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ISSUES REGARDING THE STORAGE OF
SPENT NUCLEAR FUEL

Supporting document for participation by
Gordon R. Thompson
as a panelist at a public workshop held by
the California Energy Commission
in Sacramento, California,
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## 1. Introduction

This document provides information that supports the participation of Gordon R. Thompson in a public workshop held by the California Energy Commission (CEC). The workshop will address issues related to nuclear power, and will inform the CEC's preparation of its *2005 Integrated Energy Policy Report*. Background information about nuclear power in California has been compiled in a draft report by a consultant to the CEC.[1] That report is used here as a point of departure for the presentation of additional information and perspectives.

The workshop will involve four panels of discussants. Thompson has been asked by the CEC to participate in the second panel, and to address the following questions about spent nuclear fuel:

> (i) What are the trade-offs between interim storage facilities located at either the individual reactor sites or a centralized location in the West?
> (ii) What are the implications of maintaining on-site storage of spent fuel at the individual reactor sites for at least the operating period of the reactors?
> (iii) What are the major security and safety issues associated with the storage of spent fuel?

Those questions are addressed here in reverse order. Much has been said about the merits of various options for storing spent nuclear fuel. That discussion is not always well-informed regarding security and safety issues. Accordingly, three foci of discussion are adopted here. First, security issues related to the storage and transport of spent fuel are outlined (Sections 4-10). Second, security and safety issues are factored into a discussion of the comparative merits of spent-fuel storage options (Section 11). Third, needs and opportunities for improving knowledge about nuclear-facility security are outlined (Section 12).

A discussion of security issues can involve information that is not appropriate for general dissemination. This document does not contain such information, and is appropriate for unrestricted distribution. Thompson would be willing to talk to California public officials, in a secure setting, about matters that are not appropriate for open discussion.

There is a large body of technical literature that is relevant to the storage of spent nuclear fuel. Only a portion of that literature is cited in this short document. Thompson would be willing to discuss technical issues in greater depth than is done here, and to identify the relevant literature.

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[1] MRW, 2005.

## 2. Thompson's qualifications and experience

Gordon R. Thompson is the executive director of the Institute for Resource and Security Studies (Cambridge, Massachusetts) and a research professor at the George Perkins Marsh Institute, Clark University (Worcester, Massachusetts). He was educated in science and engineering, and received a D.Phil. from Oxford University in 1973 for mathematical analysis on the stability of plasma undergoing thermonuclear fusion. Since then, he has been a technical and policy analyst on issues of energy, environment, international security, and sustainability. A substantial portion of his work has related to the security, safety and economics of nuclear facilities, including reactors, reprocessing plants, and spent-fuel storage installations.

In addition to being familiar with security and safety issues affecting nuclear facilities in the USA generally, Thompson has worked on these issues in the specific context of California. For example, he has prepared and presented testimony to the California Public Utilities Commission on the nature and costs of potential measures for enhanced defense of the Diablo Canyon nuclear station and the San Onofre Nuclear Generating Station (SONGS).[2] The Diablo Canyon testimony was on behalf of San Luis Obispo Mothers for Peace, and the SONGS testimony was on behalf of California Earth Corps.

During an investigation conducted for a German state government in 1978-1979, Thompson found that spent fuel stored at high density in a water-filled pool could ignite if water were lost from the pool. He identified acts of war as events that could cause water loss. This finding led to a German policy of using dry storage for away-from-reactor storage of spent fuel. Subsequent investigations by the US Nuclear Regulatory Commission (NRC) supported Thompson's findings about the hazards of high-density pool storage. Nevertheless, the NRC challenged related findings and recommendations by Thompson and co-authors that were published in 2003.[3] At the request of the US Congress, the National Academy of Sciences (NAS) conducted an independent investigation that vindicated the work of Thompson and co-authors.[4]

## 3. Options for managing spent fuel

The draft consultant's report for the CEC demonstrates that storage is the only near-term option for management of spent fuel from California's reactors. If the Yucca Mountain repository were to open in 2010 – which no-one expects – emplacement of spent fuel inside Yucca Mountain could continue until 2034 or 2060.[5] There is a substantial probability that the Yucca Mountain repository will never open. Thus, most or all of California's spent fuel will be stored for at least several decades, potentially for a century or longer. Storage could occur at reactor sites or elsewhere.

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[2] Thompson, 2004.
[3] Alvarez et al, 2003; Thompson, 2003.
[4] NAS, 2005.
[5] MRW, 2005, page 67.

**4. Factors relevant to the security of nuclear facilities**

No commercial nuclear facility in the USA was designed to resist attack. Facilities have some capability in this respect by virtue of design for other objectives (e.g., resisting tornado-driven missiles, containing the vapors and gases that would be released if a reactor core suffered accidental damage).

Beginning in 1994, with NRC's promulgation of a vehicle-bomb rule, each US nuclear power plant has implemented site-security measures (e.g., barriers, guards) that have some capability to prevent attackers from damaging vulnerable parts of the plant. The scope of this defense was increased in response to the attacks of 11 September 2001. Nevertheless, it continues to reflect the NRC's judgment that a "light" defense, to use military terminology, is sufficient.[6] This judgment is not supported by any strategic analysis, and contrasts with the *National Strategy for The Physical Protection of Critical Infrastructures and Key Assets*, which identifies nuclear power plants as key assets, defined as follows:[7]

> "Key assets represent individual targets whose destruction could cause large-scale injury, death, or destruction of property, and/or profoundly damage our national prestige, and confidence."

A strategic analysis of needs and opportunities for security of an item of critical infrastructure or a key asset should have three parts. It should begin with an assessment of the scale of damage that could arise from an attack. For a nuclear facility, a major determinant of this scale is the amount of radioactive material that is available for release to the atmosphere or a water body; other determinants are the vulnerability of the facility to attack, and the consequences of attack.[8] (See Sections 5-7.) The second step in the strategic analysis should be to assess the future threat environment. (See Section 8.) The third step should be to assess the adequacy of present measures to defend the facility, and to identify options for providing an enhanced defense. (See Sections 9-10.)

The analyst should seek to understand the interests and perspectives of potential attackers. To illustrate, a sub-national group that is a committed enemy of the USA might perceive two major incentives for attacking a US commercial nuclear facility. First, release of a large amount of radioactive material could cause major, lasting damage to the USA. Second, commercial nuclear technology could symbolize US military dominance through nuclear weapons and associated technologies such as guided missiles;

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[6] NRC, 2004.
[7] White House, 2003.
[8] Direct release of radioactive material is not the only potential consequence of an attack on a nuclear facility. There is also concern that radioactive or fissile material could be removed from the facility and incorporated into a radiological or nuclear weapon. In addressing security issues, this document focuses on the potential for a release of radioactive material, because the overall scale of security measures at a facility will be determined primarily by measures designed to prevent such a release.

a successful attack on a commercial nuclear facility could challenge that symbolism. Conversely, the group might perceive three major disincentives for attack. First, nuclear facilities could be less vulnerable than other potential targets. Second, radiological damage from the attack would be indiscriminate, and could occur hundreds of km downwind in non-enemy locations (e.g., Mexico). Third, the USA could react with extreme violence.

**5. The scale of radiological hazard**

The radioactive isotope cesium-137 provides a useful indicator of the radiological hazard associated with a nuclear facility. This isotope has a half-life of 30 years. Being comparatively volatile, it is liberally released from damaged fuel. It accounts for most of the offsite radiological exposure from the Chernobyl reactor accident of 1986. That event released about 2.4 MCi (27 kg) of cesium-137 to the atmosphere. For comparison, fallout of cesium-137 from atmospheric tests of nuclear weapons was about 20 MCi (220 kg).[9]

SONGS Units 2 and 3, as described in Table 1, illustrate the amount of cesium-137 in commercial nuclear facilities. Each of these pressurized-water reactors (PWRs) has an adjacent spent-fuel pool. The pools are expected to be filled by 2007-2008. Table 2 shows typical inventories of cesium-137 at SONGS Units 2 and 3.[10] The core of each reactor, consisting of 217 fuel assemblies, contains about 7.7 MCi (85 kg) of cesium-137. The spent-fuel pool at each unit will, when operating at its capacity of 1,325 fuel assemblies, contain about 68 MCi (750 kg) of cesium-137. An independent spent fuel storage installation (ISFSI) has been established at the San Onofre site. A typical dry-storage module at this ISFSI, holding 24 fuel assemblies, will contain about 0.89 MCi (9.9 kg) of cesium-137.

According to the NRC, a typical spent fuel transportation cask holds up to 4 PWR fuel assemblies for a truck cask and up to 26 PWR fuel assemblies for a rail cask.[11] The inventory of cesium-137 in shipments of spent fuel from SONGS Units 2 and 3 can be estimated as follows. Assuming that a storage canister of a dry-storage module at the ISFSI, holding 24 assemblies, would be inserted into a cask for rail shipment, and that fuel would be transported 30 years after discharge from a reactor, one finds that each truck cask (4 PWR fuel assemblies) would contain 0.14 MCi (1.6 kg) of cesium-137, while each rail cask (24 PWR fuel assemblies) would contain 0.85 MCi (9.5 kg) of cesium-137.[12]

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[9] Thompson, 2003.
[10] These inventories are calculated for the specific assumptions stated in Table 2.
[11] NRC, 2005.
[12] Cask inventories are calculated using the assumptions in the first row of Table 2.

## 6. Vulnerability of nuclear facilities to attack

Nuclear power plants and ISFSIs have vulnerabilities that arise from intrinsic factors and from design choices. The intrinsic factors derive from the basic processes and structures needed to harness nuclear fission. Notably, spent fuel from a fission reactor necessarily contains biologically harmful and heat-producing radioactive material (e.g., cesium-137). Also, reactor structures and nuclear fuel employ chemically-reactive materials. In US commercial reactors, the fuel cladding is made of zirconium alloy that can react exothermically with air or steam. The latter reaction yields hydrogen that can form an inflammable or explosive mixture.

The intrinsic vulnerabilities have been exacerbated by design choices. Two policy decisions have been especially important in this respect. First, resistance to attack has not been a design goal. Second, the NRC has allowed the nuclear industry to employ cost-saving measures that have created vulnerabilities.

Four examples illustrate the combined influence of these factors on the vulnerability of present US nuclear facilities, as follows:

• Example #1: Spent-Fuel Pool Fires
Spent-fuel pools are now equipped with high-density racks so that they can hold a much larger inventory of spent fuel than was envisioned when the pools were designed. The high-density racks have a closed configuration that is necessary to suppress criticality. As a result, loss of water from a pool would cause the spent fuel to heat up and, across a wide range of scenarios, experience a runaway zirconium-air or zirconium-steam reaction (i.e., a fire). The resulting heat production and fuel degradation would release a large amount of radioactive material to the atmosphere.[13]

• Example #2: Cascading Failures
Spent-fuel pools are immediately adjacent to reactors, and share their support systems. At many sites, including SONGS and Diablo Canyon, reactors are adjacent to each other and share support systems. The resulting interdependence means that fires, radiation fields and other effects of an attack could preclude operation of active safety systems or implementation of damage-control measures (e.g., provision of water makeup or spray to a drained spent-fuel pool), leading to cascading failures.[14]

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[13] Alvarez et al, 2003; NAS, 2005; Thompson, 2003.
[14] Thompson, 2003.

• Example #3: Reliance on Active Safety Systems
At nuclear power plants, safety systems are typically active rather than passive, and rely on AC or DC electric power. Achieving grid disconnect could be easy for attackers, forcing reliance on potentially vulnerable onsite power sources.[15]

• Example #4: Vulnerable ISFSI Modules
The dry-storage modules used at ISFSIs are not designed to resist attack. At all recently-established ISFSIs in the USA, spent fuel is contained in metal canisters with a wall thickness of about 1.6 cm. Each canister is surrounded by a concrete overpack, but this overpack is penetrated by channels that allow cooling of the canister by convective flow of air. Attackers gaining access to an ISFSI could employ readily-available skills and explosives to penetrate a canister in a manner that allows free flow of air to spent fuel, and could use incendiary devices to initiate burning of fuel cladding, leading to a release of radioactive material to the atmosphere.[16]

A determined, sophisticated group planning to attack a nuclear facility could employ a variety of modes and instruments of attack. To illustrate the vulnerability of nuclear facilities to available instruments, consider the potential for penetration of reinforced-concrete structures. Such penetration could be sought in some attack scenarios. Reactor containments and spent-fuel pools are relevant structures. At a typical PWR, the reactor vessel and associated components are inside a cylindrical, reinforced-concrete containment with a wall about 1 m thick. The adjacent spent-fuel pool has reinforced-concrete walls up to 2 m thick.

An informed attacker is likely to consider a shaped explosive charge as an instrument for penetrating a structure of this kind.[17] It is, therefore, noteworthy that the US government has published design details for a shaped-charge, cruise-missile warhead intended to penetrate rock or concrete. The warhead's purpose is to open a pathway for entry of a second, tandem-mounted charge. This warhead has a diameter of 71 cm, a length of 72 cm, and a total mass of 410 kg. When tested in 2002, it created a hole of 25 cm diameter in tuff rock to a depth of 5.9 m.[18]

One means of carrying such a device would be a general-aviation aircraft operated remotely or by a suicidal pilot. There are many suitable aircraft. For example, a Beechcraft King Air 90 will carry a payload of up to 990 kg at a speed of up to 460 km/hr. A used King Air 90 can be purchased for US$0.4-1.0 million. Note that there are more than 19,000 airports in the USA. Also, during the period 1998-2003, about 70 aircraft were stolen from general-aviation airports in the USA.[19]

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[15] NRC, 1990.
[16] Thompson, 2003.
[17] Walters, 2003.
[18] These data are from an unclassified report that is accessible on the Web. The citation is withheld here.
[19] Thompson, 2004.

## 7. Consequences of attack

A successful attack on a reactor or a spent-fuel pool could release radioactive material to the atmosphere by exploiting mechanisms that would be powered by energy sources within the facility -- stored heat, radioactive decay heat, and exothermic chemical reactions (e.g., zirconium-air or zirconium-steam). At a spent-fuel pool, the release could include 10-100 percent of the cesium-137 in the pool, together with other radioactive isotopes.[20] Analyses of reactor accidents suggest that a successful attack on a reactor could also achieve a cesium-137 release fraction of 10-100 percent.[21] The reactor release would, in addition, include short-lived radioactive isotopes such as iodine-131.

An attack on a dry-storage module of an ISFSI could potentially achieve a cesium-137 atmospheric release fraction of 10-100 percent. However, achieving this outcome would require the use of an incendiary device to initiate a zirconium-air reaction, and the availability of air to feed that reaction.[22]

The offsite impacts of an atmospheric release of radioactive material can be estimated, if a variety of assumptions are made. A group of analysts considered a hypothetical release of 35 MCi of cesium-137 at each of five nuclear-power-plant sites in the USA. The five-site average of offsite economic damage was $400 billion.[23] That estimate would rise substantially if reasonable, alternative assumptions were used in the analysis.

## 8. The future threat environment

The threat environment must be assessed over the entire period during which a nuclear facility is expected to operate. For spent-fuel storage facilities in the USA, that period could exceed a century. It should be noted that the risk of attack will accumulate over the period of operation.

Forecasting international conditions over several decades is a notoriously difficult and uncertain enterprise. Nevertheless, an implicit or explicit forecast must underlie any decision about the level of security that is provided at a nuclear facility. Prudence dictates that a forecast in this context should err on the side of pessimism. Decision makers should, therefore, be aware of a literature indicating that the coming decades could be turbulent, with a potential for higher levels of violence.[24] One factor that might promote violence is a perception of resource scarcity. It is noteworthy that many analysts are predicting a peak in world oil production within the next few decades.[25] Also, a

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[20] Alvarez et al, 2003.
[21] NRC, 1990.
[22] The same principles would apply to an attack on a spent fuel transportation cask.
[23] Beyea et al, 2004.
[24] Kugler, 1995; Raskin et al, 2002.
[25] Hirsch et al, 2005.

recent international survey shows significant degradation in the Earth's ability to provide ecosystem services.[26]

The potential for attacks on nuclear facilities has been studied for decades.[27] Nevertheless, the NRC remains convinced that these facilities require only a light defense. The NRC's position fails to account for the growing strategic significance of sub-national groups as potential enemies. Various groups of this kind could possess the motive and ability to mount an attack on a US nuclear facility with a substantial probability of success. The unparalleled military capability of the USA cannot deter such a threat if the attacking group has no territory that could be counter-attacked. Moreover, use of US military capability could be counter-productive, creating enemies faster than they are killed or captured. Many analysts believe that the invasion of Iraq has produced that outcome.

## 9. Present defense of nuclear facilities

As stated above, the NRC requires only a light defense of US nuclear facilities. Table 3 outlines the defenses that are routinely provided at a nuclear power plant. It will be seen, for example, that there is no defense from air attack. With some limited exceptions, current ISFSIs were built at the sites of nuclear power plants, and benefit to some extent from the defenses provided for those plants. As reactors are decommissioned, and away-from-reactor ISFSIs are established (e.g., at Skull Valley), an increasing number of ISFSIs will be defended on a stand-alone basis, at a lower level of defense than is provided for an operational power plant.

A light defense is also provided during transport operations. NRC regulations require the defense of spent-fuel shipments by measures that include the presence of one or two armed escorts.[28]

## 10. Options for enhanced defense of nuclear facilities

Various measures are available to provide enhanced defense of nuclear facilities. This defense could be provided remotely or locally. Measures implemented remotely will typically seek to defend many targets, not just nuclear facilities, and are of two types. First, measures can be taken to intercept or deter attackers. Second, other measures can address underlying issues that promote attacks on the USA.

For an existing nuclear facility, an enhanced defense could be provided by locally-implemented measures of the following types:[29]

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[26] Stokstad, 2005.
[27] Ramberg, 1984.
[28] 10 CFR 73.37, Requirements for physical protection of irradiated reactor fuel in transit, from the NRC website (www.nrc.gov), accessed 11 August 2005.
[29] Thompson, 2004.

- <u>Site-security measures</u>
  The potential for attackers to reach a facility and implement destructive acts could be reduced by a variety of measures. These measures could include air defense by an active system (e.g., Phalanx) or a passive system (e.g., poles and nets).

- <u>Facility-robustness measures</u>
  Measures could be taken to improve the ability of a facility to experience destructive acts without releasing a large amount of radioactive material to the environment. A high-priority measure of this kind would be to equip spent-fuel pools across the USA with low-density racks, storing the remaining spent fuel in ISFSIs in which dry-storage modules are hardened and dispersed.[30]

- <u>Onsite damage-control capability</u>
  Damage-control measures could reduce the potential for a release of radioactive material following damage to a facility. For example, new systems could be installed that could provide emergency cooling water to reactors and spent-fuel pools for days or weeks in a high radiation field.

- <u>Offsite emergency-response capability</u>
  Improved measures of offsite emergency response could reduce radiation exposure in the event of a radioactive release.

- <u>Altered mode of operation</u>
  Altering a facility's mode of operation could reduce the potential for an attack-induced release of radioactive material. For example, the power level of a reactor could be reduced at times of alert.

The equipment of spent-fuel pools with low-density racks, identified above as a high-priority measure, deserves some more discussion. This measure would yield a major reduction in risk, in two ways. First, the low-density racks would have an open configuration, thereby eliminating most scenarios in which a loss of water would cause spent fuel to heat up and ignite. Second, the inventory of spent fuel in each pool would be substantially reduced. The pools would revert to their original purpose of storing only recently-discharged fuel. Table 4 shows how this reversion could occur at SONGS Units 2 and 3. In this illustrative case, the pools would be converted to a low-density configuration over a period of 2 years.

For any new nuclear facility, there would be many opportunities to incorporate enhanced defense into the design of the facility.[31] Three complementary approaches would be available. One approach would be to design the facility for passive safety. For example, a reactor could be designed so that the fission rate naturally declines at high temperature

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[30] Alvarez et al, 2003; Thompson, 2003.
[31] Hannerz, 1983.

and heat is dissipated by radiation, conduction and natural convection. A second approach would be to harden the facility by employing thick barriers made of concrete, steel, earth, gravel, etc. A third approach would be to limit the size of a given unit and disperse the units spatially.

## 11. Comparative merits of spent-fuel storage options

Sections 4-10, above, outline security issues related to the storage and transport of spent fuel. The same discussion also addresses security issues related to reactors. That is necessary because reactors and spent-fuel pools are closely-coupled systems. For many purposes, a reactor and its pool can be regarded as a combined hazard.

The concept of safety has not been discussed to this point. That concept applies to failure conditions that are attributable to equipment malfunction, human error, or natural events. Such failure conditions are commonly described as "accidents". These fall into two classes. Design-basis accidents are explicitly foreseen during a facility's design. Accidents of greater severity are described as beyond-design-basis accidents.

Many of the enhanced-defense options that are categorized in Section 10 would yield substantial benefits in terms of safety. That is, they would reduce the probability and/or consequences of beyond-design-basis accidents. As a practical matter, therefore, a discussion of security issues subsumes most of what would be discussed in an assessment of the adequacy of present arrangements for safety.

The major security issue related to spent-fuel storage is the present risk arising from high-density pool storage. This risk could be substantially reduced by converting spent-fuel pools to a low-density configuration using open-frame racks. Additionally or alternatively, the risk arising from pool storage could be reduced, although to a much smaller degree, by other enhanced-defense measures (e.g., installing a system to spray water into a drained pool).

Fuel that is not stored in a pool could be stored in an ISFSI of the present design. The risk arising from that storage mode could be further reduced by adopting an ISFSI design in which the dry-storage modules would be hardened and dispersed. Figure 1 shows a schematic view of a potential design for hardened, dry storage of spent fuel.

An ISFSI could, in principle, be established in many possible locations. Some of the factors relevant to choosing locations and designs of ISFSIs would pertain to security, and some factors would not. There are well-established procedures for identifying, evaluating and deciding upon sites and designs for hazardous facilities. These procedures could be applied to the siting and design of new ISFSIs for California's spent fuel, although it is clear that the process would be highly controversial. From a technical perspective, a current obstacle to the application of these procedures is a lack of knowledge about relevant security issues. That matter is discussed further in Section 12.

If decision makers had access to good information about relevant security issues, they could use this information to assess the comparative risks of alternative locations and designs for ISFSIs. To take a simple example, suppose that spent fuel is currently stored at Sites A and B. Further suppose that Site A allows a higher level of security than can be provided at Site B. Finally, suppose that transportation risk is low. In this hypothetical situation, a policy of risk minimization could indicate that the spent fuel from both sites should be consolidated at Site A.

From a security perspective, there are some clear differences between the SONGS and Diablo Canyon sites. The SONGS site is smaller and more difficult to defend. However, the SONGS site is adjacent to Camp Pendleton, which could provide a site for an ISFSI that would be at least as defensible as an ISFSI at Diablo Canyon. This example shows that an assessment of the comparative risks of ISFSI options must rest upon a thorough, practical investigation of available sites.

Consolidation of spent fuel storage at a centralized location (e.g., Skull Valley) can only be consistent with risk minimization if transportation risk is low. Gordon Thompson's current judgment is that the cumulative transportation risk may be comparable to the cumulative risk of storage at a typical, present ISFSI, for a given quantity of spent fuel. If this judgment were confirmed by appropriate investigations, it would generally follow that transportation should be avoided where possible. That finding could be reinforced if enhanced-defense measures – such as the adoption of ISFSI designs employing hardened, dispersed storage – could substantially reduce the risk of storage.

If spent-fuel pools were converted to a low-density configuration, as discussed above, the spent-fuel storage risk at the site of an operating reactor would become largely decoupled from the reactor risk. Then, other factors being equal, there would be no risk benefit from transporting the spent fuel to an alternative site. Indeed, there could be a risk detriment if the alternative site lacked some of the site-security measures that are associated with an operational reactor.

## 12. Improving knowledge about nuclear-facility security

At present, the NRC is the primary source of technical information about the security of US nuclear facilities. Unfortunately, the NRC is not fully credible as a source of information on these matters. This deficiency has been demonstrated by the NRC's attempt to suppress the findings of the NAS study on spent-fuel hazards, and by intemperate and technically questionable statements by NRC officials.

California would be well advised to conduct its own investigations, alone or by working with other states through partnerships such as the Western Governors' Association. Such investigations would address sensitive information, but much of this information would not be classified in a formal sense. For example, a large part of the knowledge needed to understand a facility's vulnerability can be developed by a technical investigation that relies on basic principles and open literature. Knowledge and perspectives on the future threat environment could be gained from citizens and the many relevant experts who reside in California, through channels including open hearings.

Investigations conducted by California could address:

- the vulnerability of reactors, spent-fuel pools, ISFSIs and spent-fuel transportation to attack by sub-national groups;
- potential consequences of attack;
- the future threat environment;
- options for enhanced defense of nuclear facilities;
- potential sites and design options for ISFSIs; and
- comparative risks of spent-fuel storage options.

## 13. Conclusions

Major conclusions are as follows:

C1. Storage is the only near-term option for management of spent fuel from California's reactors. Most or all of California's spent fuel will be stored for at least several decades, potentially for a century or longer.

C2. The NRC requires only a light defense of US nuclear facilities, but this policy is not supported by strategic analysis.

C3. US commercial nuclear facilities are not designed to resist attack, and have vulnerabilities that arise from intrinsic factors and design choices.

C4. Spent-fuel pools pose a special hazard, due to their high-density configuration and proximity to reactors. Loss of water from a pool could release tens of MCi of cesium-137 to the atmosphere, compared to 2.4 MCi for the Chernobyl accident.

C5. The future threat environment is uncertain, but a pessimistic view would be prudent in the context of nuclear-facility security. Sub-national groups are of growing strategic significance as potential enemies.

C6. Options are available for enhanced defense of nuclear facilities. A high-priority option would be to convert spent-fuel pools to a low-density configuration, storing the remaining spent fuel in ISFSIs in which dry-storage modules are hardened and dispersed. This option would largely decouple the spent-fuel storage risk from the reactor risk.

C7. An assessment of the comparative risks of options for storing California's spent fuel in ISFSIs would require the development of additional knowledge. California could develop this knowledge through investigations conducted alone or with other states.

C8. Consolidation of spent fuel storage at a centralized location (e.g., Skull Valley) can only be consistent with risk minimization if the risk of transporting spent fuel is low. Gordon Thompson's present judgment is that transportation risk is not low.

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**Table 1**
**Selected Characteristics of SONGS Unit 2 and Unit 3**

| Characteristic | San Onofre Unit 2 | San Onofre Unit 3 |
|---|---|---|
| Rated power | 3,438 MWt; 1,070 MWe | 3,438 MWt; 1,080 MWe |
| Average capacity factor, 1998-2003 | 94 percent | 90 percent |
| Reactor vendor | Combustion Engineering | Combustion Engineering |
| Number of fuel assemblies in reactor core | 217 | 217 |
| Mass of uranium in a fresh fuel assembly | 485 kg | 485 kg |
| Year of first commercial operation | 1983 | 1984 |
| Year when operating license expires | 2022 | 2022 |
| Capacity of spent-fuel pool | 1,542 assemblies | 1,542 assemblies |
| Inventory of spent fuel in pool in November 1998 | 870 assemblies | 918 assemblies |
| Date when SCE predicts pool will lose space needed to receive full core offload | July 2007 | March 2008 |

**Source:** Thompson, 2004

**Table 2**
**Amounts of Cesium-137 in Nuclear Fuel Associated With SONGS Unit 2 or Unit 3**

| Category of Nuclear Fuel | Amount of Cs-137 (MCi) |
|---|---|
| One spent fuel assembly at discharge from reactor (15.8 MWt per assembly, 90% capacity factor, discharge after 54 months, 485 kgU/assembly) | 0.071 |
| One reactor core at operating equilibrium (217 assemblies, av. burnup = 50% of discharge burnup) | 7.7 |
| One spent-fuel pool at full loading (1,325 assemblies, av. age after discharge = 14 yr) | 68 |
| One ISFSI module at full capacity (24 assemblies, av. age after discharge = 28 yr) | 0.89 |

**Adapted from:** Thompson, 2004

**Table 3**
**Potential Modes and Instruments of Attack on a US Nuclear Power Plant**

| Mode of Attack | Characteristics | Present Defense |
|---|---|---|
| Commando-style attack | • Could involve heavy weapons and sophisticated tactics<br>• Successful attack would require substantial planning and resources | Alarms, fences and lightly-armed guards, with offsite backup |
| Land-vehicle bomb | • Readily obtainable<br>• Highly destructive if detonated at target | Vehicle barriers at entry points to Protected Area |
| Anti-tank missile | • Readily obtainable<br>• Highly destructive at point of impact | None if missile launched from offsite |
| Commercial aircraft | • More difficult to obtain than pre-9/11<br>• Can destroy larger, softer targets | None |
| Explosive-laden smaller aircraft | • Readily obtainable<br>• Can destroy smaller, harder targets | None |
| 10-kilotonne nuclear weapon | • Difficult to obtain<br>• Assured destruction if detonated at target | None |

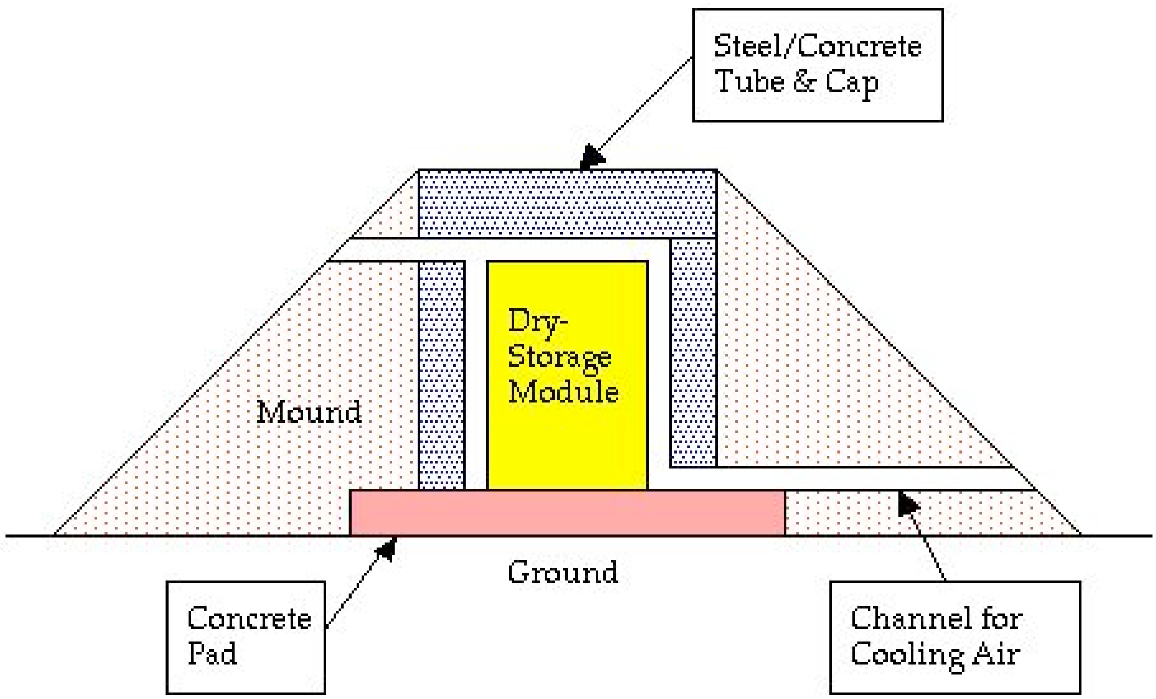
**Source:** Thompson, 2004

**Table 4**
**Two Options for Management of Spent Fuel at SONGS Unit 2 or Unit 3, Commencing in Year X and Assuming Continued Operation of the Reactor**

| Category of Spent Fuel | Number of Fuel Assemblies | |
|---|---|---|
| | Base-Case Option | Option Involving Reduction in Capacity of the Spent-Fuel Pool |
| Number of fuel assemblies in reactor core | 217 | 217 |
| Annual discharge of spent fuel from reactor | 48 (1/3 of core each 18 months) | 48 (1/3 of core each 18 months) |
| Initial capacity of spent-fuel pool (year X) | 1,542 | 1,542 |
| Reduced capacity of pool (year X+2 and thereafter) | Not applicable (capacity remains at 1,542) | 506 (4/3 core plus full offload of 1 core) |
| Initial inventory of spent fuel in pool (year X) | 1,325 (1,542 minus full offload of 1 core) | 1,325 (1,542 minus full offload of 1 core) |
| Inventory of spent fuel in pool in year X+2 and thereafter | 1,325 | 240 (5 years of reactor discharge @ 48/year) |
| Spent fuel transferred to ISFSI between year X and year X+2 | 48x2 = 96 | (48x2) + (1,325 - 240) = 1,181 |
| Annual transfer of spent fuel to ISFSI after year X+2 | 48 | 48 |
| Spent fuel transferred to ISFSI after reactor is shut down | 1,325 | 240 |

**Source:** Thompson, 2004

**Figure 1**
**Schematic View of Potential Design for Hardened, Dry Storage of Spent Nuclear Fuel**




**Notes**

(i) Cooling channels would be inclined, to prevent pooling of flammable liquid, and would be configured to preclude line-of-sight access to the dry-storage module.
(ii) The tube, cap and pad surrounding the dry-storage module would be tied together with steel rods, and spacer blocks would prevent the module from moving inside the tube.
(iii) The steel/concrete tube could be buttressed by several triangular panels connecting the tube and the base pad.