PROLIFERATION RESISTANCE ASSESSMENT OF VARIOUS METHODS OF SPENT NUCLEAR FUEL STORAGE AND DISPOSAL

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ABSTRACT

Previous proliferation resistance and proliferation risk assessments have considered nuclear material through the whole fuel cycle and not specifically focused on spent fuel storage. This project evaluates the proliferation resistance of the three main types of spent fuel storage: spent fuel pool, dry cask storage, and geological repository. The assessment methodology utilizes various intrinsic and extrinsic proliferation resistance attributes for each spent fuel storage type. These attributes are used to calculate a total proliferation resistance (PR) value. The PR values range from 0.00 to 1.00, with a greater number meaning that the facility is more proliferation resistant. Given current data, the spent fuel pool is the most proliferation resistant method for storing spent fuel. The extrinsic attributes, mainly involving safeguards measures, affect the total PR value the most. As a result, several recommendations have been made to improve the proliferation resistance of spent fuel storage.

INTRODUCTION & BACKGROUND

Increasing energy demands have caused many countries to pursue nuclear power because of the large-scale electricity output that it can provide. The World Nuclear Association estimates that nuclear power capacity will increase from the current worldwide capacity of 367 GW to anywhere from 602 to 1350 GW by 2030 [1]. This means that nuclear power capacity will double or even triple within the next 20 years. Each new power plant presents proliferation risk as it adds special nuclear material to the fuel cycle. Both existing and newly-built nuclear power plants will add more and more special nuclear material to the fuel cycle each year.

In order to prevent the diversion of nuclear material to a weapons program, the International Atomic Energy Agency (IAEA) employs safeguards on most of the nuclear material in non-nuclear weapons states (NNWS), as designated by the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). Each NNWS has a specific agreement with the IAEA in regards to safeguarding facilities and material. The goal of IAEA safeguards is to prevent, and failing that, detect the diversion of significant quantities of nuclear material from civilian facilities to nuclear weapons programs. International safeguards thus reduces the proliferation risk of a nuclear power program [2].

The IAEA measures the amount of special nuclear material in terms of significant quantities (SQs), or the estimated amount of that material theoretically needed to create a nuclear weapon. An SQ of plutonium is 8 kg, and an SQ of low-enriched uranium is 75 kg, measured in terms of the contained U-235 [2]. As of the 2010 IAEA Annual Report, there are 172,180 SQs in 674 facilities under safeguards worldwide. Of these facilities, 235 are power reactors. There are 132,505 SQs of plutonium contained in safeguarded reactor core fuel and spent fuel, over 75% of the total SQs under safeguards [3]. The accumulation of spent fuel presents the largest (in terms of the amount of material) proliferation risk in the civilian nuclear fuel cycle. Spent fuel in storage will continue to increase the proliferation risk of a nuclear power program as existing plants burn fuel and new plants are introduced into the fleet.

Due to the delay in making decisions regarding spent fuel management policy in many countries, temporary storage on or off the plant site has become the primary storage method for spent fuel. In this study, different methods of spent fuel storage are evaluated in terms of proliferation resistance, taking intrinsic and extrinsic features into account. Following this analysis, recommendations are presented to increase the proliferation resistance of current spent fuel storage methods.

SPENT FUEL STORAGE TYPES

A typical light water reactor in the United States and Europe discharges and refuels about one-fourth to one-third of the fuel in the core every 12 to 18 months. The spent fuel is then transferred to a temporary wet storage pool. The U.S. Nuclear Regulatory Commission (NRC) requires that spent fuel in the pool be under at least 20 feet of water to allow for adequate radiation shielding [4]. Spent fuel pools vary greatly in size both in the U.S. and around the world and are typically within the reactor building or in a building adjacent to the reactor. The pool is connected to the reactor by a fuel transport canal, and the fuel is usually transported by cranes. Depending on the type of reactor and fuel, the fuel assemblies may sit in baskets or casks in the pool.

Many spent fuel management policies have changed or been delayed since the construction of the first nuclear power plants. This has caused many spent fuel pools to come near or exceed capacity. Dry cask storage is a form of interim dry storage in which the spent fuel is placed in casks either directly outside of the plant or nearby. Several spent fuel assemblies are placed in a sealed metal container with a metal or concrete outer casing to shield the radiation. The fuel assemblies must have cooled for at least 5 years in the spent fuel pool before they are ready for dry storage [5].

Many countries, including the United States, have utilized dry cask storage for spent fuel. While the principle of most dry casks is the same, there are many different types of dry cask storage available. Older designs hold as few as four PWR assemblies while newer designs may hold as many as 33 PWR assemblies or 61 BWR assemblies [6]. Many of the cask designs also utilize a multi-purpose canister (MPC). The MPC is the inner metal canister of the cask that can be used for storage in a concrete cask and then be placed in a transport cask and transported elsewhere.

For countries that do not plan to reprocess their spent fuel, a deep geological repository remains the preferred option for the final disposal of most high level waste forms. A geological repository is first sited in a stable landform, preferably in an unpopulated area with no major groundwater flow. Tunnels or caverns are built into the landform at depths between 250 and 1000 meters. A receiving and handling facility is usually located outside of the entrance tunnels. Spent fuel, and other waste forms, are packaged into metal casks and sent down the tunnels to their final location. There can be several engineered barriers to keep the radioactive waste from entering the accessible environment, including the waste form itself, waste package, tunnel, and surrounding rock. These barriers can also help deter diversion of the materials. For the purpose of this study, the geological repository will be considered a spent fuel “storage” instead of “disposal” method in order to compare it to the other storage methods. While some countries around the world are in the process of citing or licensing a deep geological repository for commercial spent fuel disposal, none have officially been opened [7].

SPENT FUEL STORAGE SAFEGUARDS METHODS

As mentioned previously, the IAEA institutes safeguards on all facilities containing nuclear materials in non-nuclear weapons states that are party to the NPT. Different safeguards methods are in place for each type of spent fuel storage method. Spent fuel assemblies in the spent fuel pool are visually inspected and counted to verify the declaration of the operator. Tamper-indicating E-cup seals are placed on access points and equipment involved in moving the spent fuel. In order to detect unauthorized movement, camera surveillance is typically employed in the reactor or spent fuel pool building. IAEA Inspectors also verify a certain fraction of the assemblies to make sure that they are indeed spent fuel. Verification usually involves measuring the intensity of the light from Cerenkov radiation using a viewing device. Gamma ray counting and spectroscopy can also be performed by various devices, such as the FORK detector or the Spent Fuel Attribute Tester (SFAT) [2]. Finally, more advanced gamma and neutron fingerprinting and plutonium measurement methods are still in research and development.

Since dry cask storage facilities are relatively new forms of spent fuel storage around the world, research and development are still underway to safeguard dry casks, especially by verification. Currently, containment and surveillance (C/S) is deployed at these facilities in the form of cameras, radiation monitors, and tamper-indicating seals [8]. Ultrasonic sealing bolts are also being used on some spent fuel containers [9]. Gamma ray and neutron fingerprinting methods are being developing to verify dry casks by radiation signatures [10].

Safeguards methods have yet to be developed for the geological repository since one has yet to be in commercial operation. However, it is anticipated that these safeguards methods will involve visual inspection, cask fingerprinting (much like for dry cask storage), and portal monitoring for the operating repository. The repository would be sealed once closed and then seismic and satellite monitoring would be used to detect unauthorized movement or access [11].

PROLIFERATION RESISTANCE ASSESSMENT METHODOLOGY

Proliferation resistance (PR) is a measure of the relative increase in barriers to impede the proliferation of nuclear weapons either by diversion of nuclear material by a state or by theft by an outside organization. This study is focused on the threat of diversion by the host nation and therefore takes into account international safeguards measures rather than security measures.

Several existing proliferation resistance (PR) assessment methodologies were analyzed in terms of the applicability to spent fuel storage. The PR methodology by Charlton et al., based on multiattribute utility analysis (MAUA), was chosen since it has the most applicable PR attributes for the assessment of spent fuel storage [12]. This methodology uses various attributes (detailed later in this section) that each have a specific utility function, $u(x)$, and input, x. The result of each utility function, $u_i(x_i)$, is multiplied by its weight, w_i, and then the products are added to obtain the total proliferation resistance value, PR, as shown in the equation:

$$PR = \sum_{i=1}^{i} w_i u_i(x_i)$$

The total PR value varies from 0 to 1, where 0 means that the spent fuel storage method does not have any proliferation resistant characteristics and 1 denotes that it is very proliferation resistant.

An important assumption being made in this assessment is that the material type (spent fuel) is constant for each storage method. This is an important assumption because it eliminates many of the PR attributes originally used in this methodology. The material in storage is not considered because the actual storage *method* is being analyzed. The material in storage is assumed to be PWR or BWR assemblies with a normal enrichment and burnup of 4% and 45 GWd/tHM, respectively. The fuel is also assumed to be at least five years out of the core since the largest amount of radioactive material decays in that time. Attributes such as material attractiveness, weight, and plutonium concentration will not be considered. The only material-specific attribute that should be accounted for is dose rate from the shielded material. This will be considered because the storage method may be more proliferation-resistant if it does not shield the fuel, thus making it harder to handle.

The PR attributes and their associated utility functions were determined using expert knowledge within a multi-organization working group [12]. Certain attributes were chosen for this study based on the applicability to spent fuel storage. The PR attributes and their weights (normalized to one) are radiation dose rate (0.16), physical barriers (0.21), inventory (0.10), frequency of measurement (0.18), measurement uncertainty (0.21), and probability of unidentified movement (0.14). The radiation dose rate, physical barriers, and inventory are considered intrinsic PR attributes because they are specific to the spent fuel storage methods themselves. The frequency of measurement, measurement uncertainty, and probability of unidentified movement are considered extrinsic PR attributes because they have been added to the spent fuel storage method by institutional controls.

The radiation dose rate attribute is determined as the dose rate, x_1, in mrem/hr, for the shielded material (in the case of spent fuel storage). The utility function is given by:

$$u_1(x_1) = \begin{cases} 0\,,\ if\ x_1 \leq 0.2, \\ 0.0520833x_1 - 0.010416\,,\ if\ 0.2 \leq x_1 \leq 5, \\ 0.0035714x_1 + 0.232143\,,\ if\ 5 < x_1 \leq 75, \\ 0.00095238x_1 + 0.428571,\ if\ 75 < x_1 \leq 600, \\ 1\,,\ if\ x_1 > 600, \end{cases}$$

The physical barriers to the spent fuel play a major role in determining the accessibility to the nuclear material. Less accessible material will most likely be less attractive to divert. The utility function for the physical barriers is given in Table 1.

Table 1: Physical barriers utility function.

Physical Barrier	Utility Function Value, $u_2(x_2)$
Inaccessible	1.00
Canyon	0.90
Vault	0.75
Secure	0.50
Remote	0.25
Hands-on	0.00

The final intrinsic utility function relevant to spent fuel storage is the total inventory of the facility. This utility function is given by:

$$u_3(x_3) = \begin{cases} 1\,,\ if\ x_3 < 1, \\ \left[\frac{(30 - x_3(100/x_{max})^{\frac{1}{3}}}{7.18}\right] + 0.574\,,\ if\ 1 \leq x_3 \leq x_{max} \\ 0\,,\ if\ x_3 > x_{max} \end{cases}$$

where x_3 is the total inventory and x_{max} is the maximum inventory set at an arbitrary amount 5000 SQs. This value is chosen to allow for the distinction of very large and very small facilities.

The frequency of measurement utility function defines how frequently the nuclear material is checked. The frequency of measurement can vary from continuous to never. Table 2 shows the utility function value for each frequency of measurement. This attribute only includes the actual measurements taken to verify that the spent fuel is actually present.

Table 2: Frequency of measurement utility function.

Frequency of Measurement	Utility Function Value, $u_4(x_4)$
Continuous	1.00
Hourly	0.95
Daily	0.85
Weekly	0.75
Monthly	0.50
Quarterly	0.25
Annually	0.10
Never	0.00

Along with the frequency of measurement, the measurement uncertainty is also important. This attribute is represented as the fraction of material that is left unverified after an inspection. The utility function is therefore given by

$$u_5(x_5) = 1 - x_5$$

where x_5 is the percent of the total inventory of nuclear material verified per inspection.

As mentioned before, surveillance is an important measure in safeguards and proliferation resistance. Even though the C/S may fail, the presence of it still increases the PR value. Therefore, the probability of unidentified movement is a utility function which includes the presence of a C/S system. The utility function is given by:

$$u_6(x_6) = \frac{1}{2} - \frac{1}{2}\tanh\,(4x_6 - 2)$$

where x_6 is the probability that an SQ is moved without the detection of a surveillance. This probability is difficult to define because it depends on many factors. Therefore a ranking system dependant on the coverage of the C/S system was developed to quantify this input.

The utility function input values, $x_1 \ldots x_6$, were researched extensively to find the most current and accurate information, using various sources and data from across the world [2], [6], [7], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22]. Table 3 shows a summary of the various input values for each PR attribute utility function. Some of these values (such as for the inventory) are averages or estimates while others are exact values.

Table 3: Summary of utility function input values for each PR attribute

PR Attribute	Weight	Spent Fuel Pool	Dry Cask Storage	Geological Repository
Radiation Dose Rate	0.16	<1 – 2.5 mrem/hr	20 – 400 mrem/hr	Open: 200 mrem/hr Closed: 0 mrem/hr
Physical Barriers	0.21	Vault (0.75)	Secure (0.50)	Canyon (0.90)
Inventory	0.10	World 1998 – 536 SQ World 2011 – 500 SQ U.S. 1997 – 767 SQ U.S. 1998 – 943 SQ U.S. 2010 – 670 SQ	U.S. 1998 – 626 SQ U.S. 2010 – 360 SQ Asia 2011 – 18,000 SQ	U.S. 2011 – 87,000 SQ Europe 2011 – 9,500 SQ
Frequency of Measurement	0.18	Quarterly (0.25)	Quarterly (0.25)	Open: Quarterly (0.25) Closed: Never (0.00)
Measurement Uncertainty	0.21	High Confidence: 96% Medium Confidence: 75% Low Confidence: 39%	100%	100%
Probability of Unidentified Movement	0.14	0.25	0.50	0.75

RESULTS & ANALYSIS

In the previous section, various input values were found for each PR attribute for each storage method. For some attributes, more than one input value was found. In the “normal case” analysis, the input value with the most credibility (i.e. most supporting data available) is used, as shown in Table 4. The utility functions are multiplied by their respective weights to add to the total PR value. The input, or value of x, is shown along with the calculated PR values. The three different spent fuel storage types all have relatively similar total intrinsic PR values. However, they differ greatly in the total extrinsic PR values. The main difference is that the spent fuel pool has a lower measurement uncertainty, and thus a higher PR value, because spent fuel assemblies are actually verified, which is not the case in the dry cask storage facility or the geological repository. In addition, the spent fuel pool and dry cask storage have a higher value in the probability of unidentified movement. From the total PR value, it can be seen that the spent fuel pool ranks first in proliferation resistance while the geological repository ranks last.

Several recommendations can be made in order to increase the PR value for all three spent fuel storage types. First of all, analysis showed that changes in the intrinsic PR attributes had less of an effect on the total PR value than the extrinsic attributes. In addition, the intrinsic attributes are more difficult to change because they are inherent to the actual storage type. For example, the radiation dose rate of the storage facility should not be changed in order to enhance the proliferation resistance. Even though an increase in the dose rate increases the PR value, higher dose rates could be dangerous to the workers and inspectors in the facility.

Table 4: PR values for normal case of spent fuel storage methods.

PR Attribute	**Weight**	**Value of *x***			**PR Value**		
		Spent Fuel Pool	**Dry Cask Storage**	**Open Geological Repository**	**Spent Fuel Pool**	**Dry Cask Storage**	**Open Geological Repository**
Radiation Dose Rate	0.16	2	200	200	0.02	0.10	0.10
Physical Barriers	0.21	Vault	Secure	Canyon	0.16	0.11	0.19
Inventory	0.10	943	626	87000	0.09	0.09	0.00
Frequency of Measurement	0.18	Quarterly	Quarterly	Quarterly	0.05	0.05	0.05
Measurement Uncertainty	0.21	75%	100%	100%	0.05	0.00	0.00
Probability of Unidentified Movement	0.14	0.25	0.50	0.75	0.12	0.07	0.02
Intrinsic PR Value (max 0.47)					**0.27**	**0.30**	**0.29**
Extrinsic PR Value (max 0.53)					**0.22**	**0.12**	**0.07**
Total PR Value (max 1.00)					**0.49**	**0.42**	**0.36**

The physical barriers PR attribute is inherent to the spent fuel storage facility, as well, and cannot be altered to increase the proliferation resistance. The exception is with dry cask storage because it can be made into a “vault” facility by simply placing it in a secure building. Dry cask storage facilities are typically placed outside and surrounded by only a fence. A secure building placed around the facility would increase the PR value but would not put a significant burden on the IAEA or the operator, after the initial construction of the facility.

While the values found for average inventories of spent fuel storage facilities in the United States and across the world seemed to vary greatly, only extremely large changes in the inventory have an effect on the total PR value. The large inventories (over 5000 SQ) of centralized storage facilities and geological repositories significantly decrease the total PR value. Centralized interim dry storage facilities can be avoided by employing on-site dry storage and minimizing the build-up of spent fuel storage at reprocessing facilities, for example. If a centralized facility is necessary, then more safeguards should be put into place in order to increase the proliferation resistance.

As mentioned previously, all three of the extrinsic PR attributes had a significant effect on the total PR value, since any increase in safeguards measures would increase the proliferation resistance of a facility. However, increases in safeguards measures can also put a significant burden on the IAEA and on the operator. For example, while an increase in the frequency of measurement would increase the PR value, it would also require more inspections and thus more resources from the IAEA. It is recommended that the frequency of inspection remain quarterly for efficient and effective safeguards. However, if remote verification of spent fuel were to be developed, then the frequency of measurement could increase without putting a heavy burden on the IAEA. Increasing the frequency of measurement would also significantly increase the PR value for all spent fuel storage types. Since remote verification is not currently being developed for spent fuel storage, it will not be considered in the optimal case presented later in this section.

The IAEA currently does not verify spent fuel inside of casks at every facility, thus making the measurement uncertainty for dry cask storage and geological repository at 100%. In order to increase the proliferation resistance of these facilities, the measurement uncertainty should be decreased to the level of the spent fuel pool (75%). This would mean that a quarter of the spent fuel assemblies in the facility would need to be verified during each inspection. With the right technology and cask design, this could be done in an efficient manner, without putting a significant burden on the inspector or operator. Developing the technology and optimal cask designs to facilitate verifying spent fuel assemblies inside of the casks would significantly increase the proliferation resistance of dry cask storage and the geological repository.

The probability of unidentified movement can also be decreased in dry cask storage and geological repository facilities in order to increase the proliferation resistance. The C/S system at a spent fuel pool has total knowledge of the spent fuel assemblies, unless the system is compromised. When spent fuel assemblies are inside of casks, surveillance does not have a direct view of the assemblies themselves. For this reason, sealing bolts that can send a tampering alert real time should be used on casks. In addition, surveillance of the entire geological repository should be in place, especially while it is in the operation phase.

In addition, it is important to discuss the closed geological repository because it has a different PR value from the open repository. While the closed repository's inaccessibility increases the PR value, the lack of radiation dose rate outside the repository and lack of inspections significantly decreases the PR value. Since the closed repository is sealed, actual inspections of the casks and fuel cannot occur. However, real-time surveillance can be employed to alert the IAEA of any tampering with the spent fuel. There should be no activity in a closed repository, so the surveillance would be quite simple because any activity should set off an alarm. Therefore, it is recommended that a closed repository have IAEA surveillance in order to increase the proliferation resistance.

Table 5: PR values for optimal case of spent fuel storage methods.

PR Attribute	**Value of *x***				**PR Value**			
	Spent Fuel Pool	**Dry Cask Storage**	**Open Geological Repository**	**Closed Geological Repository**	**Spent Fuel Pool**	**Dry Cask Storage**	**Open Geological Repository**	**Closed Geological Repository**
Radiation Dose Rate	2	200	200	0	0.02	0.10	0.10	0.00
Physical Barriers	Vault	**Vault**	Canyon	Inaccessible	0.16	0.16	0.19	0.21
Inventory	943	626	87000	87000	0.09	0.09	0.00	0.00
Frequency of Measurement	Quarterly	Quarterly	Quarterly	Never	0.05	0.05	0.05	0.00
Measurement Uncertainty	75%	**75%**	**75%**	100%	0.05	0.05	0.05	0.00
Probability of Unidentified Movement	0.25	**0.25**	**0.25**	**0.50**	0.12	0.12	0.12	0.07
Intrinsic PR Value (max 0.47)					**0.27**	**0.35**	**0.29**	**0.21**
Extrinsic PR Value (max 0.53)					**0.22**	**0.22**	**0.22**	**0.07**
Total PR Value (max 1.00)					**0.49**	**0.57**	**0.51**	**0.28**
Percent Change from Normal Case					**0%**	**+36%**	**+42%**	**N/A**

The normal case from Table 4 can now be altered to reflect the above recommendations, presenting the optimal case in Table 5. As can be seen, the total PR values for dry cask storage and geological repository were significantly increased and are higher than that for the spent fuel pool. The input values of x that were altered are highlighted in bold in the table. The total PR value for spent fuel pool storage remains unchanged because no recommendations were able to be made without putting a significant burden on the inspectors and operators. However, any spent fuel storage facility could be made more proliferation resistant by simply decreasing the measurement uncertainty by verifying more spent fuel assemblies during inspections or by developing remote verification to increase the frequency of measurement. With the recommendations employed, dry cask storage would be the most proliferation resistant method of spent fuel storage. A closed geological repository is significantly less proliferation resistant than one in operation because of the lack of the ability to inspect it. Therefore, surveillance should be increased for a closed geological repository in order to increase the proliferation resistance.

CONCLUSION

The proliferation resistance assessment methodology developed in this research effectively calculates the PR values of spent fuel storage and disposal facilities. These PR values can be used to compare the relative proliferation resistance of each storage type in terms of several intrinsic and extrinsic PR attributes. The extrinsic attributes, mainly involving safeguards measures, affect the total PR value most. It was found that for current data the spent fuel pool is significantly more proliferation resistant than dry cask storage or the geological repository. As a result, several recommendations were made to improve the proliferation resistance of spent fuel storage. With more safeguards in place, on-site dry cask storage would be the most proliferation resistant. Therefore, the IAEA should continue to develop remote monitoring and cask storage verification techniques in order to improve the proliferation resistance of spent fuel.

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