Per Peterson original review of "Reducing the hazards from stored spent power-reactor fuel in the United States" by Robert Alvarez, Jan Beyea, Klaus Janberg, Jungmin Kang, Ed Lyman, Allison Macfarlane, Gordon Thompson and Frank N. von Hippel, to be published in *Science & Global Security,* spring issue, 2003.

ORIGINAL REVIEW

Review of "Reducing the hazards from stored spent power-reactor fuel in the United States."

This manuscript presents technical analysis of the potential for spent-fuel pool fires in current light-water reactors with high-density fuel storage. The paper notes that the probabilities of such fires occurring due to accidents or natural external events are quite small, and thus focuses primary of potential effects of deliberate aircraft crashes and ground assaults or sabotage. The manuscript makes no attempt to quantify the probability of such events being successful in generating spent-fuel pool fires ("We therefore propose without a probabilistic justification physical changes to spent-fuel storage arrangements..."). The paper explores the potential bounding consequences of releases of 10 to 100% of the esium inventory in a spent fuel pool with approximately 400 MT of spent fuel (typically around 20 years full power operation). Direct fatalities are not hypothesized, but the contamination of large areas of land to levels required use restrictions for decades would occur.

The authors recommend a variety of different approaches to reduce the potential consequences of attacks on spent fuel pools, including the movement of spent fuel into dry cask storage at a cost of between $3.5 and $7.0 billion. Because the paper does not analyze the probability of an attack occuring or actually generating the hypothesized consequences, it does not provide sufficient information to judge whether these investments would be justified. The authors state:

"The willingness of society to bear these costs will reflect the public's perception of the significance of the risk that is posed by spent fuel."

If the authors' primary goal is to alter the public's perception of risk, then a web site is probably a better venue than a peer-reviewed archival publication. If the purpose is to inform public policy for setting priorities toward the goal of combatting terrorism, then enough information must be provided so one can compare the relative vulnerabilities of existing nuclear infrastructure to other other civil infrastructure.

In general it is not economically practical to harden all civilian infrastructure to the level already attained by nuclear power plants, so the better investments are likely those that make terrorism more difficult to commit, such as measures to automate aircraft control systems to create "soft walls" around critical infrastructure.

This said, specific issues that should be addressed prior to any publication are:

1) The term "hazards" in the title should be changed, because the definition of hazards (Websters) includes some measure of chance or probability, and the manuscript explicitly states that does not make any estimate of probability, but instead only analyzes the potential most severe consequences of events at spent-fuel storage pools. "Worst-case potential consequences" or "Bounding consequences" would be more appropriate terminology for the title, to reflect the scope of what is actually covered in the manuscript.

2) I would question the assumed release fractions of 10 to 100% of the total cesium inventory as a consequence of a spent-fuel pool fire. The paper notes that for dry cask storage (Pg. 25), analysis estimates that that 0.04 MCi of Cs-137, of a total of 170 MCi (0.024%), would be released from spent fuel subjected to similar thermal conditions due to a protracted (5-hour) kerosene fire. The analysis predicting larger release fractions for zironium fires in spent fuel pools is not particularly compelling. Footnote 17 notes that analysis for traditional severe accidents, where fuel damage is driven primarily by decay heat, gives release fraction that approach 100% as fuel temperatures around 2000°C are reached. But this damage is generated by decay-heat, rather than zirconium-combustion. Prior to the 2000°C temperature being reached in a zirconium fire, all of the non-oxidized zirconium metal will have melted and relocated. Thus zirconium oxidation no longer provides a heat source at thesetemperatures. Normally the complete release of volatile fission products requires full melting of the fuel, and again it is difficult to see how the zirconium oxidation process could be sustained under the geometric reconfiguration that occurs prior to full fuel melting, since this reconfiguration would tend to restrict the access of oxygen to the metallic zirconium. If significant fuel melting does not occur, then cesium release must occur by solid diffusion from the ceramic fuel matrix. Because the release fraction is a critical parameter in justifying the estimated contamination consequences, better analysis is needed. It may be best to have input from an expert in severe-accident phenomenology like Dana Powers at Sandia, since it would be surprising if some estimates of fission product release fractions from zirconium-fire heated spent fuel have not been made. In any case, stronger support is needed for the 10% to 100% cesium release assumption used in calculating consequences, since it does not appear to be physically plausible based on the requirement to reach temperatures in the range of 2000°C by the process of zirconium oxidation.

3) The paper should clearly distinguish between the potential consequences of aircraft crashes and of ground assault and sabotage. The appropriate strategies for protecting civilian infrastructure from these two types of terrorist attacks are different. In particular, where large damage is assumed to the reactor building, it should be emphasized that this would be the result of the aircraft crash, but not of ground assault or sabotage. Given the more limited damage that could be achieved by ground assault and the relatively long time periods available for response prior to substantial fuel damage, the risks posed by ground assault are probably best addressed through the plant's physical protection and emergency response measures.

4) Because this manuscript is intended to inform public policy on prioritizing investments to counter terrorism, it should make some attempt to compare the consequences of spent fuel pool fires with the consequences of attacks of employing similar terrorist resources on other civilian infrastructure. In particular, it should make a comparison with the consequences of crashes of large commercial aircraft into other civilian facilities, including large sports stadiums. A casualty and damage estimate for a worst-case commercial aircraft crash into a large urban U.S. sports stadium, resulting in a fuel-air deflagration of 60 to 80% of the total fuel load, when the stadium is filled to the upper 10th percentile of its attendance, should be provided for comparison, since the worst-case consequences of this type of event are easily estimated and can be directly compared with the predicted worst-case consequences for a crash into a spent fuel pool, and we know that football and baseball stadiums are considered to be highly symbolic terrorist targets.

4) Related to (4) above, the potential approaches to further protect spent fuel pools should also include measures to reduce the potential frequency of attacks, and preferably measures that simultaneously provide benefits in protecting other civilian infrastructure. I find it quite questionable to recommend investing $7 billion in dry-cask storage systems to reduce the

hypothetical peak consequences of spent fuel fires by a factor of 4, when other investments could be made, for example into automation systems for aircraft to create "soft walls" around critical infrastructure would protect both nuclear power plants and other civilian and military infrastructure like sports stadiums, office buildings, and chemical facilities. http://ptolemy.eecs.berkeley.edu/projects/softwalls/

In the section on approaches to make spent fuel pools safer (page 17), the authors should also list changes that would reduce the probability of attacks occurring in the first place, including changes that could generate ancillary benefits by also protecting other civilian infrastructure and activities.

5. Page 7 postulates zirconium fire thermal powers ranging from 5 to 250 MWt providing the mechanism for generating the plume that transports cesium from the degraded spent fuel to the environment. But it is not clear that the cesium is released at the time that the fire would have significant thermal power (if a significant fraction is released at all), because the fire can only occur if the metallic zirconium is below its melt temperature and this is too cold for substantial damage to occur to the ceramic fuel itself.

6. Page 20 discusses the potential for criticality accidents in open-rack storage if the fuel racks are crushed. Figure 10 is difficult to interpret because it has several unlabeled curves. But it is hard to envision a crushing event that would uniformly rearrange spent fuel in such a way that k-infinity calculations (which assume an infinite, uniform fuel lattice) are relevant to predicting the potential for criticality.

7. The paper should also discuss the implications of the current analysis for the design and deployment of new nuclear power plants. For example, the new GE ESBWR design already places the spent fuel pool below grade to the side of the reactor building, and the GT-MHR and PBMR have air-cooled storage inside hardened concrete structures. One could recommend designing new LWRs for the early transfer of spent fuel to dry storage, and advise eliminating compartments and other volumes below and to the sides of spent fuel pools to eliminate the potential for damage that could cause rapid draining. In the longer term, closed fuel cycles could eliminate the zirconium combustion issue for stored spent fuel and allow improved waste forms for the cesium and other fission products, while transmuting the minor actinides that provide the primary decay-heat source that creates a limit on the capacity of repository sites like Yucca Mountain. Increased reactor core/coolant thermal inertia and passive decay-heat removal systems, protected from damage by passive barriers (massive hatch covers, backup heat rejection by conduction to ground, etc.), would also reduce physical protection requirements for protection of the reactors themselves.

POSTMORTUM ON "Reducing the hazards...."

Two major deficiencies remain in the paper "Reducing the hazards...." following my original review, as detailed here.

1) This paper still presents absolutely no quantitative analysis to determine whether the string of multiple events required to generate a large off-site release from a spent fuel pool following aircraft or other attacks would actually occur. My personal opinion is that the probability that a terrorist aircraft crash would actually result in the postulated spent-fuel pool fire is quite small. The authors present nothing to contradict my opinion. But at least the original manuscript was explicit in stating the basis for the author's policy recommendation, saying "We therefore propose without a probabilistic justification physical changes to spent-fuel storage arrangements..." I do not think that deleting this statement was an appropriate way to address my review comment, but this is what the authors did.

2) There exist other targets for large, fully-fueled commercial aircraft that we know would generate larger fatalities than our worst-case spent fuel scenario, with much higher probability. My most important review comment, that was not addressed, was to state that an alternate public policy exists--simply to reduce the probability that aircraft can be hijacked in the first place. I provided a specific reference to research now underway in this area where I believe 3 to 7 billion dollars could be much better invested than in the recommended dry casks:

http://ptolemy.eecs.berkeley.edu/projects/softwalls/

I am angry that no revision was made in response to my review comment. Absolutely no mention was made of the possibility that risk could also be reduced by decreasing the probability of the initial terrorist act, even though the probability of the initial event is clearly a contributor to the total risk. At a minimum the alternative option could have been at least mentioned in the paper, since I specifically asked for it in my review. Terrorism is different from accidents, because terrorism identifies the weakest links in our infrastructure and exploits them. Our national response to terrorism must be uniform.

I strongly believe that our design-basis-threat assumption of an active insider in a nuclear plant should extend to aircraft cockpits, and that we should design aircraft security systems accordingly, as we do the physical protection systems for nuclear power plants. The authors are either opportunistic, or are completely wrong in advocating an investment policy to harden some of our infrastructure to very high levels, while leaving other infrastructure open for terrorists to exploit. If we do see a fully-fueled commercial aircraft come down in a facility where a very large number of people are closely congregated, the press conferences conducted by the authors of this paper will get a bit of the credit. Our new National Strategy for the Physical Protection of Critical Infrastructures and Key Assets recommends a uniform approach to strengthening all areas of our civilian infrastructure; uniformity is a much more rational policy approach than that implied by the authors' lack of response to my review comments.