Environmental impact resulting from a fire at a spent nuclear fuel storage facility

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Abstract: Nuclear power reactors have created a significant quantity of used or spent nuclear fuel elements that contain some remaining nuclear fuel and by products of the fission process that are highly radioactive. Lack of a secure central repository or other permanent disposal process for spent nuclear fuel elements has resulted in long term storage of these elements in spent fuel pools at operating nuclear power plants. A recent review of the safety and security of commercial spent nuclear fuel expressed concern that terrorist activity at a spent nuclear fuel storage pool could result in a zirconium cladding fire that could create widespread radioactive contamination with dramatic impact on both the public and the environment. A scenario based on such an event is presented to demonstrate the potential impact resulting from the release and dispersion of spent fuel products.

Keywords: radiological emergency; spent nuclear fuel; terrorist attack; zirconium cladding fire.

Reference to this paper should be made as follows: Sensintaffar, E.L. and Phillips, C.R. (2007) 'Environmental impact resulting from a fire at a spent nuclear fuel storage facility', *Int. J. Nuclear Governance, Economy and Ecology*, Vol. 1, No. 3, pp.278–285.

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1 Introduction

Nuclear energy is a significant resource for producing electrical power and precludes the atmospheric pollution associated with fossil-fuel powered generators. However, when reprocessing or direct disposal of spent nuclear fuel are not options, the resulting high inventories of spent fuel stored in spent fuel pools at the reactors or independent storage facilities present a potential security and safety concern. This storage of spent fuel requires stringent safety requirements to prevent exposure to workers, incidental damage to the encapsulation material or cladding, and potentially severe consequences of the release of extremely large quantities of radioactive material due to terrorist activities. Although these storage facilities have an excellent safety record, the very large quantities of radioactive material stored in most of these facilities make them an attractive target for a terrorist attack. If successful, such an attack could result in a release of radioactive contamination comparable with a major nuclear reactor incident.

2 Background

Nuclear power reactors have been producing electrical power for almost five decades (Radiochemistry Society). The nuclear energy in this process comes from nuclear fission of enriched uranium fuel elements. A typical nuclear power reactor core contains approximately 75 metric tons of uranium (MTU) fuel that is in the form of ceramic pellets enclosed in a metal tube called a fuel rod. The metal tube or cladding for power reactors is usually an alloy made of zirconium or zircaloy. Several fuel rods are combined into an assembly that is placed into the reactor core. Over time the efficiency of the fission process in a fuel assembly is decreased, due to loss of fissionable atoms and build-up of other materials, so the fuel assembly is replaced. Typically about one-third of a reactor core, about 25 MTU, is replaced each year so a portion of the core that was installed at a given time, will be in the core for approximately three years (World Nuclear Association). The fuel element assemblies that are removed are called spent fuel and contain some remaining uranium fuel, some radioactive elements that were produced by activation or activation products, and a variety of highly radioactive isotopes referred to as fission products. Examples of some of the fission products that are frequently found in spent fuel and their inventory are shown in Table 1. There are many other fission products possible but those listed are frequently recognised for their potential to create long term heating of the fuel and significant contamination and health issues if released to the environment.

Table 1 Examples of fission products found in spent nuclear fuel (McKenna et al., 1996)

Fission product	*Half-life*	*Inventory* EBq*
Ruthenium-106	372.6 d	4.1
Cerium-144	284.4 d	3.1
Cesium-137	30.2 y	0.17
Cesium-134	2.1 y	0.28
Strontium-90	28.5 y	0.14
Iodine-131	8.0 d	3.1
Krypton-85m	4.5 h	0.89
Xenon-133	5.2 d	6.3

Notes: *The inventory assumes a Liquid Water Reactor core about 30 minutes after shutdown
EBq = 10^{18} Bq

The fission products in the spent fuel create very high radiation levels in the area surrounding the fuel. This is particularly true during the first year after the fuel is removed from a reactor, but even ten years after removal of spent fuel from a reactor, the radiation dose 1 metre away from a typical spent fuel assembly exceeds 200 Sv per hour (US Nuclear Regulatory Commission, 2002). Energy produced by the radioactive decay within the fuel elements results in heat. If heat is not removed, the assemblies can reach temperatures that can result in the rupture of the zirconium alloy cladding or even a zirconium cladding fire that can release very high concentrations of the radioactive contents. For this reason, spent fuel elements are typically stored under water in spent fuel pools. Water in the pools serves as a shield to reduce radiation to acceptable levels and as a heat transfer medium to cool the fuel (World Nuclear Association).

Very high concentrations of radioactive isotopes in the spent fuel require the fuel to be stored in the pools for the first one to five years after it is removed from a reactor. However, as some of the shorter lived radionuclides decay and consequently less heat is produced within the fuel assemblies, they can be moved to other specialised storage facilities or sent for reprocessing where the usable fuel is removed and the waste materials prepared for long term disposal. Storage for the aged spent fuel may include dry casks that shield the external radiation to acceptable levels and allow air convection to cool the assemblies or long term direct disposal facilities (US Nuclear Regulatory Commission, 2002).

Transfer of spent fuel to reprocessing, direct disposal or dry casks has been limited due to insufficient availability and public concerns. This has resulted in filling the spent fuel pools beyond the original design specifications for many reactors. Boron lined tubes have been added to the pools to reduce the potential for criticality and the fuel stored has been re-racked to as much as two to three times the original design specifications. The result is an onsite inventory of spent fuel that is the equivalent of many reactor cores. For example one nuclear power facility that utilises 88.9 MTU of fuel in its core, has an inventory of spent fuel of 764 MTU of spent fuel on hand in 1997 (US Department of Energy, International Nuclear Safety Center). The International Atomic Energy Agency (IAEA) estimated total spent fuel stored worldwide as of 2003 includes 171,000 MTU with over 10,500 MTU produced each year (International Atomic Energy Agency, 2003).

Using the above example of over 750 MTU of spent fuel at one site and the estimates of fission product inventories in Table 1, the example spent fuel pool could contain over 1.5 EBq (40 MCi) of Cs-137 in addition to other fission products, activation products and remaining uranium. This is a conservative estimate because it is based on fuel in an active core. Cs-137 and other fission products continue to build up the longer they are in the active core. Such large quantities of radioactive material located in one place could be an attractive target to a terrorist who wants to take advantage of the public's fear of radiation and the potential high impact on both public health and the economy.

3 Spent fuel pools – not an easy target

Spent fuel pools are designed to provide safe storage of the fuel assemblies and have an excellent history of safe operation. Some notable features that would be applicable to protect against a terrorist attack include (US Nuclear Regulatory Commission):

- pools are often below ground level and have very thick (2–3 m) concrete walls
- they are usually surrounded by other buildings, including the reactor containment building and other support buildings. In some cases (BWRs) the pool may be inside the reactor building
- the fuel assemblies are covered with 8 to 10 m of water above the tops of the assemblies to allow them to be lifted out of the boron lined tubes and still remain underwater
- depending on loading, it could take from several hours to several days without cooling to boil off the water in the pool. This allows time for actions that could prevent catastrophic failures
- most recent additions to a pool can be spread out to dissipate heat and reduce potential for rupture or cladding fires
- security at reactor and spent fuel storage facilities has been increased following the 9/11 terrorist attacks.

A US National Academy of Science – National Research Council report on the safety and security of commercial spent nuclear fuel storage provided the following conclusions regarding the potential for terrorist attacks on spent fuel pools (National Research Council of the National Academies of Science):

- it would be difficult for terrorists to steal enough spent fuel from storage facilities for use in significant radiological dispersal devices or dirty bombs
- successful terrorist attacks on spent fuel pools would be difficult, but possible
- if an attack on a spent fuel storage facility leads to a propagating zirconium cladding fire, it could result in the release of large amounts of radioactive material.

4 What if a terrorist attack on a spent fuel storage pool occurs?

If an attack on a spent fuel storage facility occurs that either causes the water in the pool to be released or prevents any cooling of the existing water allowing the water to evaporate, the fuel assemblies in the pool could begin to overheat. The fuel assemblies that were most recently removed from the reactor would be in danger of melting of the cladding due to their high fission product inventories and the resulting high heat of decay production. In some cases, particularly at PWRs, the whole reactor core is placed in the fuel storage pool during refuelling and maintenance operations. If this were the case, the core would greatly add to the heat load in the pool.

If the water level in the pool is reduced to expose some of the fuel assemblies, the radiation levels in the building will become very high. This would limit the ability of plant personnel to enter the area to mitigate the problem. Automatic water spray systems might reduce the heating if they are available and operational. However, assuming that the fuel continues to get hotter, then it will eventually stress the cladding material sufficiently to rupture, and release of the radioactive contents would be expected. Approximately 5% of the volatile fission products could be released due to fuel element gaps (McKenna al., 1996, Section D).

As the fuel assemblies continue to heat, oxidation of the zircaloy-cladding material will occur and if sufficiently high temperatures occur, the oxidation reaction can become self-sustaining and highly exothermic. This is referred to as a zirconium cladding fire. The oxidation process is enhanced by the presence of steam. The heat resulting from the cladding fire can add to the existing heat in the assemblies and cause the cladding fire to spread to nearby fuel assemblies. Cladding fires can lead to releases of between 10 and 100% of the volatile fission products in the fuel assemblies that are involved. The heat from the cladding fire can create convective currents that carry the volatile contaminants away from the facility where the public and the environment would be impacted.

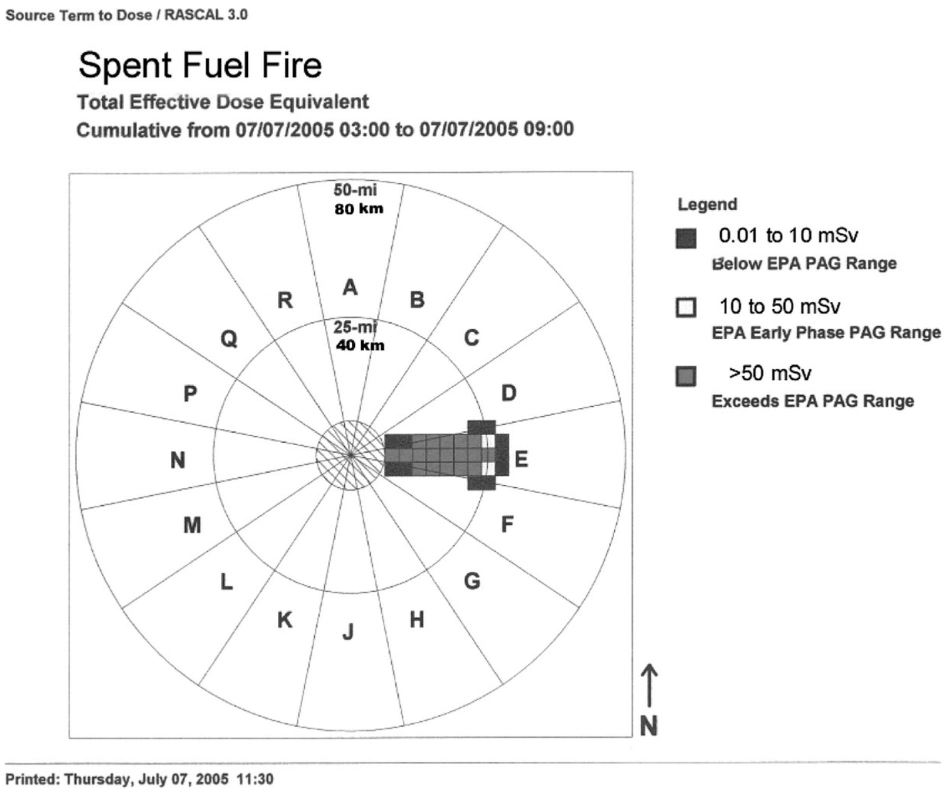
5 What is the potential impact of a spent nuclear fuel cladding fire?

The degree that contamination from a spent fuel fire could be spread to the surrounding environments and its impact on the public are subject to a large number of variables such as height of the release, temperature of the exhausted gases, wind direction and speed and many others. There are several dispersion models that are designed to estimate the spread of a release such as a spent fuel cladding fire. The authors tested three different computer based models to determine if any were appropriate for a spent fuel fire scenario. A review of recent literature also revealed several reports/papers that used such models to predict the impact of a major release of radioactive contaminants such as from a spent fuel fire. A brief summary of the information that was identified follows:

6 Dispersion models used by the authors

The computer based models NARAC web (National Atomspheric Release Advisory Center), Hotspot (National Atmospheric Release Advisory Center, 2003) and RASCAL 3.0 (US Nuclear Regulatory Commission, Version 3.0) were tested for their ability to predict the impact of a spent fuel cladding fire. NARAC and Hotspot models were not found to be well suited for this scenario. Of the three modelling programmes, the RASCAL code was found most effective and easiest to use due to its pre-programmed source terms for this scenario. A scenario based on the example reactor previously mentioned in this paper was used with a source term of three irradiated fuel batches (~75 MTU) ranging in age, from less than one year to three years, and a release duration of one day during calm conditions. Figure 1 shows the graphic display that was produced by the computer model after modification to display SI units. The predicted plume is shown to extend to over 40 km with predicted Total Effective Dose Equivalents (TEDE) in excess of 50 mSv.

Figure 1 Graphic output from RASCAL dispersion model predicting Total Effective Dose Equivalents (TEDE) greater than 50 mSv beyond 40 km from the point of release



7 Reports on impact of nuclear spent fuel fires

Several reports and articles that provided additional information on the impact of a major nuclear incident including a spent nuclear fuel cladding fire were identified. A sample of the information in these reports will be summarised here to provide additional information about the potential impact of a spent fuel fire.

The US Nuclear Regulatory Agency in the report 'Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants' NUREG-1738 (US Nuclear Regulatory Commission, 2001) did extensive testing of the risk of a significant accident at a spent fuel pool. The results indicated a very low risk of occurrence; however, the report was written in January 1991, prior to the 9/11 event and did not deal with the potential of a well planned terrorist attack. The analysis showed that the consequences of a spent fuel pool accident could be comparable to those for a severe reactor accident. The consequences would vary based on the population density around the plant and weather conditions; however, potential consequences could include nearly 200 early fatalities and thousands of latent cancer fatalities.

Two recent articles in *Science and Global Security* dealt specifically with the spent fuel issue (Alvarez et al., 2003; Beyea et al., 2003). The authors of these papers used a Wedge Model and the MELCOR Accident Consequence Code System (MACCS2), a Gaussian plume dispersion code, to estimate the impact on the surrounding environment and public from a spent fuel fire. Source terms of 0.13 EBq (3.5 MCi) and 1.3 EBq (35 MCi) of Cs-137 were used to calculate the potential impact on the surrounding environment and public. The projected plume areas that were calculated by each of these modelling systems are shown in Table 2 and compared with the estimated areas contaminated during the 1986 Chernobyl reactor accident. The predicted plume areas for both source terms and models were much greater than for the Chernobyl incident. Projected plumes were compared to population densities for five different commercial power reactors in the United States to estimate the impact on the public and the cost to purchase or decontaminate the areas back to habitable levels. The estimated cost of decontamination ranged from \$5 billion to \$199 billion US\$. Approximately 1900 cancer deaths were predicted for the 0.13 EBq release and 5700 cancer deaths for a 1.3 EBq release.

Table 2 Typical plume areas resulting from a spent fuel fire with 0.13 to 1.3 EBq of Cs-137 releases (Alvarez et al., 2003)

Release	*>3.7 TBq/km^2 (100 Ci/km^2)*	*>37 TBq/km^2 (1000 Ci/km^2)*
Chernobyl (0.0074 EBq or 2 MCi)	~700 km^2	
0.13 EBq or 3.5 MCi (MACCS2)	3500	200 km^2
0.13 EBq (Wedge model)	6000	180
1.3 EBq (MACCS2)	45,000	2500
1.3 EBq (Wedge model)	50,000	6000

8 Conclusions

There is a very large amount of spent nuclear fuel stored in spent fuel pools at nuclear reactors and independent storage facilities throughout the world. The amount of stored fuel is frequently well beyond the original design limits of the pools. Although modifications in the racking systems have been made to protect against criticality the heavy loading of the pools creates heat that could result in damage to the fuel assemblies or even zircaloy cladding fires if the cooling is not adequate. The very large quantities of radioactive material in the form of fission products, activation products and remaining uranium in the spent fuel stored at a site could be an attractive target for a terrorist. A successful terrorist attack on a spent fuel pool is not likely, due to the heavy security at the plants and the design features of the pools and cooling systems. However, if an attack were to occur and result in loss of water in the pool, allowing the spent fuel to overheat, rupture of the fuel elements or zirconium alloy cladding fires could result. The radioactive contamination that could be released into the environment from such an event could contaminate thousands of square kilometres, result in billions of dollars in economic impact and large numbers of both early and latent cancer deaths. The use of other means including dry storage casks, direct disposal and reprocessing for reducing the number of fuel assemblies stored in spent fuel pools could reduce the potential for such an incident.

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