Lessons Learned About Spent Fuel Pools From the Fukushima Accident

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Lessons Learned About Spent Fuel Pools From The Fukushima Accident, Executive Summary

EXECUTIVE SUMMARY

1.0 Overall Conclusion

The National Academy of Sciences (NAS) Committee on Lessons Learned from the Fukushima Accident has a task to examine the risks associated with drained spent fuel pools. The NAS examined this subject about ten years ago, prior to the accident at Fukushima. The earlier NAS committee examined a concept where about 80% of the spent fuel would be removed from the spent fuel pools and placed into dry casks on an accelerated basis. The remaining 20 % of the spent fuel, the hottest spent fuel, would be kept in the pool, but in a more open array. The safety of the 80 % of the spent fuel that would end up in dry casks is not in question here, but the safety of the other hottest 20% of the spent fuel is. Twenty percent of a spent fuel pool could mean as much as 7 megacuries of cesium 137. By comparison, large areas of land were contaminated when the Chernobyl accident released about 2 megacuries of cesium 137. It was claimed that this remaining 20% of the spent fuel might be safe because the fuel assemblies would be arranged in a more open array which could be air cooled if the pool water were drained.

The author of this report participated in the deliberations of this earlier NAS spent fuel pool effort and provided written and oral testimony. This report provides personal recollections of some of the unclassified portions of this earlier NAS effort. In some instances these recollections are supplemented by further insights gained after the earlier NAS effort was concluded.

A major portion of the previous NAS committee deliberations was devoted to reviewing the adequacy of dry casks. This subject is not covered in this submittal. Where events during the Fukushima accident are related to a better understanding of spent fuel pool risks, the text is printed in red.

The earlier NAS spent fuel committee did not support the concept of transferring about 80% of the spent fuel into dry casks on an accelerated basis. It is the author's view that the events at Fukushima reinforce this earlier NAS conclusion. Further, lessons learned from the Fukushima accident and further safety improvements implemented since the Fukushima accident indicate that terrorist acts are even less likely to be successful than thought before.

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2.0 OTHER MAJOR CONCLUSIONS

2.1 SECTION ONE – The previous NAS review

1. The use of air cooling to protect spent fuel in a drained spent fuel pool was not shown to be safe under a number of conditions, including blocked air flow due to debris in the spent fuel pool. Debris scattered by the explosions at Fukushima, some of which entered the spent fuel pools, demonstrated that air cooling can be unsafe. Several other potential air cooling failure modes for have been identified.
2. The original reported calculated health and economic consequences from a drained spent fuel pool were sensational, but significantly overstated. Important improvements in consequence analyses were implemented in a much less publicized addendum to the original report, written by three of the original co-authors of the report that the earlier NAS committee reviewed. Although this addendum showed major decreases in the calculated health and economic consequences, further reductions appear to be justified.
3. Should there be further NAS discussion of spent fuel pool (SFP) accidents, it is recommended that the point of reference should be the above addendum, not the original faulty report reviewed by the earlier NAS committee.
4. There are superior alternatives to relying on air cooling of spent fuel in a drained pool. First, rather than removing 80% of the spent fuel from a pool, the older and cooler spent fuel assemblies produce a safer configuration if left in the pool to act as heat sinks for the hotter spent fuel assemblies should the pool be drained. Second, even with this superior use of the older spent fuel, very small amounts of water would still need to be sprayed into a spent fuel pool to deal with issues like air flow blockage and the cooling of crushed spent fuel.
5. Once it is concluded that a small SFP water spray capability is essential to protect all the pool's spent fuel, then any remaining justification for accelerating the removal of the cooler spent fuel is eliminated.

SUMMARY: Nothing has arisen out of the Fukushima accident that contradicts the decisions made by the earlier NAS committee or indicates a greater vulnerability to natural events or terrorist acts than thought before. To the contrary, the Fukushima accident demonstrated that spent fuel pools have great structural strength and that water delivery systems, such as the fire protection system which also withstood this extreme natural event, might be used to supply make-up water to SFPs if not needed elsewhere.

2.2 SECTION TWO – Severe accident capabilities

1. In general, nuclear power plants have exhibited significant capability to withstand very large earthquakes and other large natural phenomena, such as tornadoes and hurricanes, and still achieve a safe shutdown condition. At Fukushima virtually all of the passive structures survived the largest earthquake and tsunami to ever hit Japan. This was the world's fourth largest known earthquake. The phenomenon that led to reactor core damage at Fukushima was not the direct effects of this historic earthquake but, rather, the massive and unprecedented tsunamis that caused the loss of the emergency diesel generators (EDGs).
2. All the spent fuel pools (SFPs) at Fukushima and elsewhere in Japan survived this earthquake and its tsunamis without leakage. No spent fuel became uncovered even though, in some cases, pool cooling was interrupted for many days during which some of the pool water evaporated.
3. Opening the wetwell hardened vent isolation valves in a <u>timely</u> manner would have accomplished several essential safety functions:

   First, it would have harmlessly vented the hydrogen from an elevated point outside of the reactor building.

   Second, this venting of hydrogen, and some nitrogen and steam, from the drywell would have keep the drywell leak tight, thereby preventing the flow of hydrogen into the reactor (secondary) building where it subsequently exploded.

   Third, venting the containment prevents failures of certain emergency core cooling systems [the RCIC and HPIC systems] that rely on steam driven turbines to inject water into the reactor core. Too high a containment pressure can make these steam turbines inoperable.

   Fourth, an open hardened vent would create a path to a new ultimate heat sink, the atmosphere. The normal ultimate heat sink at Fukushima is the Pacific ocean and the station blackout (SBO) ended the use of this heat sink. Without an ultimate heat sink reactors will eventually experience meltdowns.

Fifth, venting the containment in Mark I BWRs is not essential to limit radioactive releases to the environment to a small fraction of the reactor core's inventory during a core melt accident. As shown analytically, and also by the Fukushima accident, source terms were small even though the wetwell hardened vents were not opened until well after the onsite emergency power was lost. Most of the iodine and cesium ended up in the suppression pool because radioactive steam flowed from the reactor pressure vessel to the suppression pool via the safety relief line which, itself, does not rely on venting the containment. Some of the volatile radioactive material remained in the reactor vessel and some remained in the drywell, based on Sandia Laboratory analyses, with the bulk of these radioactive substances ending up in the suppression pool. Venting the containment would have reduced the small source term that did enter the environment by eliminating the leakage flow path between the drywell and the reactor building.

SUMMARY: In spite of all the complexity and confusion about the accident at Fukushima, this event can be reduced to a few simple observations:

A. Those power plants that did not lose their onsite emergency power because of the effects of tsunamis, safely shut down.

B. Those power plants that did lose all electric power and went into a long term station blackout condition might still have avoided having core melt downs if the isolation valves in the wetwell hardened vent systems could have been opened in a <u>timely</u> manner. With venting and a subsequent depressurized primary containment system, it might have been possible to supply emergency water to the reactor cores. The fire protection system survived the effects of the earthquake and the tsunamis and might have been a the source of reactor emergency cooling water if the reactor pressure vessel pressure was not too high. Other plant equipment might have been operable, such as the RCIC system, if containment pressure were not too high.

C. Steps taken since the Fukushima accident, like the addition of another layer of safety equipment through the FLEX program and through additional requirements for wetwell hardened vents to enable them to operate in a timely manner under severe accident conditions, would make a repeat of a Fukushima type of severe accident extremely unlikely. Other potential events, like severe floods, are less likely to lead to a core melt situation because of the safety improvements made in response to the Fukushima accident.

2.3 SECTION THREE - Issues not examined by the previous NAS review

1. There were two important previously unreviewed connections between BWR reactor cores and their SFPs:(1) the transport of hydrogen from the primary containment to the reactor building where subsequent explosions resulted in significant debris scattered into the SFPs and (2) significant miscalculations about the effects of pool drainage events and the need for much larger offsite emergency responses.
2. The transport of hydrogen from the primary containment to the reactor building could have been prevented at Fukushima by the timely opening of the isolation valves in the wetwell hardened vent system.
3. Over-evacuation at Fukushima has been reported[1] to have led to over 1100 excess deaths. A contributing factor may have been the call by the former head of the NRC for Americans to evacuate 50 miles from Fukushima. There is never any justification for such a large evacuation. <u>Further, even if the spent fuel pools had failed, there is no technical reason for offsite emergency responses to a spent fuel pool incident to differ from responding to a reactor core accident.</u> This indicates a basic lack of understanding on the part of those that urged such a massive and harmful offsite emergency response.

SUMMARY: It appears that the over-evacuation lesson has not yet been learned in the United States. Offsite emergency planning at US nuclear power plant sites needs to be overhauled.

2.4 SECTION FOUR – An overlooked lesson from Fukushima?

The amount of radioactive material released to the environment was a small fraction of the total radioactive inventory on site. Why weren't these releases far larger? Understanding why these releases were so limited must be a fundamental lesson to come out of the Fukushima experience.

1. "Commentary on Fukushima and beneficial effects of low radiation", Dr.Jerry M. Cuttler, Canadian Nuclear Society Bulletin 34(1): 27-32, (2013).

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MAIN REPORT

Background

About ten years ago a committee of the National Academy of Sciences reviewed the safety of spent fuel pools at US nuclear power plants. Concerns had been raised that fires in drained spent fuel pools could lead to very large releases of Cesium-137 with a subsequent large number of latent fatalities and a very large contaminated area. An analysis [1] by R. Alvarez, et al, estimated that some 50,000 to 250,000 cancer fatalities might occur with $250 to $1,700 billion dollars in economic losses, if 10% or 100% of the radioactive cesium in a spent fuel pool was released to the environment, respectively. These 10% and 100% release figures are sort of a sensitivity analysis; a specific analysis of the amount of cesium that might be released was not performed.

The Alvarez report recommended that the coolest 80% of the spent fuel at nuclear power plants be relocated out of these pools and placed into dry casks. The remaining 20% of the spent fuel, the hottest spent fuel, would remain in the pool in a more open array where, it was claimed, this spent fuel could be passively air cooled if some event caused the pool to be drained.

1.0 SECTION ONE - The previous NAS review

1.1 SAFETY CONCERNS ABOUT AIR COOLING OF SPENT FUEL

Forced convection of air to cool spent fuel in a drained spent fuel pool was not considered in the Alvarez report because it would not work if there were a station blackout condition, such as occurred at Fukushima. However, using natural convection of air to cool spent fuel in a drained spent fuel pool presents several safety issues:

1.1.1 NEED FOR A LONG TERM SOLUTION

Air cooling of spent fuel does not provide a long term solution to a drained pool. The significant amount of water that normally covers spent fuel when submerged in a spent fuel pool leads to a very low level of radiation above the pool. This low level of radiation permits plant personnel to move about safely in the vicinity of the

1. “Reducing the hazards from stored spent power-reactor fuel in the United States”, Robert Alvarez, et al, *Science & Global Security11, 2003.*

top of the spent fuel pool. If this pool water were absent, the spent fuel would be exposed. Radiation levels above the pool would be very high and capable of causing a lethal dose in short period of time. In order to permit safe recovery actions, such as removing the spent fuel, the pool would have to be filled with water. Even if air cooling of spent fuel could work, this would not provide a long term solution because of the need to prevent high doses to plant personnel in the vicinity of the uncovered spent fuel. Further, possible degradation of hot spent fuel in a surrounding air environment, which was not examined in the Alvarez report, may also preclude air cooling as a long term solution to a drained spent fuel pool. There is a need to refill a drained spent fuel pool with water because air cooling does not provide a long term solution to a pool drainage event.

The spent fuel pools at Fukushima did not leak from the magnitude 9 earthquake, aftershocks, huge tsunamis with flooding of some areas within the nuclear plants, and explosions large enough to destroy major structures, such as the reactor building. Water levels in the pools at Fukushima decreased due to evaporation, but the spent fuel was never uncovered. These pools have had these water levels restored to their design depths, permitting recent activities to remove some of the spent fuel assemblies.

1.1.2 Debris problems

The Alvarez report identified a concern that air flow could be obstructed if debris entered the pool. This is a valid concern and was reinforced by presentations Professor von Hippel[2] made to the earlier NAS committee years ago. Hydrogen explosions at Fukushima led to debris in the spent fuel pool (s). Photographs[3] of the Fukushima spent fuel pools clearly show debris lying on top of the spent fuel. Had any of the spent fuel pools at Fukushima actually lost all of its water, this debris from an explosions likely would have prevented adequate air cooling of the spent fuel, even if the majority of the spent fuel had been transferred to dry casks as recommended in the Alvarez report.

2. "Briefing for the Board on Radioactive Waste Management, National Academy of Sciences, Professor Frank von Hippel, Washington, D.C., December 3, 2003, page 25."
3. Attachment to TEPCO report on the Fukushima accident, Figure 3, attachment section 9-4 and Figure 6, attachment section 9-5 See: http://www.tepco.co.jp/en/press/corp-com/release/betu12_e/images/120620e0106.pdf

In some cases the ceiling of the reactor building fell down from the hydrogen explosions, making it more difficult to observe the status of the spent fuel pools. Scattered debris also can make access to important plant areas more difficult.

1.1.3 Incomplete modeling

The air flow analysis presented in the Alvarez report modeled the inflow of cooler air through an opening in the side of the reactor building and the exiting of warmer air through an opening in the ceiling. However, there are an unknown number of other possible locations in the reactor building where openings might occur. Further, the sizes of such openings are unknown. There is concern that in some scenarios the hot air exiting the spent fuel might stagnate inside the reactor building, thereby blocking adequate air flow through the spent fuel. The heat production in different fuel assemblies varies depending upon its burnup history in the reactor core and how long it has been in the spent fuel pool. To provide adequate cooling the air flow through each assembly must be sufficient for that particular assembly. An assembly-by-assembly analysis of the adequacy of the air flow was not presented in the Alvarez report. It is unknown if the warm air exiting from one fuel assembly would somehow interfere with the air exiting from a nearby fuel assembly.

The possibility of a drained spent fuel pool with no openings in the reactor building was not considered in the Alvarez report. Critics of the present spent fuel pool arrangement have warned against possible terrorist attacks. Yet if there were a terrorist attack that caused pool drainage without creating holes in the reactor building, the whole Alvarez air cooling approach would fail.

At Fukushima there were collapses of reactor building ceilings at the units that experienced explosions. This geometry is completely different from the air flow geometry assumed in the Alvarez report.

The highly selective geometry of the air cooling arrangement presented in the Alvarez report is optimistic and does not cover the full range of possible air flow configurations, some of which would be inadequate to cool the spent fuel.

1.1.4 Crushed spent fuel

The spent fuel in the Alvarez analysis is assumed to be intact and in its original design configuration. However, any force large enough to cause drainage of a massive spent fuel pool structure might also crush part of the spent fuel. For example, some kind of a missile that pierced the spent fuel pool structure would likely crush some of the spent fuel. The possibility of crushed fuel assemblies was also recognized by Professor von Hippel in his presentation to the earlier NAS committee. However, the Alvarez report did not analyze the ability to adequately cool a crushed spent fuel debris bed by natural convection of air. It is unknown if crushed debris beds would be the source of fires in a drained spent fuel pool which relied on air cooling.

1.1.5 Blocked air flow

Air flow through the spent fuel by natural convection can not commence until there is a complete unblocked pathway. Assuming no water makeup and a hole in the spent fuel pool structure, the pool water level would first decrease down to the height of the hole in the pool structure. Further decreases in the pool water level would occur as decay heat from the spent fuel boiled off the remaining pool water. The steam generated by boiling the pool water would be sufficient to cool the spent fuel (steam cooling) until such time as the pool water level dropped to about the bottom quarter of the spent fuel bundle, about the bottom 3 feet of the spent fuel. Once this low pool water level is reached, not enough steam might be generated to adequately cool the top of the spent fuel. Until such time as when the remaining bottom three feet of pool water is boiled off, plus additional water in the very bottom of the pool where spent fuel bundles rest upon support structures, air flow would be blocked. The top of the spent fuel could become overheated and perhaps cause a zirconium cladding fire. It has been estimated that it would take several hours before such a zirconium fire might start under these conditions. No analysis was provided in the Alvarez paper to indicate that zirconium fires would not start at the top of the spent fuel before the air flow blockage was cleared by the boil off of the remaining water. It appears that unless all openings in the spent fuel pool structure are directly in the bottom of the pool, all other pool drainage accidents would occur through the pool's vertical surfaces. Accidents that cause leakage through vertical pool surfaces will experience air flow blockage for a period of time during which the top of the spent fuel might overheat and cause a fire. Professor von Hippel recognized[4] that partial drainage could block the natural convection of air.

1.1.6 CONCLUSION

Based on the above unresolved safety concerns, the acceptability of natural convection air cooling of spent fuel in a drained spent fuel pool was not demonstrated in the Alvarez report.

1.2 CONSEQUENCE ANALYSIS DEFECTS

1.2.1 INCORRECT POPULATION SIZE

A review of the Alvarez report published in Science and Global Security (S&GS) in 2003 revealed that the assumed population that might be at risk was far too high. This error was corrected in an additional analysis and published as an addendum[5] to the original Alvarez report. The Alvarez report utilized an average population of 250 people per square kilometer. The corrected average population density in the addendum is 80 people per square kilometer for the first 400 kilometers, dropping to 20 persons/ square kilometer after 400 kilometers out to 625 kilometers, for the 100% of the pool's cesium release case. This corrected population analysis in the addendum showed very large decreases in the calculated number of latent fatalities and economic damages, as shown in Table 1, below. The addendum numbers are the average of five different nuclear sites in the US. This addendum is part of the record of the earlier NAS effort.

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4. "Briefing for the Board on Radioactive Waste Management, National Academy of Sciences, Professor Frank von Hippel, Washington, D.C., December 3, 2003, page 12
5. "Damages from a Major Release of ^{137}Cs into the Atmosphere of the United States", Dr. Jan Beyea, Dr. Ed Lyman, and Professor Frank von Hippel, Science and Global Security, 12:125-136, 2004.

Table 1: Number of Latent Fatalities, Economic Damages

	10% Release Number of Latent Fatalities	100% Release Number of Latent Fatalities	10% Release Billions of Dollars in Economic Damages	100% Release Billions of Dollars in Economic Damages
S&GS 1/13/2003 Alvarez Report, end-notes 29 and 70	50,000	250,000	250	1700
S&GS Addendum, 2004, page 132	2,000	5,700	100	370
Reduction Factor	25	44	2.5	4.6

1.2.2 Problems with collective doses and the LNT assumption

Although the addendum corrected one major defect in the original Alvarez report, other issues remain. Even these corrected numbers of latent fatalities may still be too high. As the authors of the addendum pointed out "... most of the population radiation dose occurs at large distances (small doses to large numbers of people)…". However many health physics professionals[6] do not subscribe to converting collective societal exposures of low levels of radiation to a specific number of latent fatalities.

Alvarez's use of a conversion factor[7] of one latent fatality per 1700 person-rems is completely at odds with the warnings[8] of the International Commission on Radiological Protection to avoid such an inappropriate calculation.

6. The Health Physics Society and the French Academy of Sciences reject the linear non-threshold model to quantitatively predict the health effects of low level radiation exposure.
7. End note # 28 in "Reducing the hazards from stored spent power-reactor fuel in the United States", Robert Alvarez, et al, *Science & Global Security11, 2003*.

Others[9] have argued that there may not be adverse health effects for radiation exposures below 0.2 r/day. It may be valuable for the present NAS Committee to know how many of the addendum's projected latent fatalities are calculated to occur at exposures less than 0.2 r/day. If an exposure of 0.2 r/day did not lead to adverse health effects, there would be considerably smaller calculated latent fatalities and calculated offsite economic damage.

Also missing from the addendum is any comparison of the projected number of latent fatalities to the number of non-radiological cancer fatalities in the vast area calculated to be at risk. The addendum analysis does not provide the mean areas associated with its MACCS2 analysis, so the 100% and 10% release areas from the Alvarez report are used here. In the Alvarez 100% release model, the assumed wedge area extends out to about 625 kilometers and has a width of approximately 80 kilometers, for an approximate area of 50,000 square kilometers. The Alvarez report assumed 250 people per square kilometer for a total population at risk of 12.5 million people for the 100% release case, i.e. 35 megacuries of Cesium-137. When the more realistic population densities of the addendum of 80 persons/square kilometer out to 400 kilometers and 20 persons/square kilometer beyond 400 kilometers is used, the affected population in a wedge analysis comes to about 3.0 million people. If about 20% of this 3 million persons died from cancer from non-spent fuel pool accident causes, i.e., natural causes, this amounts to about 600,000 cancer fatalities. Even if the addendum numbers of 5700 latent fatalities were correct for the 100% release case, this would be about a one percent increase from a <u>hypothetical</u> release of Cesium-137 compared to the <u>actual</u> cancer fatalities from natural causes. The addendum's latent cancer fatalities would be spread out over many years. It is unlikely that such an increase, if it existed, would even be detectable statistically.

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8. The International Commission on Radiological Protection (ICRP) in its Publication 103 (2007): "The collective effective dose quantity is an instrument for comparing radiological technologies and protection procedures, predominantly in the context of occupational exposure. Collective effective dose *is not* intended as a tool for epidemiological risk assessment, and it is *inappropriate* to use it in risk projections. The aggregation of very low individual doses over extended time periods is inappropriate, and *in particular, the calculation of the number of cancer deaths based on collective effective doses from trivial individual doses should be avoided."*
9. "Commentary on Fukushima and beneficial effects of low radiation", Dr.Jerry M. Cuttler, Canadian Nuclear Society Bulletin 34(1): 27-32, (2013).

1.2.3 ADDITIONAL HEALTH CONSEQUENCE MODELING ISSUES

Unanalyzed in the Alvarez report is the impact of changing wind direction during the time of the postulated release of Cesium-137. The Alvarez report modeled the plume from the spent fuel fire as a very long unidirectional wedge. However, wind directions change fairly often. For example, at the Indian Point site wind directions change, on average, about once an hour. The calculated affected areas in the Alvarez report would be different if changing wind directions were accounted for. It is possible that a larger area might come under the plume when changing wind directions are accounted for, but at a lower cesium concentration. Different areas with different cesium concentration levels would affect the calculated economic damages.

During the Fukushima accident a considerable fraction of the release that occurred was carried out over the Pacific ocean. If there had been a spent fuel fire at Fukushima like that postulated by Alvarez, some fraction of the released cesium would likely be carried out to sea and therefore would not cause land contamination. Wind directions changed during the Fukushima accident, they changed during the Chernobyl accident, and they change frequently as recorded by meteorological measurements taken at many nuclear plant locations. The economic losses claimed in the Alvarez report are overstated to the extent that some of the released Cesium-137 would end up in oceans or other large bodies of water located near many nuclear sites. In the Fukushima case about a quarter of the cesium released during the accident ended up in the Pacific Ocean.

It is common practice in radiation dose consequence analyses, such as those performed by the MACCS2 computer code, to utilize large numbers of weather scenarios. Among these scenarios are rain scenarios. If the time of release of any cesium from a drained spent fuel pool coincided with a rainstorm, the area affected by the release could be far smaller. The addendum to the Alvarez report used a MACCS2 atmospheric model with median dispersion and azimuthally-averaged radial population densities. This is an improvement over the Alvarez wedge model, however, the addendum does not clarify if multiple weather scenarios, including precipitation scenarios, were used for the five sites it examined.

The Alvarez wedge model assumes that individuals are exposed to radiation for a period of ten years. There does not seem to be any accounting for dose reductions when people are indoors or spend portions of these ten years outside of the assumed wedge area. These omissions result in significantly overstating exposure levels and therefore calculated latent fatalities. There does not seem to be any adjustment for the person-rems accumulated by people who subsequently die from non-spent fuel pool cesium releases. When calculated latent fatalities are overstated, so are the postulated economic consequences. This is because cancer deaths are valued at $4 million dollars each in the Alvarez and addendum analyses.

There is no technical basis to assume single wind speed, single direction, non-rain scenario wedge shaped release as was done in the Alvarez report. This is particularly true since superior consequence models, like the MACCS2 code, are in general practice and was used in the addendum which was written by three of the same authors that wrote the Alvarez report. It is not clear why the wedge model was used in the Alvarez report since using the MACCS2 computer code was within the capabilities of the authors.

In addition to inadequate consequence modeling with a wedge shaped release, the likelihood of a 100% release of cesium assumption should have been examined more closely. Some insights might be gained by examining the Chernobyl accident. It has been reported[10] that the power level in this accident increased by a factor of 100 in just four seconds. This power excursion energy was further supplemented by the energy from burning graphite in the Chernobyl reactor core. The Chernobyl design did not have a containment building, just a very low pressure confinement building. In that sense it resembles the reactor buildings at Mark I BWRs which also have very limited pressure retaining capabilities. Yet, in Chernobyl, only about 40% of the Cesium-137 was released into the environment (2 megacuries of Cesium-137) and the other 60% of the cesium remained on site.

It could be useful to compare the number of megawatt-seconds produced by the Chernobyl power excursion and the graphite fire to create the ratio of curies of Cesium-137 released per megawatt-second. One could then determine how many megawatt-seconds might be generated by zirconium-steam reactions in a spent fuel pool, if 100% of the spent fuel caught fire. The number of megacuries of Cesium-137 that might be released to the environment could be estimated by calculating 2R,

10. “Exposures from the Chernobyl accident”, UNSCLEAR 1988 Report, Appendix D, page 3.

where R is the ratio of the 100% of the pool's zirconium-steam released energy, in megawatt-seconds, to the number of megawatt-seconds generated during the Chernobyl accident.

1.2.4 CONCLUSION

The analytical basis for calculating consequences as presented in the Alvarez report is technically unsupportable and greatly overstates consequences. Important improvements in consequence analyses were implemented in the addendum, yet consequences still appear to be overstated. Therefore, if there are still concerns about fires in spent fuel pools, the point of reference should be the addendum, not the original faulty Alvarez report.

1.3 ALTERNATIVES TO AIR COOLING OF SPENT FUEL

Because there are many safety questions about the Alvarez air cooling approach to reducing risks in spent fuel pools, attention turns to two other alternatives. Even if there were zero projected latent fatalities, significant land areas might become contaminated by accidents in a spent fuel pool. The accident at Chernobyl underscores this. As stated before, even though only about 2 megacuries of Cesium-137 were released, the resultant contaminated land area is extensive. Thus, more must be done rather than relying on a concept like the one proposed in the Alvarez report.

1.3.1 BETTER USE OF THE COOLEST SPENT FUEL

Instead of removing up to 80% of the spent fuel and placing these coolest fuel assemblies in dry casks, analyses showed that there were benefits to using these assemblies as heat sinks for the hottest fuel assemblies. Detailed analyses were made, which probably appear in the classified material in the earlier NAS spent fuel committee. It appears that surrounding the hotter spent fuel assemblies with cooler spent fuel assemblies is superior to placing these same cooler fuel assemblies in dry casks. It is assumed that these classified analyses show that no offloading of spent fuel is needed to adequately air cool spent fuel in a drained spent fuel pool, provided that the cooler fuel assemblies act as heat sinks for the hotter assemblies and that the issues of crushed fuel, debris in the pool, and water blockage at the bottom of the spent fuel were overcome. Even under unfavorable conditions, like a period of air flow blockage, surrounding hotter spent fuel assemblies with cooler ones has the benefit of a slower heat up rate for the spent fuel. This slower heat up rate provides additional time during which other SFP protective actions might be attempted.

1.3.2 ADVANTAGES OF WATER SPRAYS

Although there are safety benefits to surrounding the hotter spent fuel with the cooler spent fuel, more has to be done. The fuel rods in the spent fuel assemblies were designed to be cooled by water, not air. Water has many advantages over air as a heat transfer medium. A cubic foot of water can absorb about 3500 times more energy per degree rise than a cubic foot of air. This means that water spray systems are far more compact than air-cooled systems; modest pipe sizes[11] would do according to the Alvarez report. A pipe size with a one inch diameter should be able to deliver one liter of water per second with a small pressure difference driving force. Such small water spray systems are far less likely to be impacted by the initiating event that caused pool drainage than the much larger air cooling system. This small water system size is an important consideration in minimizing hypothetical threats from terrorist attacks originating outside of the reactor building.

The importance of debris in the pool in a water spray system is greatly reduced compared to an air cooling system. Water will "seek its own level" which means that water will flow around objects that might deter air flow. Water could come in contact with the spent fuel from below the debris blockage to provide adequate cooling. Air can not readily do this.

Water, in addition to providing excellent heat transfer capabilities and also shielding plant personnel working near the spent fuel pool, has other advantages over air. Escaping cesium might combine with water to form cesium hydroxide which is very soluble. This means that the cesium hydroxide might remain close to the spent fuel pool if it were absorbed in some wet surface or "puddle of water". Thus water can serve as a source term reduction medium.

Finally, water can be sprayed into the pool in a variety of ways that would not be applicable to air cooling. For example, at Fukushima, water was sprayed into different spent fuel pools by a truck normally used to deliver cement. Water was also sprayed into the spent fuel pools from a water cannon truck. This delivery flexibility is another benefit of water spray systems in minimizing the risks from hypothetical terrorist attacks.

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11. "Reducing the hazards from stored spent power-reactor fuel in the United States", Robert Alvarez, et al, *Science & Global Security11, 2003,* page 26.

The recovery actions taken at Fukushima to protect the spent fuel pool are consistent with earlier recommendations[12] made in 2002 by the National Research Council which stated "…emergency cooling of the (spent fuel) in the case of an attack could probably be accomplished using "low tech" measures that could be implemented without significant exposure of workers to radiation".

Analyses have shown that the amount of water needed to cool a spent fuel pool by evaporation is very small. This is because the decay heat generation is only a small fraction of the full power energy production. After just one week decay heat production is 0.2% [0.002] of full power heat production. The amount of water needed for evaporative cooling has been likened to a mist, if this cooling water were distributed evenly throughout an empty spent fuel pool. The amount of water that is needed to cool the spent fuel is covered by the Panlyon presentation, assumed to be in the classified report of the earlier NAS spent fuel committee.

The spent fuel at Fukushima from all the power plants was in their respective spent fuel pools for 100 days or more. The most recent spent fuel loading occurred at Unit 4 which shut down on November 30, 2010, some 100 days before the earthquake and tsunami struck on March 11, 2011. Tokyo Electric Power Company (TEPCO) has made a detailed calculation[13], fuel assembly by fuel assembly, of the decay heat generated by Fukushima plants 1 through 4, as reproduced in Table 2, below.

Table 2: Spent Fuel Pool Decay Heat in Megawatts

	When the accident occurred (3/11)	Three months after the accident (6/11)
Unit 1	0.18	0.16
Unit 2	0.62	0.52
Unit 3	0.54	0.46
Unit 4	2.26	1.58

12. "Making the Nation Safer: The Role of Science and Technology in Countering Terrorism", National Research Council, 2002.

13. Attachment to TEPCO report on the Fukushima accident, Table 2, attachment 9-1 See: http://www.tepco.co.jp/en/press/corp-com/release/betu12_e/images/120620e0106.pdf

In order to remove 2.26 megawatts only about one liter of water needs to be evaporated/per second. Three months after the accident the Unit 4 spent fuel pool heat production decreased to 1.58 megawatts. In order to remove 1.58 megawatts only about 0.7 liters of water need to be evaporated/per second. The Alvarez report[14] provides a number of 3 liters/ second based on an earlier analysis done by Sandia labs. The smaller Fukushima number is likely the result of a more detailed analysis done by TEPCO using the actual fuel assembly-by-fuel assembly heat generation rates. The overall conclusion here is that very small quantities of water need be sprayed into a drained spent fuel pool per second to prevent the fuel from overheating.

Because the necessary water spray rate is so small, the main safety concerns for water spray systems are timing and reliability. If the pool is not leaking and pool water is just being lost through evaporation, then between one to ten days or more are available to start the water spray process, where the one day figure represents a case where the pool had just had spent fuel added to it.

Once pool water levels have dropped to the bottom quarter of the spent fuel assemblies steam cooling might be insufficient to prevent overheating. So the minimum time before there might be overheating of the tops of the spent fuel assemblies is the sum of the time needed to get to the bottom three foot mark, plus a few hours if the pool is leaking at a point above the bottom three foot mark. Less time might be available to initiate water sprays into the pool if the leakage point was below the bottom three foot mark. However this lower leakage point also means that it would take less time to clear the water that would be causing an air flow blockage. Finding the minimum time to initiate SFP water sprays may have been part of the Panlyon analyses, identified before.

The reliability concern is centered around assuring that whatever event caused pool drainage did not also impair the water spray capability. However, the small size of these water spray systems and the multiple ways to introduce water into a spent fuel pool should produce a very reliable mitigation system.

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14. "Reducing the hazards from stored spent power-reactor fuel in the United States", Robert Alvarez, et al, *Science & Global Security11, 2003,* page 25.

1.3.3 Conclusions

1. Even if 80% of the spent fuel was removed from the spent fuel pool, water cooling would still be necessary. Once it is concluded that safety concerns require some means of cooling the hottest spent fuel with water, then cooling the remaining cooler fuel assemblies is simple. Since these cooler fuel assemblies are also valuable as heat sinks if left in the pool, there is very little to be gained by implementing the Alvarez concept.

2. The much smaller size of water spray systems and the much greater flexibility in delivering water to a spent fuel pool compared to natural air convection systems are important considerations when dealing with terrorist concerns. On the subject of postulated terrorist events, the Fukushima accident provides further insights. It has been postulated that an attack on a spent fuel pool by a light aircraft loaded with explosives might cause a spent fuel pool to fail if these explosives were ignited above the pool. However, the huge hydrogen explosions that destroyed the reactor buildings at Fukushima were not sufficient to cause pool leakage or failure. It appears that the small plane explosion terrorist scenario is unlikely to cause pool leakage.

2.0 SECTION TWO - Severe accident capabilities

Even in station blackout conditions where all EDG electrically driven safety equipment would be inoperable, there is still a great deal of capability to cope with severe accidents at nuclear power plants.

2.1 Large safety margins

Nuclear power plants were designed to ensure that a power plant would be put into a safe shutdown condition if a design basis accident occurred. Like bridges, buildings, and other major structures there is a large margin built into nuclear power plants. This margin enables nuclear power plants to withstand many severe accident challenges that are more challenging than the original design basis accidents. For example, the containment failure pressure[15] for the nuclear power plants at the Indian Point, New York were calculated to be 250% greater than the nominal design pressure. The primary containments at Fukushima IF2 plant also exhibited a pres-

15. "Lessons from the Indian Point Hearing", H. Specter, Nuclear Safety, Volume 27, No.3, July-September 1986.

sure capability well in excess of its nominal design pressure. Pressure measurements reproduced in a paper by Sandia National Laboratory[16] showed that the primary containment of the IF2 remained leak tight up a pressure of around 110 psi, well above the design pressure. Even at this elevated pressure the IF2 containment did not fail catastrophically, but leaked instead. Further, none of the Fukushima primary containments that were exposed to explosive forces collapsed or failed in some other manner.

2.2 History of withstanding large natural events

Nuclear power plants have demonstrated significant capability to withstand major natural events such as hurricanes, tornadoes, flooding, and earthquakes. Category 3 hurricanes Irene and Sandy struck the east coast of the United States without causing failures among the large number of nuclear power plants in the areas they affected. In 1992 a category 5 hurricane, Hurricane Andrew, struck the Turkey Point nuclear plants in southern Florida. There was a loss of offsite power causing the emergency diesel generators to start and place the plant in a safe shutdown condition. There was no damage to the containment buildings. The Turkey point power plants are built to withstand winds up to 235 miles per hour, far in excess of the maximum winds recorded for category 5 hurricanes.

Other large natural forces have struck nuclear power plants in the United States. The Browns Ferry plants in Alabama were struck by tornadoes which severed seven transmission lines that provided offsite power to this site. All three plants automatically shut down safely. The Fort Calhoun plant in Nebraska has survived a flood where all offsite power was lost, but all emergency safety systems operated normally. In 2011 the North Anna plant in Virginia withstood a beyond design basis 5.8 magnitude earthquake.

2.3 Fukushima specifics

The body of knowledge about the ability of nuclear power plants to withstand large natural forces was significantly expanded by the accident at Fukushima. The earthquake was a magnitude 9, the largest ever to strike Japan, and the associated tsunami was the largest ever to strike Japan[17]. Not only did the structures survive the

16. “MELCOR Simulation of the Severe Accident at the Fukushima IF2 Reactor”, Figure 10, Jesse Phillips, et al, 2012 ANS Winter Meeting and Nuclear Technology Expo. San Diego, California, November 11-15, 2012.

earthquake and large aftershocks, so did many active components and systems in those plants that did not experience a station blackout.

A report[18] by seismic expert John Richards stated “The plant’s operator, TEPCO, asked EPRI to coordinate a team to inspect Fukushima Daini for earthquake and tsunami damage and to discuss with them their plans for improving the plant in the future. Our team inspected several buildings and evaluated a broad range of mechanical and electrical equipment, including pumps, motors, valves, tanks, batteries, transformers, switchgear, heat exchangers, fans, and electrical distribution panels. Following this comprehensive review, we concluded the earthquake didn’t damage any safety-related structures, systems or components.”

The important lesson here is that not only did the passive structures at these power plants survive this enormous earthquake, so did many of the active components. Even those power plants that had reactor core damage showed many of their active components functioned as designed until onsite electric power was lost. For example, even the emergency diesel generators (EDGs) at the plants that did suffer core damage operated for about a half an hour after the earthquake struck the area. These EDGs operated until the tsunami ended this capability.

Because of the accident at Fukushima we have had an extreme test of the capability of these nuclear power plants to survive the direct effects of enormous earthquakes. The plants that did experience core damage did so as a result of the tsunami, an secondary effect of this enormous earthquake, but not the direct effects of the earthquake itself. This experience, plus that at the North Anna plant, indicates that sites that are not susceptible to tsunamis or other secondary effects that would lead to a long term station blackout are likely to survive major earthquakes without significant damage to safety related structures or active components.

Based on the above, it is important to focus on the effects of tsunamis and the effects of tsunamis on spent fuel pools, in particular. The tsunamis did flood a number of areas within these plants[19].The overall conclusion about Fukushima is that

17. Attachment to TEPCO report on the Fukushima accident, Sections 3-17 and 3-10, See: http://www.tepco.co.jp/en/press/corp-com/release/betu12_e/images/120620e0106.pdf
18. “Seismic Expert Explains Work in U.S. Nuclear Industry, Lessons From Japan”, Nuclear Energy Institute Post, January 6, 2012.

the tsunamis did not cause the spent fuel pools to leak or fail in some other manner. It can be argued that the elevated location of the Mark-I spent fuel pools make them less vulnerable to flooding from any cause. This extra height reduces the chance of a direct impact on the sides of the pool by the force of a flooding event. Other plant designs have their spent fuel pools at or below grade. Even if there were an layer of water on a spent fuel pool from a flooding incident, this additional layer of water itself should not be a safety concern.

Very large external events will likely cause a loss of offsite power which may not be recovered for an extended period of time. The major concern from the tsunamis, or from very large external events in general, is the possible additional loss of sources of emergency onsite electric power, e.g., the EDGs and the DC power from batteries which could then lead to an extended blackout condition. During this extended blackout condition there can be a loss of the normal ultimate heat sink. Unless there is recovery of this ultimate heat sink or a alternative ultimate heat sink is established, core damage is expected to occur. Loss of offsite power for an extended period of time is also an issue for coping with terrorist events.

However, it is possible to prevent core damage even for extended blackout conditions. In order to accomplish this a pathway to some ultimate heat sink must be established and some means to supply water to the reactor core to remove decay heat must also be established. The safety improvements described below may be capable of accomplishing both of these tasks.

Even though a large number of active components/ systems remained functional during the accident at Fukushima, not all did. Although TEPCO was eventually able to open the wetwell vent for Unit 3, it could not avoid a core melt due to an inability to depressurize the reactor pressure vessel in time to enable water injection by fire trucks. The author does not know if this inability to depressurize the reactor pressure vessel was because RCIC had already become inoperable because of high containment pressure.

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19. Attachment to TEPCO report on the Fukushima accident, Sections 3-9,3-10, 3-11, 3-12, and 4-4. See: http://www.tepco.co.jp/en/press/corp-com/release/betu12_e/images/120620e0106.pdf

2.4 Safety improvements

A number of actions have been taken to reduce the likelihood that there could be an extended period of no offsite or onsite electrical power. Following the 9/11 terrorist attack on the United States additional capability was put into nuclear power plants to deal with extreme events. Following the accident at Fukushima even more capability was introduced through the FLEX program. The FLEX program was an extension of the earlier response to potential terrorist attacks and other extreme events. Dispersing additional pumps, generators, battery banks, chargers, compressors and hoses among various locations will provide multiple redundancies to obtain power and water for the key safety functions of reactor cooling and spent fuel pool cooling. Additional emergency equipment will be stationed in secure offsite support centers.

Because the FLEX program disperses this additional safety equipment throughout the nuclear power plants, reactor core protection should be improved in spite of difficulties in getting access to locations blocked by debris.

Although BWRs like those at Fukushima have a great deal of capability to cope with severe accidents, one design weakness has been identified. The hardened wetwell vent is normally isolated and its isolation valves can not easily be opened during a total loss of electric power. Opening these valves by hand under accident conditions would be difficult and dangerous, at best. Even though these isolation valves were not opened early in the accident sequences, this did not prevent most of the radioactive material that was released from the reactor cores from entering the suppression pool where they were trapped. However, according to analyses performed by Sandia National Laboratories, these closed isolation valves resulted in the pressure in the primary containment building rising to the point that there was leakage from the primary containment building to the reactor building. This leakage contained nitrogen, steam, some radioactive material, and large amounts of hydrogen gas. Later this hydrogen gas exploded in the reactor building. A more detailed explanation[20] of this accident sequence is available. The unopened hardened vent isolation valves led to large explosions which scattered debris throughout the reactor building, including some debris into the spent fuel pool.

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20. "MELCOR Simulation of the Severe Accident at the Fukushima IF1 Reactor", Randall Gauntt, Donald Kalinich, Jeffrey Cardoni and Jesse Phillips, Sandia National Laboratory.

There are simple, straightforward ways to prevent a repeat of such a scenario. They include an approach where these hardened vent isolation valves are placed in a “normally open” passive configuration, as described[21] in the material already submitted to this NAS Fukushima Lessons Learned committee. This normally open configuration does not need electric power to assure hardened vent operation. Alternatively, these hardened vent isolation valves could be opened with either a dedicated electric power source, as some utilities have done, or may be opened with power generation equipment that is available through the FLEX upgrades. The benefit of having FLEX emergency electric power to open these isolation valves is that it gives the plants operators more venting options. It may be advisable to initially vent the primary containment starting at a low drywell pressure, then close these vents. Additional opening and closing of the vent isolation valves could then take place as accident conditions warrant such actions.

With the ability to open hardened vent isolation valves, either passively or actively, the primary containments at Fukushima would not have reached pressures that caused leakage of radioactive material and hydrogen into the reactor buildings. Explosions would have been avoided, there would not have been debris scattered all about and even less radioactive material would have entered the environment.

The importance of being able to vent the primary containment under station blackout conditions has been recognized as one of the major “Lessons Learned”. An example of this is the response from the Nuclear Regulatory Commission[22] in its “Order Modifying Licenses With Regard To Reliable Hardened Containment Vents”. The nuclear industry has performed specific analyses so that this NRC Order can be properly implemented.

2.5 Conclusion

Nuclear power plants, including those at Fukushima and their spent fuel pools, have exhibited significant capability to withstand very large earthquakes and other large natural phenomena and still be able to maintain a safe condition. The major concern about the effects of severe natural phenomena is the potential for losing both offsite

21. “Fukushima and Nuclear Safety Culture in the United States”, Herschel Specter, RBR Consultants, Inc., February, 2013 (previously submitted to the NAS Lessons Learned From Fukushima Committee).
22. EA-12-050, Issuance of Order to Modify Licenses With Regard to Reliable Hardened Containment Vents”, USNRC, March 12, 2012.

and onsite EDG electric power, such as through a tsunami situation like that at Fukushima. Safety upgrades, like those made after 9/11 and through the FLEX system, and enabling BWRs to open the isolation valves in their hardened vent lines, means that the risks from large natural phenomena are much smaller today.

3.0 SECTION THREE - Issues not examined in the previous NAS review

Two issues related to spent fuel pools that were not reviewed in the earlier NAS committee: Interactions between core damage events and SFPs, and offsite emergency responses to SFP damage events.

3.1 Unreviewed reactor and SFP interactions

Previous NAS studies about spent fuel pool accidents (or terrorist acts) did not review interactions between core damage events and challenges to the SFP, but the accident at Fukushima demonstrated two such interactions. One of these interactions is the priority use of the fire protection system to inject water into a troubled reactor core rather than using the fire protection system to supply water to the spent fuel pool through the spent fuel pool cooling system. The other interaction is the creation of debris, some of which ended up in SFPs. This debris is the result of explosions in the reactor building from hydrogen generated in damaged reactor cores.

The Fukushima fire protection system survived the earthquake, aftershocks, flooding from the tsunamis, and explosions. The priority use of the fire protection system at Fukushima was to protect the reactor core. If emergency equipment, such as those in the FLEX program, were available at the time of the Fukushima accident and could be used to cool the reactor core, the fire protection system, in addition to FLEX equipment, would then be available to add water to the spent fuel pools via the fuel pool cooling system. Since the spent fuel pools did not leak, one doesn't have to spray the water into the SFP; just keep the spent fuel covered and this could have been accomplished with the fire protection system supplying water to the fuel pool cooling system.

The second interaction between the reactor core and the SFPs was the creation of debris, some of which ended up in the pools. As discussed before, the creation and scattering of this debris because of explosions in the reactor building could have been prevented with a timely opening of the hardened vent isolation valves.

3.2 Offsite emergency responses to SFP damage events

The comparison between radiologically caused early fatalities at Fukushima and those caused by fear, over-evacuation, and long term sheltering has already been made. The World Health Organization places of the number of early fatalities from radiation at the Fukushima accident at zero, while other analyses attribute about 1100 excess deaths to fear, over-evacuation, and long term sheltering.

The announcement by the former head of the US NRC who recommended that Americans evacuate out to 50 miles from Fukushima has been strongly criticized[23]. It was wrong. It is reported that "… top officials of the U.S. Nuclear regulatory Commission concluded that the spent fuel pool in Reactor No. 4 at Fukushima Daiichi must be dry". As it turned out, this was not the case and the spent fuel at Reactor No. 4 was always covered with water.

What is also troublesome about this serious mistake is that, even if the spent fuel pool at Reactor No. 4 had run dry, there was still no technical reason to call for a 50 mile evacuation. Off site emergency responses for events at spent fuel pools are more than adequately covered by the same plans as would be used in a core damage event. The most recent addition of spent fuel to the SFP at Reactor No.4 occurred 100 days before the accident at Fukushima. With an 8 day half life, I-131 from the most recent spent fuel addition to the pool at Reactor No. 4 would have decreased by 12.5 half lives. i.e., by a factor of 5650 leaving essentially zero iodine in the spent fuel pool.

Iodine-131 is the dominant cause of early health effects and is the principle reason to evacuate downwind areas if levels of this isotope in a plume are too high. Cesium-137 is the dominant cause of projected latent fatalities and for land contamination. The former Chairman's announcement indicates that a short term, highly localized, Iodine-131 based, high dose rate issue was confused with its opposite: a long term, spread out, Cesium-137 dominated, low dose rate issue. The Alvarez

23. "Shaken Faith After the Fukushima disaster, a U.S. mistake undermined the Japanese government", Paul Blustein, Slate, 2013.

report does not make this mistake. No early fatalities or early injuries were listed, even for an assumed 35 megacurie release of Cesium-137.

Simultaneously, NRC sponsored research at Sandia National Laboratory, the SOARCA program, has also calculated very small releases of iodine and cesium from station blackout sequences in the Peach Bottom plant, a Mark 1 BWR similar to the plants at Fukushima. The Sandia source term for SBO sequences in Mark I plants is so small, early fatalities would not occur, even if there were no evacuation.

It appears that the over-evacuation lesson has not yet been learned in the United States. The NRC still calls for each nuclear site to conduct periodic Evacuation Time Estimates, assuming that the whole Emergency Planning Zone is to be evacuated. Tests of emergency plans which simulate massive evacuations are wrong. These actions send the wrong message to the public. To best protect the public, evacuations should be far more limited and focused on the innermost one to two miles around a nuclear plant with downwind sheltering and selective relocations where there are hot spots.

Over-evacuation, large numbers of excess deaths, fundamental mistakes made about any connection between drained SFP and the need for greatly over-enlarged offsite emergency responses, confusion between the health effect roles played by iodine and cesium, and the very small and slowly evolving source terms calculated by Sandia analyses that indicate that evacuation may not even be necessary to avoid early health fatalities, and wrong messages from the NRC underscore the need to improve emergency planning in the United States.

Offsite emergency planning at US nuclear power plant sites needs to be overhauled.

4.0 SECTION FOUR - An overlooked lesson from Fukushima?

Following the accident at Three Mile Island questions were raised as to why wasn't the release of radioactive material into the environment more severe. Fukushima experienced the worst earthquake in recorded history of Japan, large aftershocks, enormous tsunamis, explosions, flooding of some rooms at the site, station blackouts, and debris scattered about the reactor buildings. Yet the releases of radioactive material[24] were small, about 5.4 megacuries of I-131 and about 0.35 megacuries of Cesium-137.

The question “Why were these radioactive releases so small?” needs to be asked and answered.

5.0 FINAL THOUGHTS

1. At Fukushima, all three core melts might have been avoided if the wetwell hardened vent isolation valves could have been opened in a timely manner.

2. The spent fuel was never in danger.

3. Offsite emergency planning in the US needs to be overhauled.

4. Why the radioactive releases were as small as they were at Fukushima needs to be investigated.

5. Offsite risks from nuclear power plants are almost entirely economic/land contamination risks. Health risks are exceedingly small.

24. “Source term estimation of atmospheric release due to the Fukushima Dai-ichi Nuclear Power Plant accident by atmospheric and oceanic simulations.”, Takoya Kobayashi, et al, Journal of Nuclear Science and Technology, 15 March, 2013.