MEMORANDUM

Date: **December 17, 2013**

From: **Bob Alvarez**

Subject: **High Burnup Spent Power Reactor Fuel**

Introduction

Since the 1990's, U.S. reactor operators are permitted by the U.S. Nuclear Regulatory Commission (NRC) to effectively double the amount of time nuclear fuel can be irradiated in a reactor, by approving an increase in the percentage of uranium-235, the key fissionable material that generates energy. In doing so, NRC has bowed to the wishes of nuclear reactor operators, motivated more by economics than spent nuclear fuel storage and disposal.

Known as increased "burnup" this practice is described in terms of the amount of electricity in gigawatts (GW) produced per day with a ton of uranium.

Reactor fuel burnups have gradually increased on the average to ~50 GWd/t for Pressurized Reactors (PWR) and 43GWd/T for Boiling Water Reactors (BWR). [1] Projected burnups are estimated to increase. (See Figure 1) The current maximum peak burnup limit is 62MWd/t. Reactor operators would like to increase burnups to 75GWd/t..[2] As of 2008, the NRC allows reactors using uranium fuel to operate at the highest burnup rates of any country in the world.[3]

Inadequate Technical Basis for Storage and disposal

While the move to high burnup in U.S. power reactors has improved the nuclear power sales, it remains a significant impediment to the safe storage and disposal of spent nuclear fuel. For more than a decade the problems and concerns associated with high burnup spent nuclear fuel have increased, while the resolution of these problems remains illusive. For instance:

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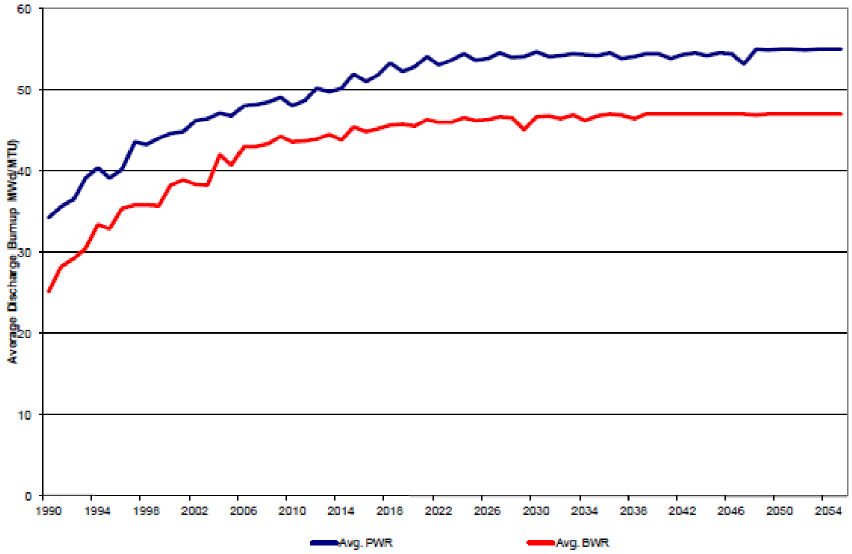
[1] E. Supko, Impacts Associated with Transfer of Spent Nuclear Fuel from Spent Fuel Storage Pools to Dry Storage After Five Years of Cooling, Revision 1, Electric Power Research Institute, August 2012.

[2] V. Jain, G. Cragnolino and L. Howard, A review Report on High Burnup Spent Nuclear Fuel Disposal Issues, Center for Nuclear Waste Regulatory Analyses, San Antonio, Texas, CNWRA 2004-08, September 2004, p.xv.

[3] Erik Kolstad, Nuclear Fuel Behaviour in Operational Conditions and Reliability, Prepared for IPG meeting-Workshop on Fuel Behaviour, Argonne National Laboratory, September 2008, p. 10

Figure 1.Historical and Projected Average BWR and PWR Discharge Burnups
(Source: Supko/EPRI 2012)



- In 2000, several years after granting increased burnups for U.S. power reactors the U.S. Nuclear Regulatory Commission admitted, “ There is limited data to show that the cladding of spent fuel with burnups greater than 45,000 MWd/MTU will remain undamaged during the licensing period.” [4]

- In 2003 the Electric Power Research Institute concluded: “For the most part, the current licensing basis for dry storage of spent fuel is largely based on fuel examinations and dry storage performance demonstrations performed in the 1980s and 1990s. Spent fuel used in the dry storage performance demonstrations had discharge burnups of ~36 GWd/MTU, or less.”[5]

- In 2010 researchers at Oak Ridge National Laboratory reported to the NRC that, “the majority of isotopic assay measurements available to date involve spent fuel with burnups of less than 40 GWd/MTU and initial enrichments below 4 wt % 235U, limiting the ability to validate computer code predictions and accurately quantify the uncertainties of isotopic analyses for modern fuels in the high burnup domain.”[6]

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4 U.S. Nuclear Regulatory Commission, Standard Review Plan for Spent Fuel Dry Storage Facilities, Final Report NUREG-1567, March 2000. P. 6-15. http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1567/sr1567.pdf

[5] Electric Power Institute, Dry Storage Demonstration for High-Burnup Spent Nuclear Fuel Feasibility Study, September 2003, p.5-1.

[6] G. Ilas and I.C. Gauld, Analysis of Experimental Data for High-Burnup PWR Spent Fuel Isotopic Validation—Vandellós II Reactor, ORNL/TM-2009/32, p. 1. http://info.ornl.gov/sites/publications/files/Pub22621.pdf

- That same year the Nuclear Waste Technical Review Board reported that: “Only limited references were found on the inspection and characterization of fuel in dry storage, and they all were performed on low-burnup fuel after 15 years or less of dry storage. Insufficient information is available yet on high-burnup fuels to allow reliable predictions of degradation processes during extended dry storage, and no information was found on inspections conducted on high-burnup fuels to confirm the predictions that have been made.”[7]

- In 2012, EPRI reported that: “R&D work will continue especially in concert with introduction of new cladding materials” [and] “R&D work will continue especially in concert with introduction of new cladding materials...[and a] Key question: Given what we learned, how does that knowledge support existing –or coming up with new– regulatory guidance?” [8]

- In 2012, the official publication of the National Academy of Engineering of the National Academy of Sciences raised similar concerns about the viability of high-burnup fuel by noting, “the technical basis for the spent fuel currently being discharged (high utilization, burnup fuels) is not well established… the NRC has not yet granted a license for the transport of the higher burnup fuels that are now commonly discharged from reactors. In addition, spent fuel that may have degraded after extended storage may present new obstacles to safe transport.”[9]

Impacts

EPRI pointed out in 2005 that: “*Failure to resolve, in a timely manner, regulatory issues associated with interim dry storage and transportation of high-burnup spent fuel would result in severe economic penalties and in operational limitations to nuclear plant operators.* [Emphasis added.]”[10]

Since that time, there remain several issues of concern that impact the storage and disposal of high-burnup spent nuclear fuel. With higher burn up, nuclear fuel rods undergo several potentially risky changes that include:

- Increasing oxidation, corrosion and hydriding of the fuel cladding. Oxidation reduces cladding thickness, while hydrogen (H3) absorption of the cladding to form a hydrogen-

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[7] United States Nuclear Waste Technical Review Board, *Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel, December 10, 201*0.

[8] Albert Machiels, Electric Power Research Institute, High-Burnup – 10 Years Later, Used Fuel and HLW Management Technical Advisory Committee Washington, DC September 13, 2012

9 National Academy of Engineering, Managing Nuclear Waste, Summer 2012, pp 21, 31. http://www.nae.edu/File.aspx?id=60739

[10] Electric Power research Institute, Application of Critical Strain Energy Density to Predicting High-Burnup Fuel Rod Failure, September 2005, P.vi.

based rust of the zirconium metal from the gas pressure inside the rod can cause the cladding to become brittle and fail;[11]

- Higher internal rod gas pressure between the pellets and the inner wall of the cladding leading to higher fission gas release. Pressure increases are typically two to three times greater.[12]
- During a power release at high burnup cladding can deform and fail.[13]
- Elongation or thinning of the cladding from increased internal fission gas pressure;[14]
- Structural damage and failure of the cladding caused by hoop (circumferential) stress; [15]
- Increased debris in the reactor vessel, damaging and rupturing fuel rods;[16]
- Cladding wear and failure from prolonged rubbing of fuel rods against grids that hold them in the assembly as the reactor operates (grid to rod fretting).[17]
- Oxidation of irradiated fuel pellets during extended storage.[18]
- A significant increase in radioactivity and decay heat in the spent fuel. [19]
- A potentially larger number of damaged spent fuel assemblies stored in pools[20]
- Upgraded pool storage with respect to heat removal and pool cleaning.[21]
- Requiring as much as 150 years of surface storage before final disposal. [22]
- Increased costs for disposal due to decay heat.[23]
- Potential repository criticality [24]
- Increased radiation doses following geologic disposal[25]

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[11] U.S. Nuclear Regulatory Commission, Rulemaking Issue, Notation Vote, Memorandum from: R.W. Borchardt, Executive Director for Operations, Subject: Proposed Rulemaking – 10CFR 50.46c Emergency Core Cooling System Performance During Loss-of-Coolant Accidents (RIN 3150-AH42), SECY-12-0034, March 1, 2012, p. 2. http://www.nrc.gov/reading-rm/doc-collections/commission/secys/2012/2012-0034scy.pdf

[12] U.S. Nuclear regulatory Commission, Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants, October 2000, P. 45. http://pbadupws.nrc.gov/docs/ML0104/ML010430066.pdf

[13] Stafano Caruso, c*haracterisation of high-burnup LWR fuel rods through gamma tomography*, ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE, April 2007.

[14] Op cit ref. 12.

[15] Ibid

[16] International Atomic Energy Agency, Impact of High-Burnup Uranium Oxide and Mixed Uranium – Plutonium Oxide Water Reactor Fuel on Spent Fuel Management, IAEA Nuclear Energy Series, No.. NF-T-3.8, June 2011. P. 39. http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1490_web.pdf

[17] Ibid.

[18] Op Cit Ref. 7.

[19] Op. cit ref. 16.

[20] Ibid p. 51.

[21] Ibid. p.1.

[22] Zhiwen Xu, Mujid S. Kazimi and Michael Driscoll, Impact of High Burnup on PWR Spent Fuel Characteristics, Nuclear Science and Engineering, 151, 261-273 (2005), http://ocw.internet-institute.eu/courses/nuclear-engineering/22-251-systems-analysis-of-the-nuclear-fuel-cycle-fall-2005/readings/impact.pdf

[23] Ibid.

[24] Zhen Xu, Designing Strategies for Optimizing High Burnup in Pressurized Reactors, Massachusetts Institute of Technology, Department of Nuclear Engineering, January 2003.

[25] Sitakanta Mohanty, Lynn Tipton, Razvan Nes, and David Pickett, High-Burnup of Spent Nuclear Fuel and Its Implications for Disposal Performance Assessments, Symposium on the Scientific Basis for Nuclear Waste Management XXXVI at the 2012 Materials Research Society Fall Meeting, Boston, Massachusetts, USA, November 25─30, 2012

- Swelling and closure of the pellet-cladding gap- increasing cladding stresses, creep and stress corrosion cracking of cladding in extended storage. [26]
- Embrittlement of cladding due to decreases in fuel temperatures during extended storage.[27]

There is growing evidence that as a result of higher burn-ups nuclear fuel cladding cannot be relied upon as a primary barrier to prevent the escape of radioactivity, especially during dry storage. This has not been lost on the nuclear industry and staff of the NRC for several years now. Damage in the form of pinhole leaks, and small cracks that could lead to breaching of fuel cladding is "not explicitly defined in [NRC] Regulations, staff guidance or standards."[28]

Source Term and Decay Heat

Given these uncertainties the U.S. Department of Energy (DOE) and the NRC have provided general estimates of the radionuclide content of spent nuclear fuel based on current and previous burnup assumptions. According to DOE the estimated average long-lived radioactivity for a typical PWR and BWR assembly having lower burnup at the time of geological disposal are 88,173.69 curies and 30,181.63 curies respectively. [29] For current burnups the NRC estimates that the post discharge radioactive inventory of spent fuel for a typical PWR and BWR assemblies are 270,348.26 curies and 127,056.67 curies respectively (See Figure 2). [30] Approximately 40 percent of the total estimated radioactivity for lower and high burnup is Cs-137.

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[26] op cit. Ref 7.

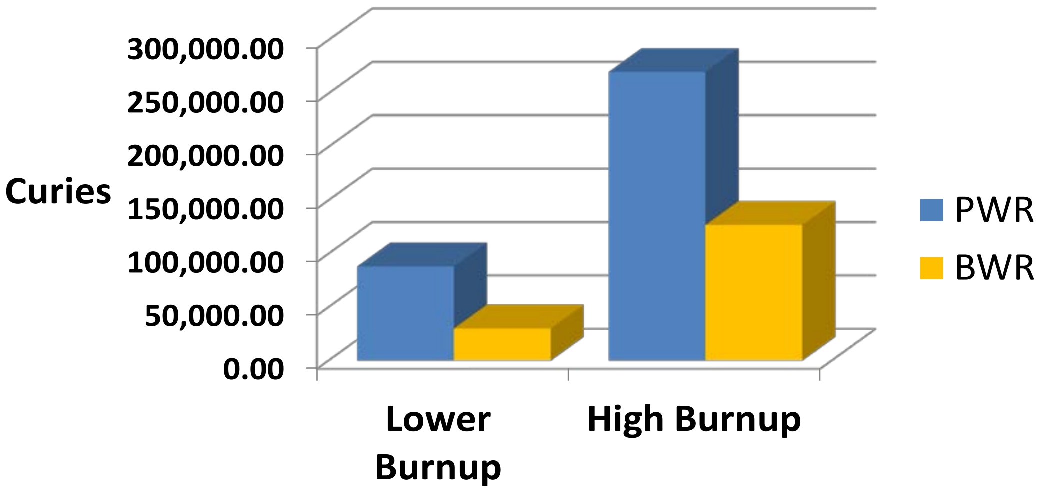
[27] Ibid.

[28] RE Einziger et al., Damage in Spent Nuclear Fuel Defined by Properties and Requirements, U.S. Nuclear Regulatory Commission, Spent Fuel Project Office, June 2006. http://pbadupws.nrc.gov/docs/ML0608/ML060860476.pdf

[29] U.S. Department of Energy, Final Environmental Impact Statement, for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada, 2002, Appendix A, Tables A-7, A-8, A-9, A-10, (PWR/ Burn up = 41,200 MWd/MTHM, enrichment = 3.75 percent, decay time = 23 years. BWR/ Burn up = 36,600 MWd/MTHM, enrichment = 3.03 percent, decay time = 23 years.)

[30] U.S. Nuclear Regulatory Commission, Characteristics for the Representative Commercial Spent Fuel Assembly for Preclosure Normal Operations, May 2007, Table 16, p.44-45. http://pbadupws.nrc.gov/docs/ML0907/ML090770390.pdf

Figure 2 estimated radioactivity in a U.S. spent nuclear fuel assembly



Sources: DOE EIS-0250, Appendix A, http://energy.gov/sites/prod/files/EIS-0250-FEIS-01-2002_0.pdf
NRC http://pbadupws.nrc.gov/docs/ML0907/ML090770390.pdf

This substantial increase in spent nuclear fuel radioactivity has also resulted in a commensurate increase in decay heat. After removal, the spent fuel gives off a significant amount of heat as the radioisotopes decay. After removal, the spent fuel gives off a significant amount of heat as the radioisotopes decay(see Figures 3 and 4). The offload of a full reactor core at a PWR is estimated to give off about 42,000 BTU/hr (12,310 watts).[31] Within one year the heat output of the spent fuel diminishes by about ten times. The decay heat for a five-year cooled PWR assembly with a discharge exposure of 55 GWd/MTU is approximately 1,500 watts.[32] The decay heat for a five-year cooled BWR assembly with a discharge exposure of 48 GWd/MTU is approximately 480 watts.[33]

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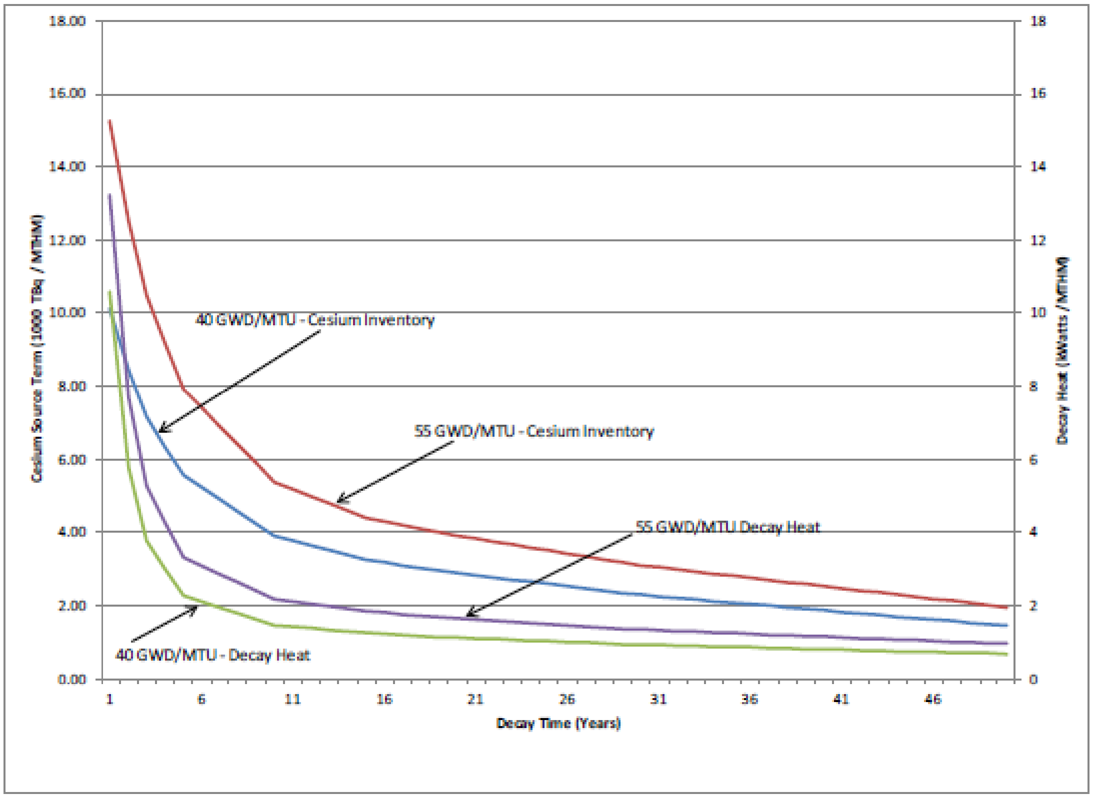
31 U.S. Nuclear Regulatory Commission, Safety Evaluation by the Office of Nuclear Safety Regulation Related to Amendment No. 131 to Facility Operating License No. NPF-10 and Amendment 120 to Facility Operating License No. NPF-15, Docket Nos. 50-361 and 50-362, October 1996, P. 6. http://pbadupws.nrc.gov/docs/ML0220/ML022000232.pdf

32 Op Cit Ref.1.

[33] Ibid.

Figure 3 PWR SNF Assembly Decay Heat (right axis) and Cesium Inventory (left axis) as a Function of Burnup and Cooling Time



Source: Supko/EPRI 2012

Within one year the heat output of the spent fuel diminishes by about ten times. After 10 years it drops by another factor of ten. By 100 years the decay heat has dropped another five times, but still gives off significant heat.[34] However, the decay heat remains substantially high throughout the operation of the reactors and well after they are closed.

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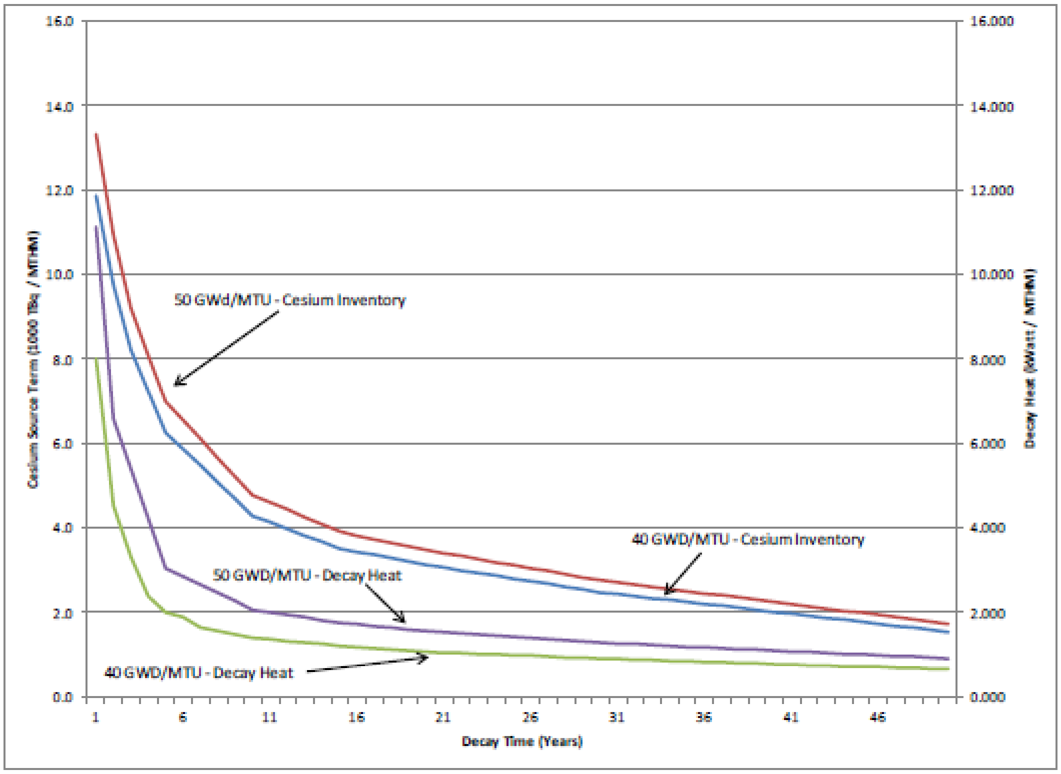
[34] Op Cit Ref. 4.

Figure 4 ***BWR SNF Assembly Decay Heat (right axis) and Cesium Inventory (left axis) as a Function of Burnup and Cooling Time [***



(Source: Supko/E{RI 2012)

Control of decay heat is a key safety factor for spent fuel storage and its final disposal in a geological repository. Storage of spent nuclear fuel in pools requires continuous cooling for an indefinite period to prevent decay heat from igniting the zirconium cladding and releasing large amounts of radioactivity into the environment.

Zirconium cladding of spent fuel is chemically very reactive in the presence of uncontrolled decay heat. According to the National Research Council of the National Academy of Sciences the build up of decay heat in spent fuel in the presence of air and steam:

> “ is strongly exothermic – that is, the reaction releases large quantities of heat, which can further raise cladding temperatures… if a supply of oxygen and or steam is available to sustain the reactions.. The result could be a runaway oxidation – referred to as *a zirconium cladding fire* – that proceeds as a burn front (e.g., as seen in a forest fire or fireworks sparkler)...As fuel rod temperatures increase, the gas pressure inside the fuel rod increases and eventually can cause the cladding to balloon out and rupture.[original emphasis] “[35]

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[35] National Research Council, Board on Radioactive Waste Management, Committee on the Safety and Security of Commercial Spent Nuclear Fuel Storage, National Academes Press (2006), p. 38-39.

The Nuclear Regulatory Commission (NRC) has performed several studies to better understand this problem. In 2001, the NRC concluded:

> "… it was not feasible, without numerous constraints, to establish a generic decay heat level (and therefore a decay time) beyond which a zirconium fire is physically impossible."[36]

In terms of geologic disposal, decay heat, over thousands of years, can cause waste containers to corrode, negatively impact the geological stability of the disposal site and enhance the migration of the wastes.[37]

EPRI points out that radiocesium inventories have greatly increased as well as decay heat. It contends that a return to open-rack cooling of SNF would result in a reduction in the potential source term of 43% to 53% for a PWR and 47% to 48% for a BWR.

Wet Storage Issues

The accumulation of high-burnup spent nuclear fuel in pools adds to the growing concern over age and deterioration of spent fuel pool storage systems. A 2011 NRC-sponsored study, concluded," *as nuclear plants age, degradations of spent fuel pools (SFPs), reactor refueling cavities…are occurring at an increasing rate, primarily due to environment-related factors. During the last decade, a number of NPPs have experienced water leakage from the SFPs [spent fuel pools] and reactor refueling cavities.*[38] The authors of this study also indicate that accurate assessment of aging of spent fuel pools is uncertain because, "*it is often hard to assess their in situ condition because of accessibility problems…. Similarly, a portion of the listed concrete structures are either buried or form part of other structures or buildings, or their external surfaces are invisible because they are covered with liners.* [39] .

High-density racks in spent fuel pools at U.S. power plants pose potential criticality safety concerns associated with the deterioration of neutron absorbing panels that allow spent fuel rods to be more closely packed. Since 1983, several incidents have occurred at reactors around the U.S. with these panels in which the neutron-absorbing materials deteriorated, and in some cases, bulged, causing spent fuel assemblies, containing dozens of rods each, to become stuck in submerged storage racks in the pools. This problem could lead to structural failures in the storage racks holding the spent fuel rods in place.

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http://www.nap.edu/openbook.php?record_id=11263&page=38
,http://www.nap.edu/openbook.php?record_id=11263&page=39

[36] U.S. Nuclear regulatory Commission, Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants, October 2000, P. ix. http://pbadupws.nrc.gov/docs/ML0104/ML010430066.pdf

[37] R. Wigeland, T.Taiwo, M. Todosow, W. Halsey, J. Gehin, Options Study – Phase II ,Department of Energy, Idaho National Laboratory, INL/EXT-10-20439, September 2010. http://www.inl.gov/technicalpublications/Documents/4781584.pdf

[38] U.S. Nuclear regulatory Commission, A summary of Aging Effects and Their Management in Reactor Spent Fuel Pools, Refuelling Cavities, TORI and Safety-Related Concrete Structures, NUREG/CR-7111 (2011). P. vxiii. http://pbadupws.nrc.gov/docs/ML1204/ML12047A184.pdf

[39] Ibid.

According to the NRC in May 2010:

> The conservatism/margins in spent fuel pool (SFP) criticality analyses have been decreasing…The new rack designs rely heavily on permanently installed neutron absorbers to maintain criticality requirements. *Unfortunately, virtually every permanently installed neutron absorber, for which a history can be established, has exhibited some degradation. Some have lost a significant portion of their neutron absorbing capability. In some cases, the degradation is so extensive that the permanently installed neutron absorber can no longer be credited in the criticality analysis* [emphasis added].[40]

For example, in 2007, South California Edison (SCE) reported to the NRC that Boraflex neutron absorbing panels have deteriorated to the point at the San Onofre Nuclear Generating Station Units 2 and 3 spent nuclear fuel pools where it was doubtful they could be credited to prevent criticality. SCE proposed installing borated stainless steel tube guide inserts, and to add more neutron absorbing boron to the pool water.[41] According to SCE deterioration from erosion, over a period of 15 months, increased the level of particles from disintegrated neutron absorbing panels in the pool water by 134 percent.[42] These particles place an additional strain on pool water cleaning systems.

NRC's response to this problem has been to allow operators to add additional boron to the pool water to compensate for the loss of re-criticality protection from deteriorated neutron absorbing panels. However, boron is implicated in possible deterioration of the reinforced concrete holding the spent fuel pools. Concrete "could be negatively impacted by adverse environments of borated water or where there is the possibility of alkali aggregate material reactivity."[43]

Equipment installed to make high-density pools safe exacerbates the danger of spent fuel cladding ignition, particularly with high burnup spent fuel. In high-density pools at pressurized water reactors, fuel assemblies are packed about nine to 10.5 inches apart, just slightly wider than the spacing inside a reactor. To compensate for the increased risks of a large-scale accident, such as a runaway nuclear chain reaction, pools have been retrofitted with enhanced water chemistry controls and neutron-absorbing panels between assemblies.

The extra equipment restricts water and air circulation, making the pools more vulnerable to systemic failures. The ability to remove decay heat from spent fuel pools to prevent boiling corresponds to the amount of water displaced in the pool by spent fuel and the equipment that allows for its tight packing. High density storage also impacts the ability of water to flow through the pool. If the equipment collapses or fails, as might occur during a destructive

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40 U.S. NRC, Office of Nuclear Reactor Regulation, On Site Spent Fuel Criticality Analyses, NRR Action Plan, May 21, 2010. http://pbadupws.nrc.gov/docs/ML1015/ML101520463.pdf

41 South California Edison, Letter to the NU.S. Nuclear regulatory Commission, Subject: Docket Nos. 50-361 and 50-362 Amendment Application Numbers 243, Supplement 1 and 227, Supplement 1 Proposed Change Number (PCN)566, Revision 1, Request to Revise Fuel Storage Pool Boron Concentration, San Onofre Nuclear Generating Station Units 2 and 3, June 15, 2007, Enclosure 2,p. 2. http://pbadupws.nrc.gov/docs/ML0717/ML071700097.pdf

42 Ibid.

[43] Op. Cit Ref. 38, p.xiv.

earthquake or terrorist attack, air and water flow to exposed fuel assemblies would be obstructed, causing a fire, according to the NRC’s report. Heat would turn the remaining water into steam, which would interact with the zirconium, making the problem worse by yielding inflammable and explosive hydrogen.