropriately-equipped attacker could exploit stored chemical energy in the zirconium cladding of the stored spent fuel. Such an attacker would arrange for penetration of the container to be accompanied by the initiation of combustion of the cladding in air. Combustion would generate heat that could liberate radioactive material from the fuel to the outside environment. Initiation of

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[84] Parry et al, 2000, paragraph 29.

combustion could be facilitated by the presence of zirconium hydride in the fuel cladding, which is a characteristic of high-burnup fuel. The NRC Staff has noted that zirconium hydride can experience auto-ignition in air.[85]

There is a body of literature that addresses aspects of the vulnerability of dry-storage modules for ISFSIs. Consider some examples. <u>First</u>, NAC International has analyzed the impact of a Boeing 747-400 aircraft on a NAC-UMS storage module of the type discussed in Section 2.2 of this report.[86] According to NAC, this analysis shows that failure of the fuel container would not occur, either from impact or fire. <u>Second</u>, analyses of aircraft impact have been done in Germany in connection with the licensing of ISFSIs that employ CASTOR casks. In Germany, ISFSIs are typically located inside buildings to provide some protection against anti-tank missiles, a practice which creates the potential for pooling of jet fuel following an aircraft impact. As a result, the intensity and duration of fire has become a key issue in technical debates about the release of radioactive material following an aircraft impact.[87] <u>Third</u>, in a test done in Germany in 1992, a shortened CASTOR cask containing simulated fuel assemblies made from depleted uranium was penetrated by a static, shaped charge, in order to simulate attack by an anti-tank missile.[88] The metal jet created by the shaped charge caused a small amount of finely-divided uranium to be released from the cask, but this test did not account for several important factors that are discussed in the following paragraph. <u>Fourth</u>, analyses of aircraft, cruise-missile and dummy-bomb impact on a dry-storage module have been done in connection with the licensing of the proposed Skull Valley ISFSI. The accompanying technical debate suggests that the magnitude of the radioactive release following penetration of a fuel container would be sensitive to the fraction of a fuel assembly's inventory of radionuclides, such as cesium-137, that would be present in the pellet-cladding gap region.[89]

The literature that is exemplified in the preceding paragraph addresses only some of the attack scenarios and physical-chemical phenomena that would be addressed in a comprehensive assessment of the vulnerability of dry-storage

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[85] Collins et al, 2000, page A1B-3.

[86] McCough and Pennington, 2002).

[87] Hirsch, 2002.

[88] Lange et al, 2002.

[89] Resnikoff, 2001.

modules. Such an assessment would consider a range of instruments of attack, including anti-tank missiles, manually-placed charges, a vehicle bomb or an aircraft bomb. Modes of attack that promote zirconium ignition would be considered. Factors that would be accounted for include: (i) the presence of zirconium hydride in fuel cladding; (ii) radioactive-decay heat in fuel pellets; (iii) a pre-attack temperature characteristic of an actual, operating module; and (iv) source-term phenomena (such as the gap inventory of radionuclides) that are characteristic of high-burnup fuel. There is no evidence from published literature that a comprehensive vulnerability assessment of this kind has been made. Some components of a comprehensive assessment may have been performed secretly. For example, there are rumors of NRC-sponsored tests that have combined penetration of a fuel container with incendiary effects. Given the information that is available, it is prudent to assume that a variety of modes and non-nuclear instruments of attack could release to the atmosphere a substantial fraction of the radioactive inventory of a dry-storage module.

As indicated in Section 4.1 of this report, it is prudent to assume that a low-yield nuclear weapon (with a yield of perhaps 10 kilotonnes of TNT equivalent) may be used as an instrument of attack at an ISFSI. A thorough assessment of the vulnerability of ISFSI modules to such an attack would require detailed analysis. Absent such an analysis, rough judgements can be made. Consider, for example, a 10-kilotonne ground burst at an unhardened, surface-level ISFSI of the usual US type. It is reasonable to assume that any module within the crater area would, as a result of blast effects and heating by the fireball, become divided into fragments, many of them small enough to travel downwind for many kilometers before falling to earth. A 10-kilotonne ground burst over sandstone, which is perhaps representative of an ISFSI, would yield a crater about 68 meters in diameter and 16 meters deep.[90]

As an indication of the potential release of radioactive material following a nuclear detonation at an ISFSI, consider a 10-kilotonne groundburst at an ISFSI that employs vertical-axis fuel-storage modules with a center-to-center distance of 5.5 meters, as would be the case for the proposed Diablo Canyon facility. Given a large, square array of such modules, about 120 modules would fall within the 68-meter diameter of the anticipated crater. Thus, it is reasonable to assume that 100 percent of the volatile radionuclides (such as cesium-137) in 120

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[90] Glasstone, 1962, Chapter VI.

modules, together with a lesser fraction of the non-volatile radionuclides, would be carried downwind in a radioactive plume. This quantity could be an over-estimate, because the ISFSI has finite dimensions and is not an infinite array, or it could be an under-estimate, because damage to modules outside the crater is not considered. Note that a NAC-UMS module, as used at Maine Yankee, can hold 24 PWR fuel assemblies or 56 BWR fuel assemblies.[91] The HI-STORM 100 modules that would be used at the proposed Diablo Canyon ISFSI can each hold 32 PWR fuel assemblies.[92]

The two preceding paragraphs show that a nuclear-weapon attack on an unhardened, undispersed ISFSI could yield a huge release of radioactive material. However, it should be noted that an attack with non-nuclear instruments is more likely, and that such an attack on an ISFSI would yield a much smaller release. By comparison with an ISFSI , a high-density spent-fuel pool is much more vulnerable. All that is necessary to initiate a pool fire is to remove water from the pool, which an attacking group could accomplish in various ways. A group that has seized control of a nuclear power plant could empty the pool(s) simply by siphoning or pumping.

4.3 Consequences of Attack

The offsite radiological consequences of a potential attack on a nuclear facility can be estimated with widely-used, computer-based models. In order to apply such a model, one must have an estimate of the accident "source term". The source term is a set of characteristics -- magnitude, timing, etc. -- that describe a potential release of radioactive material to the atmosphere. Using this source term, together with weather data for the release site, the model can estimate the magnitude of each of a range of radiological impacts at specified locations downwind.

A full analysis of this type is beyond the scope of this report. Instead, some scoping calculations are presented here, focussing on one radioactive isotope -- cesium-137. This isotope is a useful indicator of the potential, long-term consequences of a release of radioactive material. Cesium-137 has a half-life of 30 years, and accounts for most of the offsite radiation exposure that is

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[91] Stone and Webster, 1999.

[92] PG&E, 2001a.

attributable to the 1986 Chernobyl reactor accident, and for about half of the radiation exposure that is attributable to fallout from nuclear weapons tests in the atmosphere.[93] Cesium is a volatile element that would be liberally released during nuclear-facility accidents or attacks. For example, an NRC study has concluded that a generic estimate of the release fraction of cesium isotopes during a spent-fuel-pool fire -- that is, the fraction of the pool's inventory of cesium isotopes that would reach the atmosphere -- is 100 percent.[94] It is reasonable to assume such a high release fraction because cesium is volatile, because a fire in a high-density pool, once initiated, would eventually involve all of the fuel in the pool, and because pool buildings are not designed as containment structures.

The Indian Point site provides an illustration of the inventories of cesium-137 at nuclear facilities. Three nuclear power plants have been built at this site. Unit 1 had a rated power of 590 MW (thermal) and operated from 1962 to 1974.[95] Unit 2 has a rated power of 2,760 MW (thermal), commenced operating in 1974, and remains operational. Unit 3 has a rated power of 2,760 MW (thermal), commenced operating in 1976, and remains operational. Unit 2 and Unit 3 each employ a four-loop Westinghouse PWR with a large, dry containment. The reactor cores of Unit 2 and Unit 3 each contain 193 fuel assemblies.[96]

Unit 2 and Unit 3 are each equipped with one spent-fuel pool. The capacity of the Unit 2 pool is 1,374 fuel assemblies, while the capacity of the Unit 3 pool is 1,345 fuel assemblies.[97] Both pools employ high-density racks. As of November 1998, the Unit 2 pool contained 917 fuel assemblies, while the Unit 3 pool contained 672 fuel assemblies.[98] It can be assumed that the number of fuel assemblies in each pool has increased since November 1998.

The inventory of cesium-137 in the Indian Point pools can be readily estimated. Three parameters govern this estimate -- the number of spent fuel assemblies, their respective burnups, and their respective ages after discharge. Assuming a

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[93] DOE, 1987.

[94] Sailor et al, 1987.

[95] Thompson and Beckerley, 1973, Table 4-1.

[96] Larson, 1985, Table A-2.

[97] "Reactor Spent Fuel Storage", from NRC website (www.nrc.gov), 30 May 2001.

[98] Ibid.

representative, uniform burnup of 46 GW-days per tonne, one finds that the 917 fuel assemblies that were in the Unit 2 pool in November 1998 now contain about 42 million Curies (460 kilograms) of cesium-137. The 672 fuel assemblies that were in the Unit 3 pool in November 1998 now contain about 31 million Curies (350 kilograms) of cesium-137. Additional amounts of cesium-137 would be present in any fuel assemblies that have been added to these pools since November 1998.

For comparison, the cores of the Indian Point Unit 2 and Unit 3 reactors each contain about 6 million Curies (67 kilograms) of cesium-137. Also, it should be noted that the Chernobyl reactor accident of 1986 released about 2.4 million Curies (27 kilograms) of cesium-137 to the atmosphere. That release represented 40 percent of the Chernobyl reactor core's inventory of 6 million Curies (67 kg) of cesium-137.[99] Also, atmospheric testing of nuclear weapons led to the deposition of about 20 million Curies (220 kilograms) of cesium-137 across the land and water surfaces of the Northern Hemisphere.[100]

As another comparison, consider a HI-STORM 100 dry-storage module that contains 32 PWR fuel assemblies. Assuming that these fuel assemblies have an average post-discharge age of 20 years, this module would contain about 1.3 million Curies (14 kilograms) of cesium-137.

Now consider the potential for a spent-fuel-pool fire at Indian Point. As explained above, it is reasonable to assume that 100 percent of the cesium-137 in a pool would be released to the atmosphere in the event of a fire. The cesium-137 would be released to the atmosphere in small particles that would travel downwind and be deposited on the ground and other surfaces. The deposited particles would emit intense gamma radiation, leading to external, whole-body radiation doses to exposed persons. Cesium-137 would also contaminate water and foodstuffs, leading to internal radiation doses.

One measure of the scope of radiation exposure attributable to deposition of cesium-137 is the area of land that would become uninhabitable. For illustration, one can assume that the threshold of uninhabitability is an external, whole-body dose of 10 rem over 30 years. This level of radiation exposure, which would

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[99] Krass, 1991.

[100] DOE, 1987.

represent about a three-fold increase above the typical level of background (natural) radiation, was used in the NRC's 1975 Reactor Safety Study as a criterion for relocating populations from rural areas.

A radiation dose of 10 rem over 30 years corresponds to an average dose rate of 0.33 rem per year.[101] The health effects of radiation exposure at this dose level have been estimated by the National Research Council's Committee on the Biological Effects of Ionizing Radiations.[102] This committee has estimated that a continuous lifetime exposure of 0.1 rem per year would increase the incidence of fatal cancers in an exposed population by 2.5 percent for males and 3.4 percent for females.[103] Incidence would scale linearly with dose, in this low-dose region.[104] Thus, an average lifetime exposure of 0.33 rem per year would increase the incidence of fatal cancers by about 8 percent for males and 11 percent for females. About 21 percent of males and 18 percent of females normally die of cancer.[105] In other words, in populations residing continuously at the threshold of uninhabitability (an external dose rate of 0.33 rem per year), about 2 percent of people would suffer a fatal cancer that would not otherwise occur.[106] Internal doses from contaminated food and water could cause additional cancer fatalities.

The increased cancer incidence described in the preceding paragraph would apply at the boundary of the uninhabitable area. Within that area, the external dose rate from cesium-137 would exceed the threshold of 10 rem over 30 years. At some locations, the dose rate would exceed this threshold by orders of magnitude. Therefore, persons choosing to live within the uninhabitable area would experience an incidence of fatal cancers at a level higher than is set forth above.

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[101] At a given location contaminated by cesium-137, the resulting external, whole-body dose received by a person at that location would decline over time, due to radioactive decay and weathering of the cesium-137. Thus, a person receiving 10 rem over an initial 30-year period would receive a lower dose over the subsequent 30 -year period.

[102] National Research Council, 1990.

[103] Ibid, Table 4-2.

[104] The BEIR V committee assumed a linear dose-response model for cancers other than leukemia, and a model for leukemia that is effectively linear in the low-dose range. See National Research Council, 1990, pp 171-176.

[105] National Research Council, 1990, Table 4-2.

[106] For males, 0.08 x 0.21 = 0.017. For females, 0.11 x 0.18 = 0.020.

For a postulated release of cesium-137 to the atmosphere, the area of uninhabitable land can be estimated from calculations done by Dr Jan Beyea.[107] Three releases of cesium-137 are postulated here. The first release is 42 million Curies, representing the fuel that was present in the Indian Point Unit 2 pool in November 1998. The second postulated release is 31 million Curies, representing the fuel that was present in the Indian Point Unit 3 pool in November 1998. (Actual, present inventories of cesium-137 in the Unit 2 and Unit 3 pools are higher than these numbers, assuming that fuel has been added since November 1998.) The third postulated release is 1 million Curies, representing the cesium-137 inventory in a dry-storage ISFSI module that contains 32 PWR fuel assemblies. This third release does not represent a pool fire or a predicted release from an ISFSI. Instead, it is a notional release that provides a scale comparison.

For typical weather conditions, assuming that the radioactive plume travels over land rather than out to sea, a release of 42 million Curies of cesium-137 would render about 95,000 square kilometers of land uninhabitable. Under the same conditions, a release of 31 million Curies would render about 75,000 square kilometers uninhabitable. A release of 1 million Curies would render uninhabitable about 2,000 square kilometers. For comparison, note that the area of New York state is 127,000 square kilometers. The use of a little imagination shows that a spent-fuel-pool fire at Indian Point would be a regional and national disaster of historic proportions, with health, environmental, economic, social and political dimensions.

For attack scenarios involving the use of a nuclear weapon on a spent-fuel-storage facility, it is instructive to compare the long-term radiological significance of the nuclear detonation itself with the significance of the release that the detonation could induce. For example, detonation of a 10-kilotonne fission weapon would directly generate about 2 thousand Curies (21 grams) of cesium-137.[108] Yet, this weapon could release to the atmosphere tens of millions of Curies of cesium-137 from a spent-fuel pool or an unhardened, undispersed ISFSI.

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[107] Beyea et al, 1979.

[108] SIPRI, 1981, page 76.

4.4 Defense in Depth

Four types of measure, taken together, could provide a comprehensive, defense-in-depth strategy against acts of malice or insanity at a nuclear facility. The four types of measure, which are described in the following paragraphs, are in the categories: (i) site security; (ii) facility robustness; (iii) damage control; and (iv) emergency response planning. The degree of protection provided by these measures would be greatest if they were integrated into the design of a facility before its construction. However, a comprehensive set of measures could provide significant protection at existing facilities.

<u>Site-security measures</u> are those that reduce the potential for implementation of destructive acts of malice or insanity at a nuclear site. Two types of measure fall into this category. Measures of the first type would be implemented at offsite locations, and the implementing agencies might have no direct connection with the site. Airline or airport security measures are examples of measures in this category. Measures of the second type would be implemented at or near the site. Implementing agencies would include the licensee, the NRC and, potentially, other entities (e.g., National Guard, Coast Guard). The physical protection measures now required by the NRC, as discussed in Section 2.3 of this report, are examples of site-security measures of the second type. More stringent measures could be introduced, such as:

> (i) establishment of a mandatory aircraft exclusion boundary around the site;
> (ii) deployment of an approaching-aircraft detection system that triggers a high-alert status at facilities on the site;
> (iii) expansion of the DBT, beyond that now applicable to a nuclear power plant, to include additional intruders, heavy weapons, lethal chemical weapons and more than one vehicle bomb; and
> (iv) any ISFSI on the site to receive protection equivalent to that provided for a nuclear power plant.

<u>Facility-robustness measures</u> are those that improve the ability of a nuclear facility to experience destructive acts of malice or insanity without a significant release of radioactive material to the environment. In illustration, the PIUS reactor design, as discussed in Section 2.3, was intended to withstand aerial bombardment by 1,000-pound bombs without suffering core damage or releasing

a significant amount of radioactive material to the environment. An ISFSI could be constructed with a similar degree of robustness. At existing facilities, a variety of opportunities are available for enhancing robustness. As a high-priority example, the spent fuel pool(s) at a nuclear power plant could be re-equipped with low-density racks, so that spent fuel would not ignite if water were lost from a pool. As a second example, the reactor of a nuclear power plant could be permanently shut down, or the reactor could operate at reduced power, either permanently or at times of alert. Other robustness-enhancing opportunities could be identified. For a nuclear power plant whose reactor is not permanently shut down, robustness could be enhanced by an integrated set of measures such as:

> (i) automated shutdown of the reactor upon initiation of a high-alert status at the plant, with provision for completion of the automated shutdown sequence if the control room is disabled;
> (ii) permanent deployment of diesel-driven pumps and pre-engineered piping to be available to provide emergency water supply to the reactor, the steam generators (at a PWR) and the spent fuel pool(s);
> (iii) re-equipment of the spent fuel pool(s) with low-density racks, excess fuel being stored in an onsite ISFSI; and
> (iv) construction of the ISFSI to employ hardened, dispersed, dry storage.

<u>Damage-control measures</u> are those that reduce the potential for a release of radioactive material from a facility following damage to that facility due to destructive acts of malice or insanity. Measures of this kind could be ad hoc or pre-engineered. One illustration of a damage control measure would be a set of arrangements for patching and restoring water to a spent fuel pool that has been breached. Many other illustrations can be provided. It appears, from the list of additional measures set forth in Section 2.3 of this report, that the NRC's recent orders have required licensees to undertake some planning for damage control following explosions or fires. Additional measures would be appropriate. For example, at a site housing one or more nuclear power plants and an ISFSI, the following damage-control measures could be implemented:

> (i) establishment of a damage control capability at the site, using onsite personnel and equipment for first response and offsite resources for backup;
> (ii) periodic exercises of damage-control capability;

(iii) establishment of a set of damage-control objectives -- to include patching and restoring water to a breached spent fuel pool, fire suppression in the ISFSI, and provision of cooling to a reactor whose support systems and control room are disabled -- with accompanying plans; and
(iv) provision of equipment and training to allow damage control to proceed on a radioactively-contaminated site.

<u>Emergency-response measures</u> are those that reduce the potential for exposure of offsite populations to radiation, following a malice- or insanity-induced release of radioactive material from a nuclear facility. Measures in this category would in many respects be similar to emergency planning measures that are designed to accommodate "accidental" releases of radioactive material arising from human error, equipment failure or natural forces (e.g., earthquake). However, there are two major ways in which malice- or insanity-induced releases might differ from accidental releases. First, a malice- or insanity-induced release might be larger and begin earlier than an accidental release.[109] Second, a malice- or insanity-induced release might be accompanied by deliberate degradation of emergency response capabilities (e.g., the attacking group might block an evacuation route). Accommodating these differences could require additional measures of emergency response. Overall, an appropriate way to improve emergency-response capability at a nuclear-power-plant site could be to implement a model emergency response plan that was developed by a team based at Clark University in Massachusetts.[110] This model plan was specifically designed to accommodate radioactive releases from spent-fuel-storage facilities, as well as from reactors. That provision, and other features of the plan, would provide a capability to accommodate both accidental releases and malice- or insanity-induced releases. Major features of the model plan include:[111]

(i) structured objectives;
(ii) improved flexibility and resilience, with a richer flow of information;

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[109] Present plans for emergency response do not account for the potential for a large release of radioactive material from spent fuel, as would occur during a pool fire. The underlying assumption is that a release of this kind is very unlikely. That assumption cannot be sustained in the present threat environment.

[110] Golding et al, 1992.

[111] Ibid, pp 8-13.

(iii) precautionary initiation of response, with State authorities having an independent capability to identify conditions calling for a precautionary response[112];
(iv) criteria for long-term protective actions;
(v) three planning zones, with the outer zone extending to any distance necessary;
(vi) improved structure for accident classification;
(vii) increased State capabilities and power;
(viii) enhanced role for local governments;
(ix) improved capabilities for radiation monitoring, plume tracking and dose projection;
(x) improved medical response;
(xi) enhanced capability for information exchange;
(xii) more emphasis on drills, exercises and training;
(xiii) improved public education and involvement; and
(xiv) requirement that emergency preparedness be regarded as a safety system equivalent to in-plant systems.

4.5 A Strategy for Robust Storage of Spent Fuel

The preceding section of this report sets forth a defense-in-depth strategy for nuclear facilities. Within the context of that strategy, it would be necessary to establish a nationwide strategy for the robust storage of spent fuel. This strategy must protect all spent fuel that has been discharged from a reactor but has not been emplaced in a repository.

Wet storage in pools, and dry storage in ISFSIs, are the two available modes of interim storage of spent fuel. As pointed out in Section 2.1 of this report, thousands of tonnes of US spent fuel will remain in interim storage for decades, even if a repository opens at Yucca Mountain. If a repository does not open, the entire national inventory of spent fuel will remain in interim storage for many decades. Thus, the robust-storage strategy for spent fuel must minimize the overall risk of interim storage throughout a period that may extend for 100 years or longer. Moreover, this interim storage strategy must be compatible with the eventual emplacement of the spent fuel in a repository in a manner that minimizes long-term risk.

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[112] A security alert could be a condition calling for a precautionary response.

From Sections 4.2 and 4.3 of this report, it is evident that storing spent fuel in high-density pools poses a very high risk. Dry storage of spent fuel, even employing the present practice that is described in Section 2.3, poses a significantly lower risk. Thus, a robust-storage strategy must assign a high priority to re-equipping every spent fuel pool with low-density racks, to prevent self-ignition and burning of fuel if water is lost from a pool.[113] The excess fuel, for which space would no longer be available in the pools, would be transferred to ISFSIs. When a nuclear power plant is shut down, the fuel remaining in its pool(s) would be transferred to an ISFSI after an appropriate period of cooling. These steps would dramatically reduce the overall risk of spent-fuel storage. A further, substantial reduction of the overall risk would be obtained by employing hardened, dispersed, dry storage at every ISFSI.

Section 2.1 of this report discusses factors that argue against shipping spent fuel to an away-from-reactor ISFSI. Some of these factors are economic in nature. However, three factors affect the overall risk of interim storage. First, shipment to an away-from-reactor ISFSI would increase the overall transport risk, because fuel would be shipped twice, first from the reactor site to the ISFSI, and then from the ISFSI to the ultimate repository. Second, an away-from-reactor ISFSI would hold a comparatively large inventory of spent fuel, creating a potentially attractive target for an enemy. Third, there is a risk that a large, away-from-reactor ISFSI would become, by default, a permanent repository, despite having no long-term containment capability. These three factors must be considered in minimizing the overall risk of interim storage.

5. Considerations in Planning Hardened, Dispersed, Dry Storage

5.1 Balancing Short- and Long-Term Risks

Interim storage of spent fuel could lead to eventual emplacement of the fuel in a repository at Yucca Mountain. In this case, fuel would remain in interim storage for several decades. That period is long enough to require action to reduce the very high risk that is posed by pool storage, and the smaller but still significant

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[113] Further protection of the spent fuel that remains in pools could be provided by a variety of site-security, facility-robustness and damage-control measures of the kind that are described in Section 4.4 of this report.

risk that is posed by unhardened, undispersed ISFSIs. However, in this case the long-term risk posed by spent-fuel management would not be relevant to interim storage. The long-term risk, which will be significant for many thousands of years, would be associated with the Yucca Mountain repository.

If a repository does not open, a different problem will arise. That problem is the possibility that society will extend the life of interim-storage facilities until they become, by default, repositories for spent fuel. These facilities would function poorly as repositories, and the environment around each facility would become contaminated by radioactive material leaking from the facility. This outcome would pose a substantial long-term risk. The prospect of society acting in this improvident manner may seem far-fetched, but becomes more credible when one examines the history of the Yucca Mountain project. That project is politically driven, and is going forward only because previously-specified technical criteria for a repository have been abandoned.[114]

Any current planning for the implementation of interim storage must account for the possibility that a repository will not open at Yucca Mountain. Thus, the design approach that is adopted for a hardened, dispersed, dry-storage ISFSI must balance two objectives. One objective is that the facility should be comparatively robust against attack. The second objective is that the facility should not have features that encourage society to allow the facility to become, by default, a repository.

Consideration of the second objective dictates that the ISFSI should not, unless absolutely necessary, be located underground. Therefore, the first objective should be pursued through a design in which the ISFSI modules are stored at grade level (i.e., at the general level of the site). Hardening would then be achieved by placing steel, concrete, gravel or other materials above and around each module. The remaining protection would be provided by dispersal of the storage modules.

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[114] Ewing and Macfarlane, 2002.

5.2 Cost and Timeframe for Implementation

As discussed in Section 2.1 of this report, forecasts show a rapid expansion in dry-storage capacity across the USA over the coming years. NAC International predicts that about 30 percent of US commercial spent fuel will be in dry-storage ISFSIs by 2010, as compared with 6 percent at the end of 2000. Vendors have developed a comparatively cheap technology for dry-storage ISFSIs, in response to to industry preferences. This technology involves the placement of spent fuel into metal containers that are stored inside structures or overpacks made primarily from concrete. The resulting modules are placed close together in large numbers on concrete pads in the open air. A preference for vertical-axis modules seems to be emerging.

Re-equipping US spent fuel pools with low-density racks would create a large additional demand for dry-storage modules. This demand should be met as quickly as possible, in view of the very high risk that is posed by high-density pool storage. Also, the cost of the additional storage capacity should be minimized, consistent with the achievement of performance objectives. Thus, it is desirable that module designs already approved by the NRC be used. However, any module that is used for a hardened, dispersed ISFSI must be capable, when hardened, of resisting a specified attack. This requirement did not exist when module designs were approved by the NRC. Also, it is desirable that modules be capable of retaining their integrity for 100 years or more, which was not a requirement when module designs were approved by the NRC. A module that does not have a long-life capability may need to be replaced at some point if it is used in an ISFSI that serves for an extended period. Finally, the design of a module should allow for the eventual transport of spent fuel from an ISFSI to a repository.

Of the module designs already approved by the NRC, monolithic casks such as the CASTOR may be more capable of meeting attack-resistance and long-life requirements than are modules that employ a thin-walled metal container inside a concrete structure or overpack. However, monolithic casks are more expensive. Thus, it would be convenient if some or all of the cheaper and more widely-used module designs proved to be capable of meeting attack-resistance and long-life requirements. This outcome would minimize the cost of offloading fuel from pools to hardened, dispersed dry storage, and would expedite this transition.

The development of detailed requirements for attack resistance and long life is a task beyond the scope of this report. Section 7 of the report sets forth a process for developing attack-resistance requirements, drawing upon experiments. When that process is completed, it will be possible to determine which of the already-approved module designs can be used for hardened, dispersed, dry storage.

5.3 Design-Basis Threat

The specification of a DBT for a nuclear facility inevitably reflects a set of tradeoffs. In the case of a hardened, dispersed, dry-storage ISFSI, five major considerations must be balanced. First, the ISFSI must protect spent fuel against a range of possible attacks. Second, the cost of the ISFSI should not be dramatically higher than the cost of an ISFSI built according to present practice. Third, the timeframe for building of the ISFSI should be similar to the timeframe for building an ISFSI according to present practice. Fourth, the ISFSI should not, unless absolutely necessary, be built underground. Fifth, it should be possible to construct an ISFSI of this kind at every US nuclear-power-plant site.

These considerations suggest a two-tier DBT for a hardened, dispersed, dry-storage ISFSI. This DBT might have the following structure:

Tier I

There should be high confidence that the release of radioactive material from the ISFSI to the environment would not exceed a small, specified amount in the event of a direct attack on any part of the ISFSI by:

(i) a TOW missile;
(ii) a specified manually-placed charge;
(iii) a specified vehicle bomb;
(iv) a specified explosive-laden general-aviation aircraft; or
(v) a fuel-laden commercial aircraft.

Tier II

There should be reasonable confidence that the release of radioactive material from the ISFSI to the environment would not exceed a specified amount in the event of a ground burst, at any part of the ISFSI, of a 10-kilotonne nuclear weapon.

5.4 Site Constraints

At each ISFSI site there will be a site-specific set of constraints on the development of a hardened, dispersed ISFSI. Some constraints will be political, financial or in some other non-physical category. Other constraints will be physical, reflecting the geography of the site. Of the physical constraints, the most significant will be the land area required for dispersal of dry-storage modules.

At many nuclear-power-plant sites, ample land area will be available for dispersal. At some, smaller sites, it may not be possible to achieve the desired degree of dispersal, but this deficiency might be compensated by increased hardening. At the smallest sites, it may be necessary to relax the requirement that the ISFSI should not be built underground. This step would allow a substantial increase in hardening, to offset the limited degree of dispersal that could be achieved. At especially-constricted sites, it might be necessary to ship some spent fuel from the site to an ISFSI elsewhere.

6. A Proposed Design Approach for Hardened, Dispersed, Dry Storage

An ISFSI design approach that offers a prospect of meeting the above-specified DBT involves an array of vertical-axis dry-storage modules at a center-to-center spacing of perhaps 25 meters. Each module would be on a concrete pad slightly above ground level, and would be surrounded by a concentric tube surmounted by a cap, both being made of steel and concrete. This tube would be backed up by a conical mound made of earth, gravel and rocks. Further structural support would be provided by triangular panels within the mound, buttressing the tube. The various structural components would be tied together with steel rods. Air channels would be provided, to allow cooling of the dry-storage module. These channels would be inclined, to prevent pooling of jet fuel, and would be configured to preclude line-of-sight access to the dry-storage module.

Further analysis and full-scale experiments would be needed to determine whether this design approach, or something like it, could meet the DBT and other requirements that are set forth in Section 5, above. Ideally, these requirements could be met while using dry-storage modules that are approved by the NRC and are in common use. Another objective would be that the hardening elements (concentric tube, cap, tie rods, mound, etc.) could be built and assembled comparatively quickly and cheaply. These elements would not be high-technology items.

As an illustration of the benefits of dispersal, consider an attack involving a ground burst of a 10-kilotonne nuclear weapon. In Section 4.2 of this report, it was noted that the nuclear detonation could excavate a crater about 68 meters in diameter and 16 meters deep. If dry-storage modules had a center-to-center spacing of 5.5 meters, as is typical of present practice, about 120 modules could fall within the crater area and suffer destruction. However, if the center-to-center spacing were 25 meters, as is proposed here, only 6 modules could fall within the crater area and suffer destruction.

Within this design approach it would be possible to trade off, to some extent, hardening and dispersal. As suggested in Section 5.4, above, dispersal could be reduced and hardening could be increased at smaller sites. Detailed, site-specific analysis is needed to determine how such tradeoffs might work.

An alternative design approach could be used at a few sites where space is insufficient to allow wide dispersal. In this approach, a number of dry-storage modules would be co-located in an underground, reinforced-concrete bunker. Similar bunkers would be dispersed across the site to the extent allowed by the site's geography. At an especially-constricted site, it might be necessary to reduce the overall inventory of spent fuel in order to meet design objectives. Thus, some spent fuel from the site would be shipped to an ISFSI elsewhere.

7. Requirements for Nationwide Implementation of Robust Storage

7.1 Experiments on Vulnerability of Dry-Storage Options

Section 5.3 of this report outlines a DBT for hardened, dispersed, dry storage of spent fuel. Section 6 describes a design approach that offers a prospect of meeting a DBT of this kind, together with other requirements that are set forth in Section 5. Further investigation is needed to determine the extent to which the various requirements can be met. This determination would be made at two levels. First, the investigation would determine if the DBT and other requirements set forth in Section 5 are broadly compatible with the proposed design approach or something like it. Second, assuming an affirmative determination at the first level, the investigation would go into more detail, exploring the various tradeoffs that could be made.

An essential part of this investigation would be a series of full-scale, open-air experiments. These experiments would be sponsored by the US government, and would be conducted at US government laboratories and testing centers. The experiments would involve a range of non-nuclear instruments of attack, including anti-tank missiles, manually-placed charges, vehicle bombs and aircraft bombs. Each instrument of attack would be tested against several test specimens that would simulate alternative design approaches for a hardened, dispersed ISFSI.

A separate set of experiments would be conducted in contained situations. These experiments would study the potential for release of radioactive material following penetration or prolonged heating of a fuel container. Factors discussed in Section 4.2 of this report, such as the presence of zirconium hydride in fuel cladding, would be accounted for.

7.2 Performance-Based Specifications for Dry Storage

The investigation called for in Section 7.1 would establish the technical basis for a set of performance-based specifications for hardened, dispersed, dry storage of spent fuel. These specifications would include a detailed, precise formulation of the DBT. Also included would be design guidelines for meeting the DBT, and an allowable range of design parameters within which tradeoffs could be made. The specifications would apply not only to the design of external, hardening elements, but also to dry-storage modules.

Establishing a comprehensive set of specifications would call for the exercise of judgement. There is no purely objective basis for deciding upon one level of required performance as opposed to another. However, judgement must be exercised with full awareness of the wide-ranging implications of a particular choice. As discussed in Section 3 of this report, the defense of US nuclear facilities should be seen as a key component of homeland security and international security.

In view of the national importance of the needed set of specifications, these should be developed with the full engagement of stakeholders. Relevant stakeholders include citizen groups, local governments and state governments.

Processes are available that could allow full engagement of stakeholders while protecting sensitive information.[115]

7.3 A Homeland-Security Strategy for Robust Storage

A robust-storage strategy for US spent fuel would have two major components. The first component would be to re-equip the nation's spent-fuel pools with low-density racks, and to provide other defense-in-depth measures to protect the pools. The second component would be to place all spent fuel, other than the comparatively small amount that would now be stored in low-density pools, into hardened, dispersed, dry-storage ISFSIs.

Fast, effective implementation of this strategy would require decisive action by the US government. It would require expenditures that are comparatively small by national-security standards but are nonetheless significant. At present, there is no sign that action will be taken. The US government in general seems largely unaware of the threat posed by the present practice of storing spent fuel. The NRC seems unable to understand the extent to which it is failing in its duty.

A new paradigm is needed, in which spent-fuel-storage facilities are seen as pre-deployed radiological weapons that await activation by an enemy. Correcting this situation is an imperative of national defense. If the NRC continues to undermine national defense, it should be bypassed or disbanded. Citizens should insist that Congress and the executive branch promptly initiate a strategy for robust storage of spent fuel, as a key element of homeland security.

8. Conclusions

The prevailing practice of storing most US spent fuel in high-density pools poses a very high risk because knowledgeable attackers could induce a loss of water from a pool, causing a spent-fuel fire that would release a huge amount of radioactive material to the atmosphere. Nuclear reactors are also vulnerable to attack. Dry-storage modules used in ISFSIs have safety advantages in comparison to pools and reactors, but are not designed to resist a determined attack.

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[115] Thompson, 2002a, Sections IX and X.

Thus, nuclear power plants and their spent fuel can be regarded as pre-deployed radiological weapons that await activation by an enemy. The US government in general and the NRC in particular seem unaware of this threat. US nuclear facilities are lightly defended and citizens are exposed to the risk of widespread radioactive contamination. This situation is symptomatic of an unbalanced US strategy for national security, which is a potentially destabilizing factor internationally.

A strategy for robust storage of US spent fuel is needed, whether or not a repository is opened at Yucca Mountain. This strategy should be implemented as a major element of a defense-in-depth strategy for US civilian nuclear facilities. In turn, that defense-in-depth strategy should be a component of a homeland-security strategy that provides solid protection of our critical infrastructure.

The highest priority in a robust-storage strategy for spent fuel would be to re-equip spent-fuel pools with low-density, open-frame racks. As a further measure of risk reduction, ISFSIs should be re-designed to incorporate hardening and dispersal. These measures should not be implemented in a manner such that an ISFSI may become, by default, a repository. Therefore, a hardened ISFSI should not, unless absolutely necessary, be built underground. Also, the cost and timeframe for implementing hardening and dispersal should be minimized. These considerations argue for the use, if possible, of dry-storage modules that are already approved by the NRC and are in common use.

Preliminary analysis suggests that a hardened, dispersed ISFSI meeting these criteria could be designed to meet a two-tiered DBT. The first tier would require high confidence that no more than a small release of radioactive material would occur in the event of a direct attack on the ISFSI by various non-nuclear instruments. The second tier would require reasonable confidence that no more than a specified release of radioactive material would occur in the event of attack using a 10-kilotonne nuclear weapon.

Three major requirements must be met if a robust-storage strategy for spent fuel is to be implemented nationwide. First, appropriate experiments are needed. Second, performance-based specifications for dry storage must be developed with stakeholder involvement. Third, robust storage for spent fuel must be seen as a vital component of homeland security.

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