NUCLEAR CONTROL INSTITUTE
Washington, D.C.

Comments on the Storage and Disposition of Weapons-Usable Fissile Materials Draft Programmatic Environmental Impact Statement

Public and Occupational Health and Safety Impacts of Plutonium Disposition Alternatives

Revision 1: October 9, 1996

E.S. Lyman
Nuclear Control Institute

Conversion of surplus weapons-usable plutonium (WU-Pu) to the spent fuel standard can provide a great benefit to disarmament and non-proliferation, especially if there is reciprocal action on the part of Russia. However, this significant benefit comes at a price. All disposition options under consideration in the DPEIS involve multi-year campaigns involving large-scale processing of WU-Pu and other extremely hazardous radionuclides. Furthermore, for the large fraction of surplus WU-Pu that is now in the form of weapons components, WU-Pu in relatively stable solid form must be converted to highly dispersible intermediate process streams and subjected to a number of energetic processes such as oxidation and treatment at high temperature. Because of the possibility of a catastrophic accident in a processing facility or during irradiation in a nuclear reactor, the implementation of disposition will be associated with a substantial increase in the risk of dispersal of a large quantity of WU-Pu.

For this reason, a major objective of the DPEIS should be the presentation of a thorough and consistent evaluation of the occupational and public health risks of different WU-Pu disposition options. Disposition options should be ranked according to the risks that they pose, and this ranking should play an important role in the final selection.

It has often been argued that environmental impacts need not be a decisive factor in choosing a WU-Pu disposition option because the risks of any option will be small compared to those incurred when the WU-Pu was produced. However, this argument in no way negates the desirability of strictly limiting further harm from the aftermath of the Cold War. If the opportunity now exists to carry out the disposition program in a way that minimizes health and safety impacts, common sense dictates that the lowest-impact option should be given the most serious consideration, assuming it is not disqualified by other factors such as deleterious non-proliferation impact or excessive cost or delay.

The DPEIS, however, fails to accomplish this objective. The methodology it uses for evaluating and comparing the safety risks of different disposition options is logically inconsistent and confusing. Furthermore, possibly as a consequence of the large number of different groups involved in its preparation, it contains contradictory factual information. The errors and questionable assumptions in the documents referenced by the DPEIS cast considerable doubt on its quantitative accuracy.

The most problematic consequence of the inconsistencies plaguing the DPEIS analysis is an exaggeration of the risks of the immobilization options relative to the reactor-based options. This must be corrected in the final version in order to provide a fair presentation of the evaluation and ranking of the safety risks of the various options.

Such a presentation would show that the health and safety impacts of the immobilization options will be substantially lower than those of the reactor options. However, as shown below, the DPEIS is structured to minimize the significance of this fact. Whether deliberate or not, this has the effect of biasing the whole document toward the reactor options.

1. Inconsistencies in the DPEIS health and safety methodology

a) Incompleteness of accident evaluation criteria

In Section M.5.1.1., it is stated that "the potential for facility accidents and the magnitudes of their consequences are important factors in the evaluation of ... storage and disposition alternatives," and that "the health risk issues are twofold." These two issues are identified as 1) whether accidents at any of the facilities pose unacceptable health risks to workers or the public, and 2) whether alternative locations for facilities can provide lesser public or worker health risks.

This list of issues to be considered in evaluating accident impacts of disposition is clearly incomplete. In particular, the question of whether alternative *disposition options at a given location*, rather than alternative *locations*, can provide "lesser public or worker health risks" does not seem to be regarded in the DPEIS as a worthy criterion for consideration. This is confirmed by the absence of a graph in the Summary comparing accident impacts of different options. But such a comparison is clearly legitimate and meaningful, and therefore essential.

Discounting the relevance of the comparative accident impacts of different disposition options biases the DPEIS analysis toward the reactor options. This is not completely clear from the data provided by the DPEIS itself. According to the DPEIS, the *maximum* risks of cancer fatalities to workers and the public resulting from accidents at a plutonium vitrification facility are two to three orders of magnitude below those resulting from accidents involving evolutionary LWRs (Ev-LWRS).1 On the other hand, data in the DPEIS implies that the expected risks, computed by weighting the consequences of individual accident sequences with their expected probabilities, are comparable for the two options. However, when the many problems with the DPEIS accident analysis are corrected, as detailed below, we expect that the immobilization options will prove to have significantly lower impacts than the reactor options with respect to all measures of accident severity, including "expected" risks.

The DPEIS downplays the significance of "discernible differences [in health and safety impacts] among alternatives" by stressing that although in some cases the potential accident risks of the immobilization options are indeed much lower than those of the reactor options, "the risks associated with implementing any of the alternatives is small,"2 a statement provided without adequate justification. Particularly problematic is the use of generic probabilistic risk assessment (PRA) results to provide values for the absolute accident risks of different options. It is widely accepted that while PRAs are useful in understanding comparative risks, e.g. how modifications to a particular plant can improve safety, they are far less useful (and credible) in generating values of absolute risk.

The credibility of the absolute risk values cited in the DPEIS is further damaged by the numerous errors, omissions and inconsistencies contained in the analysis of reactor accidents (especially in existing LWRs), which could lead to an underestimation of the actual risks of using MOX by several orders of magnitude. Some of these are described in more detail below.

The DPEIS does not explain its risk methodology clearly. A section on "risk" purports to argue that the risks from accidents during plutonium disposition should be considered in the context of other, more common risks, such as death from accidental poisoning. However, even this discussion is misleading since it uses as an example a comparison of the *annual* risk from a plutonium storage accident (itself one of the smallest accident risks tabulated in the DPEIS) over the *lifetime* risks from these more common hazards, thereby overstating them by a factor of 70.3 If, for instance, one considers the annual risk as a result of an accident at an Ev-LWR, the difference between the risks of the reactor disposition option and the "common risks" cited in the DPEIS are not as striking. The (lifetime) risk from accidental poisoning, according to the DPEIS, is 1/1000, so the annual risk is 1.4�$^{-5}$; the expected risk from an Ev-LWR accident at the Oak Ridge plant is given as 1.2 10^{-8} (pg. M- 366). If this value were adjusted to correct for the underestimation by several orders of magnitude of volatile and semi-volatile releases in a beyond-design- basis accident (see below), it becomes apparent that some of the activities listed in the DPEIS can have risks approaching the so-called "common" risks.

Although it can be useful to put the absolute risks of disposition activities into perspective, this should not be used to obscure the fact that the immobilization options provide minimum-risk alternatives for WU-Pu disposition.

b) Absence of explicit evaluation of can-in-canister immobilization options

Some of the WU-Pu disposition options under consideration in the DPEIS can be implemented in a variety of ways. In Volume I, Section 2.4, p. 2-76, the methodology that was used for determining which variant of a particular disposition option should be chosen for full evaluation in the DPEIS is discussed. In particular, it is stated that "bounding" variants were selected, e.g. those which were likely to have environmental impacts equal to or greater than all the other variants under consideration. This approach was used to explain why only the "greenfield" immobilization options that require a new, shielded immobilization plant were explicitly analyzed, rather than the options that "piggyback" on operations at existing facilities, such as the can-in- canister (CIC) approach at the Defense Waste Processing Facility (DWPF) at the Savannah River Site (SRS). The CIC approach will have lower environmental impacts than greenfield approaches because in the latter approach, only the incremental risks associated with WU-Pu immobilization would be charged to the disposition program.

This could be a legitimate approach, provided that it were consistently applied, which is not the case in the DPEIS. The DPEIS evaluates reactor options that require construction of new, evolutionary LWRs (Ev-LWRs) *and* those involving irradiation of MOX fuel in existing LWRs (Ex-LWRs) (except in the important category of accident impacts). This is apparently not judged in the DPEIS to be inconsistent with the approach used for immobilization options because it treats the reactor proposals as different "options," rather than variants of the same option. However, this is merely a semantic distinction.

Because only incremental impacts are considered in the Ex-LWR case, but not in any of the immobilization options, the reader can get the misleading impression that the Ex-LWR reactor option could have comparable or even lower normal radiological impacts than any of the immobilization options (e.g. Summary, Figs. S-17 and S-18; Attachment B, pgs. S-142 to S-145) and can even provide a net benefit (although this benefit disappears when the impacts of MOX fabrication are considered). The DPEIS even goes as far as to include a section on the incremental benefits of using MOX fuel in reducing the health impacts of the nuclear fuel cycle, a section which is completely irrelevant to the particular mission of WU-Pu disposition and is completely wrong as well (see below).

For consistent treatment of "incremental" radiological impacts, there should be a comparison of the Ex-LWR options with the CIC options. In these options, plutonium first would be immobilized in glass or ceramic, without the addition of cesium-137 for spiking purposes, and packed in small cans. These cans would then be placed in the DWPF canisters prior to filling with HLW glass. The incremental environmental impacts of this approach would be those associated with operation of the plutonium immobilization line only (assuming that the introduction of the small cans would not have a detrimental effect on DWPF operations, as results from cold testing of CIC at DWPF clearly indicate).

One can show, using figures given in the DPEIS, that the incremental normal radiological impacts of CIC options would be about two orders of magnitude smaller than those from a greenfield immobilization facility. This can be seen most easily by comparing the doses received by the public from normal operation of the ceramic immobilization facility in the deep borehole option, in which case no cesium-137 is used, and those from a greenfield ceramic immobilization facility, in which case cesium-137 is added directly to the ceramic during processing. From Tables M.2.9-3 and M.2.9-4 of the DPEIS, one sees that routine emissions of plutonium from ceramic immobilization facilities located at SRS account for about 4% and 2% of the total dose to the maximally exposed individual (MEI) and the committed effective population dose equivalent, respectively, the rest being due to Cs-137 emissions.

Similar reasoning can be applied to the accident analysis of greenfield immobilization facilities given in the DPEIS to extract the incremental risks associated with CIC. For example, the annual risk to the MEI from accidents at a greenfield vitrification facility at SRS is 1.1�$^{-10}$, according to Table M.5.3.5.2-6. To obtain the incremental impacts of the CIC approach, one should only consider accidents resulting in releases of plutonium and subtract the doses due to Cs-137 releases. This approach yields an annual risk from CIC to the MEI at SRS of 1.6� 10^{-12}, about a factor of one hundred smaller than the greenfield risk.

Because the CIC approach has significantly smaller radiological impacts than the greenfield immobilization, and because it is analogous to the Ex-LWR option, it should be treated as a distinct option and fully evaluated in the PEIS.

c) Absence of evaluation of incremental accident impacts of the existing LWR option

The DPEIS assumes that there are no incremental accident risks associated with the substitution of MOX for low-enriched uranium (LEU) in Ex-LWRs, which makes this option appear to be essentially zero-risk. This statement is simply not justifiable for a number of reasons which are discussed in detail below. In fact, the incremental accident risk of this option may well exceed the absolute risk of the Ev-LWR option.

d) Incorrect analysis of "avoided human health impacts" due to substitution of MOX for LEU

Volume II, Section 4.9 of the DPEIS is entirely wrong and should be corrected or deleted from the final version. In attempting to compare the risks of the MOX and LEU fuel cycles, the authors of the section seem to have forgotten that MOX fuel is about 95% uranium. Thus it is completely wrong to claim, as they do, that there are no health impacts associated with the uranium mining, milling and conversion stages in the MOX cycle. The stage of the cycle which is bypassed is uranium enrichment, which is well-known to have very low health impacts anyway.

Although not explicitly stated, the authors may be assuming that depleted uranium stockpiles will be used to fabricate MOX fuel, in which case the associated mining and milling steps (but not conversion) will be avoided. This is a legitimate point, but by the same reasoning, one can also give credit to stockpiles of uranium that can be used in the LEU route, such as LEU obtained from the blend-down of surplus HEU. The relatively small amount of electricity that would be generated from MOX fuel fabricated from surplus warhead plutonium could easily be displaced by the LEU equivalent of about 30 tonnes of HEU. Thus one cannot consistently assign an incremental health benefit to the US MOX program.

e) Inappropriateness of 80-km limit for consideration of public health impact

The restriction of evaluation of public health impacts to within an 80-km radius of the facility in question leads to some peculiar inconsistencies in the comparison of immobilization and MOX options. For instance, according to the DPEIS the CANDU option appears to have no public health impacts on the U.S. population, other than those resulting from the small risk associated with the production and transport of MOX fuel within the U.S. Yet a quick look at a map reveals that a release of radiation from the Bruce A station in Ontario would most likely affect a large portion of the northeastern United States, although mostly at distances greater than 80 km.

Furthermore, the 80-km truncation conceals the fact that a large-scale reactor accident can have national and even global impact, whereas an accident at an immobilization facility would in all likelihood be much more limited in geographical range. This is because both the source term and the energy available for dispersion would be much smaller in the case of the immobilization facility. *Thus truncating consideration of public health impacts at 80 km greatly overestimates the risks associated with immobilization compared with MOX.*

2. Serious flaws in the safety analysis of reactor options

The health and safety analysis of the MOX options in the DPEIS contains such serious flaws that DOE should discard the analysis as written and start over, proceeding in a clear and logical manner. *The use of MOX in LWRs or CANDUs -- in particular, full-core MOX utilizing weapons-grade plutonium as proposed in the DPEIS -- is a novel practice associated with numerous unsolved and potentially very serious safety risks.* Experience with LWR MOX use in other countries, which is often cited by promoters of the MOX options, is of limited applicability to the planned US program because the foreign programs utilize plutonium with different isotopic contents, lower MOX core fractions, and fuel without integral burnable absorbers. In addition, experience to date with the use of MOX has revealed a number of significant safety issues which remain unresolved. The existing LWR (Ex-LWR) option, which is probably the MOX option most likely to be chosen, must be singled out for special concern. Yet the DPEIS contains no accident analysis specific to this option.

The DPEIS dispenses with fundamental issues of MOX safety in one paragraph, in which it alludes to "separate studies" (which were mistakenly left unreferenced) that "indicate that the use of MOX fuel in a ... LWR does not increase the risk and consequences of accidents."4 Most of these source documents turn out to be studies based entirely on reactor vendor analyses which purport to confirm the safety of using MOX in their reactors. However, at least one of the reactor vendors freely admitted to us that its in-house analyses were biased and unreliable.5 Closer examination of these studies reveals that they in no way provide adequate justification for the above statement in the DPEIS. In fact, at least one of the references, the National Academy of Sciences study "Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options," actually contradicts the statement, by estimating that the consequences of a severe accident could increase by 10-20% as a result of the substitution of MOX for LEU. Such an increase, far from being insignificant, could overwhelm the radiological impacts of any of the other disposition options. Furthermore, the discussion below indicates that the NAS may have underestimated the incremental consequences.

DOE may have judged that this shoddy and incomplete accident analysis was sufficient for the purposes of the DPEIS because, if the MOX option were chosen, safety issues would be dealt with later in the context of NRC review of the procedure. However, this defeats the purpose of the whole exercise, which is to inform decision-making with an accurate comparative assessment of risks. To conform to the spirit of NEPA, a deeper understanding of the potential risks involved with the use of MOX in LWRs in this country must be acquired prior to the public comment period and should not be deferred until after decisions are made. The NRC and independent experts should be brought in at the DPEIS stage to provide alternative perspectives on the outstanding safety issues. This would be a prudent course of action, since unanticipated safety questions that arise later in the process could serve to cause unacceptable delays in disposition.

The only DPEIS reactor alternative for which any information concerning accident impacts is provided is the Evolutionary LWR (Ev-LWR) option. In the Summary, the reader is informed that "comparable data are not available" for the existing (Ex-LWR) option. DOE may be assuming here that the accident impacts of the Ev-LWR option bound those of the Ex-LWR, since the full impact of an accident would have to be charged to plutonium disposition in the former case, whereas in the latter case, one only need consider incremental impacts, e.g. the difference in risk between an existing reactor fueled with MOX and the same reactor fueled with LEU. Since the DPEIS claims without justification that there is no difference in risk, it implies that the Ex-LWR is a zero-risk option. However, this logic is faulty and renders the accident analysis in the DPEIS unusable for decision-making purposes.

a) Inadequacy of the Ev-LWR accident analysis in general

Before addressing whether the risk values resulting from the LEU-fueled Ev- LWR accident analysis contained in the DPEIS are also valid for a MOX-fueled Ex- LWR, it should be pointed out that these values are inaccurate even for the case to which they are supposed to explicitly pertain. The Ev-LWR analysis included in the DPEIS greatly understates the potential risks of an accident involving a LEU-fueled LWR, even one of "evolutionary" design. The "evolutionary" designs, such as the GE ABWR, do not contain the advanced safety measures, such as those proposed for the European Power Reactor, which would nearly eliminate the risk of a catastrophic off-site release of radiation (e.g. a double containment structure), and thus are still vulnerable to such events. However, Ev-LWR vendors claim that the risk of such events will be greatly reduced relative to the current generation of Ex-LWRs.

The most severe Ev-LWR beyond design-basis accident included in the DPEIS is an anticipated transient without scram (ATWS), followed by loss of core cooling, core meltdown, and late containment failure. The frequency of this accident is listed as 1.7�$^{-7}$ per reactor-year. However, the associated radionuclide source term, which references the General Electric Advanced Boiling Water Reactor (ABWR) Safety Analysis Report and studies prepared by a consultant for another purpose, is much smaller than that which could conceivably result from a loss-of-containment accident.[6]

For instance, the postulated release of Cs-137 to the environment is 230 curies (Ci), which is seen to correspond to a release fraction of 1.8�$^{-5}$ when compared to the end-of-cycle Cs-137 Ev-LWR core inventory of 1.3�$^{-7}$ Ci given in a source document (which itself reference ABWR safety analyses).[7] This release is substantially below the maximum possible release of cesium, which is semi-volatile and can be almost completely evolved from the core during a meltdown. It is now accepted that 20-40% of the cesium core inventory was released to the environment during the Chernobyl accident.

In fact, if one looks at the entire ABWR severe accident spectrum, which does not appear in the DPEIS but is included in one of the source documents,[8] one sees that the Cs release fraction can be as great as 3.5�$^{-1}$ in a certain class of accidents known as Release Class (RC) 5, whereas a release of 2�$^{-5}$ in the DPEIS accident appears to corresponds to a Release Class 2 event, which is said to occur with a frequency of 1.3�$^{-7}$. There is a similar disparity in iodine release fractions between RC5 and RC2. RC2 is also characterized by zero release of other semi-volatiles (e.g. Te, Ru) and low-volatiles (e.g. Sr and Ba). While the RC5 release fraction is a factor of 20,000 greater than the one assumed in the DPEIS, the associated accident frequency is listed as 2.2�$^{-8}$, which is only a factor of ten smaller. Thus the risk of the RC5 accident (e.g. probability times consequences) due to cesium emission is on the order of one thousand times greater than that of the DPEIS accident. Of the eight release classes listed, four have larger risks associated with them than RC2, the one included in the DPEIS. There is no legitimate basis for excluding these other accidents from consideration. However, their exclusion artificially underestimates the potential environmental impacts of reactor disposition relative to the immobilization options, leading to erroneous conclusions.

b) Inadequacy of the Ev-LWR accident as an upper bound for Ex-LWR accident impacts

There are two interrelated reasons why the Ev-LWR accident analysis in the DPEIS cannot be considered to be bounding or conservative with regard to the potential accident impacts of the MOX options.

First, it is based on analysis of an Ev-LWR fueled with LEU instead of MOX, and thus completely sidesteps the complex but crucial issue of whether and to what extent severe accident parameters, such as core damage frequencies (CDFs) and source terms, may differ for an Ev-LWR fueled with full-core MOX rather than LEU.[9]

Second, the Ev-LWR analysis contains numerous assumptions with regard to safety features which are specific to advanced reactor designs and simply do not apply to the MOX options based on use of existing LWRs (Ex-LWR) or CANDUs. For instance, advanced LWRs are assumed to have CDFs at least an order of magnitude smaller than those associated with LWRs operating today. Also, the source terms employed in the beyond design-basis accident analyses are based on assumptions about the likelihoods of various accident scenarios which are indisputably invalid for currently operating reactors (and may not even be valid for Ev-LWRs, which to date exist largely on paper).

To assess whether the Ev-LWR case is bounding or not with respect to accident impacts, one must determine, in light of these two factors listed above, whether the incremental risks of substituting

MOX for LEU in Ex-LWRs may actually exceed the absolute risk values for (LEU-fueled) Ev-LWR operation provided in the DPEIS. The best way to do this consistently would be to derive complementary cumulative distribution functions (CCDFs) for all three options and compare them.

Determination of the incremental risks of the Ex-LWR option is bound to be an extremely difficult and uncertain exercise. However, it is central to the whole disposition question. *The public will want to know if there is significant risk involved in introducing MOX into Ex-LWRs and whether there are safer alternatives. The DPEIS sheds no light on this question and therefore fails to accomplish its mission.*

Rather than try to determine which alternatives are bounding and which are not, the PEIS should simply provide enough information to accurately carry out the following comparisons: the incremental risks of the CIC immobilization options vs. the incremental risks of the Ex-LWR option (evaluated in a technically justifiable manner), and the risks of the greenfield immobilization options vs. the risks of the greenfield reactor options. The absence of such comparisons in the DPEIS makes it extremely difficult for the reader to obtain a clear understanding of the relative environmental impacts of the reactor and immobilization options.

Below, we will discuss a number of issues which support the notion that *the substitution of MOX for LEU in Ex-LWRs may increase both the consequences and the probabilities of severe accidents by significant factors.*

i) Beyond design-basis accident consequences: the issue of low-volatile source terms

The question of whether the consequences of a beyond design-basis accident in an Ex-LWR (e.g. core meltdown and containment failure) would change significantly if the reactor were fueled with MOX instead of LEU depends on the relative radionuclide inventories of the two cores and the radiological impact of the differences. The primary distinction is that the in-core inventories of the transuranic actinides Pu, Am and Cm are all greater by substantial factors in MOX cores. The magnitude of these factors, which depends on the initial plutonium loading in the fuel, is approximately on the order of 3 for plutonium isotopes, 5 for americium isotopes and 4 for curium isotopes at the end-of- cycle. (For MOX fabricated with reactor-grade plutonium, the curium inventory is greater by an additional factor of 10). Neptunium inventories actually are smaller in MOX cores, but the difference is only about a factor of two. Since these radionuclides are alpha-emitters with very high inhalation and ingestion radiotoxicities, and many have long half-lives, they can contribute significantly to the committed doses incurred following a reactor accident, especially via the ingestion and resuspension pathways, even if only a small fraction of the core inventory is released.

Using an argument dating at least as far back as GESMO, the Generic Environmental Impact Statement on the Use of Mixed-Oxide Fuel in Light-Water Reactors, DPEIS references claim that the increase in actinide inventories in a MOX core will not affect the consequences of an Ex-LWR accident because "plutonium and other insoluble fuel isotopes are not included in the releases to the environment."10 Thus according to this logic, it does not matter whether the inventory of actinides is greater in a MOX core because they are low-volatile species and will not be released to the environment even if the containment fails.

This argument is, plainly speaking, incorrect. There are circumstances under which significant releases of low-volatile radionuclides can occur.

First of all, the best possible laboratory for loss-of-containment accidents, the Chernobyl event, has demonstrated that significant and wide- ranging dispersal of non-volatile radionuclides is possible in beyond-design- basis accidents. The recently issued OECD review of the Chernobyl source term has concluded that the release fraction for low-volatile core constituents, including the actinides, was approximately 3.5%. Moreover, non-volatile fuel fragments were discovered as far away as Greece, over one thousand kilometers away.11

The often-repeated argument that a Chernobyl-type accident cannot happen here does not mean that the dispersal behavior of the Chernobyl core does not have relevance for Western LWRs, should they be subject to beyond design-basis accidents with loss of containment (provided that the differences in core melt chemistry are taken into account). In fact, the NRC has acknowledged in the past that low-volatile releases as high as several percent of core inventory were possible in such accidents and incorporated this information into its state-of-the-art LWR probabilistic risk assessment (PRA), NUREG-1150.12

The DPEIS relies on vendor documents to support its claim that the release of low-volatile radionuclides would be insignificant in a beyond design-basis Ex-LWR accident. For example, the LWR PEIS Data Report quotes release fractions to the environment taken from a Westinghouse Hanford Company report. For low- volatile radionuclides, these values are all extremely small (the largest is 0.3%). The report then claims that these values are consistent with NRC's latest rulemaking on the issue of core-to-containment release fractions, NUREG- 1465, "Accident Source Terms for Light-Water Nuclear Power Plants."13

It is true that NUREG-1465 tends to support the use of low-volatile release fractions lower than those used in NUREG-1150 and closer to the ones used by industry. This is not a coincidence, since the industry played a large role in revising NUREG-1465 to their liking. As described below, a careful look at the history of NUREG-1465, its supporting documentation and its domain of applicability indicates that *the low-volatile release fractions it recommends are not sufficiently conservative for use in accident analysis of Ex- LWRs. It is therefore not relevant to the use of MOX in Ex-LWRs and should not be referenced in the DPEIS in this context.* (A separate question is whether it has any validity at all).

The release behavior of the low-volatile radionuclides to containment from the molten reactor core during a severe accident is highly complex and dependent on details of accident progression that are not well understood; consequently, predictions of low-volatile release fractions are characterized by uncertainties spanning at least four orders of magnitude.14 This uncertainty has been exploited by the nuclear industry, which consistently chooses the lower bound of the range in its own assessments.

NRC originally issued a draft of NUREG-1465 in which the low-volatile release fractions were similar to those used in NUREG-1150, e.g. on the order of 2-3%. These values were strongly disputed by industry, which preferred release fractions hundreds of times lower, such as those proposed by EPRI (the Electric Power Research Institute) for use in assessments of Ev-LWRs.

Rather than try to establish a rational and conservative basis for source term estimation, NRC submitted to industry pressure and lowered the NUREG-1465 low-volatile release fractions by a factor of approximately 50. Was this change warranted? Not according to the Advisory Committee on Reactor Safeguards (ACRS), which wrote that "these adjustments need to be better justified or not be made."15 However, the ACRS' recommendation was ignored.

Industry comments on the draft of NUREG-1465 consisted of two main arguments as to why they believed its low-volatile release fractions were too high.16 First, they alluded to recent research that "demonstrated" that low-volatile release fractions from melted fuel were indeed much smaller than those assumed in NUREG-1150. Second, they argued that the use of mean values of release fraction data was not appropriate for the low-volatile radionuclides, because the uncertainty distributions range over many orders of magnitude. In distributions of this type, the mean is unduly influenced by values at the extreme upper end of the range. The EPRI low-volatile release fractions were based on the median of the distribution, which was typically two to three orders of magnitude below the mean.

The evidence supporting the industry position was summarized in a document prepared for DOE's Advanced Light Water Reactor (ALWR) Program by a consulting firm, Los Alamos Technical Associates (LATA).17 This report, which appears to have been accepted uncritically by NRC, is fundamentally flawed in at least one major respect and draws conclusions which are inconsistent with other NRC documents. The LATA report refers to a few experiments which observed small low-volatile release fractions, but notably omits discussion of one experiment in particular, the ST test series at the Annular Core Research Reactor (ACRR) at Sandia National Laboratories.18 The ST test series were noteworthy for their observation of unexpectedly high release fractions for low-volatile elements, such as europium (RF = 6.4%).

The LATA report referred to the ST series in passing, without describing their results, but dismisses them as irrelevant because they were conducted in a reducing atmosphere, which he contends "represents a special case that may exist only locally for brief periods of time in an accident." It neglected to mention that the ST series was conducted explicitly to evaluate the impact of a reducing atmosphere on fission product release, an environment which was not adequately represented in the existing database. This information was necessary, according to the authors of the ST-1 report, because "there are ... regions of actual reactor cores that are expected to be in atmospheres of nearly pure hydrogen during severe accidents."19

In fact, one of the major sources of uncertainty in charting the progression of reactor accidents is the temporal and spatial variation in oxidation potential that may occur in a particular sequence. The ST series of experiments demonstrate that these uncertainties are closely related to uncertainties in low-volatile release fractions. This point, although undoubtedly known to NRC staff, does not seem to have been taken into account when uncritically revising downward the NUREG-1465 release fractions according to the erroneous industry contention that "all" recent data support such a revision.

The question of oxidation potential is especially important with regard to americium. The volatility of metallic americium is greater by several orders of magnitude than that of the oxide, whereas for the other actinides the difference between metal and oxide volatility is not as great.

A major uncertainty in prediction of the release fraction of low-volatile radionuclides is associated with the vulnerability of Ex-LWRs to a class of accidents known as high-pressure melt expulsion (HPME) events. These are events in which the reactor vessel fails at high pressure leading to ejection of the molten core into the containment at high velocity and significant aerosol formation. HPME provides a mechanism by which relatively large fractions of low-volatiles can be converted to aerosol form in the containment atmosphere and therefore be subject to release into the environment. They should be distinguished from events in which the bulk of the core remains essentially intact throughout the meltdown.

According to NRC, the mean values of low-volatile release fraction uncertainty distributions into containment associated with HPME events in PWRs can be as high as 7%. One should note that the median values of these distributions are only about one order of magnitude less than the mean values, as opposed to the distributions of low-volatile in-vessel release fractions, in which the median is two to three orders of magnitude below the mean. Thus the industry argument that the mean values of low-volatile release fraction distributions do not accurately characterize the distributions does not apply to the HPME case.

HPME is of particular concern because of its relationship to another phenomenon known as Direct Containment Heating (DCH), in which the high heat transfer rates from the fuel aerosol causes a rapid rise in containment temperature that could lead to containment overpressurization and failure. HPME events, which are associated with both large low-volatile releases to containment and large probabilities of containment failure, can therefore result in large releases of low-volatiles to the environment as well.

These effects underscore the point that realistic source terms can only be generated by thorough analysis of specific accident sequences. NUREG-1465 provides representative release fractions for generic loss-of-containment accidents. As other NRC documents have pointed out, for radionuclides with release fractions spanning several orders of magnitude, such as the low-volatile species, neither the mean nor any other single measure contains enough information to accurately characterize the distribution. Knowledge of the actual details of the distribution is required to assess the likelihood of significant low-volatile releases in a particular accident sequence for a particular plant. Generic conclusions, such as those which appear in the DPEIS, are completely meaningless.

Given that large uncertainties in the prediction of low-volatile release fractions still exist, how significant is this issue on the actual consequences of a severe accident involving a MOX-fueled Ex-LWR? According to the DPEIS, it is not significant at all, because "other radioisotopes that are released in an accident have more serious impacts on human health than the Pu used in the MOX fuel."20 However, not only is this statement an oversimplification (e.g. the increase in transplutonium actinides is ignored), but it is also wrong. Because of the relative radiotoxicity and longevity of some of the actinides, they can have significant impacts on accident consequences. According to a study done at Sandia, which used the MACCS code to evaluate the relative importance of different radionuclides to the public health consequences of a severe LWR accident, it was found that the curium isotopes in particular were highly significant both for early and long-term exposures.21 While the results obtained in that paper depend on the specific assumptions used in their model, they are useful to obtain a qualitative understanding of the importance of curium and the other actinides.

For instance, according to the results of the Sandia study, the ratio of the contribution of curium to cesium with respect to the total number of latent cancers resulting from an accident would be about 0.1, assuming Chernobyl release fractions of 0.4 for Cs and 0.035 for Cm, and core inventories characteristic of a LEU-fueled LWR. For a W-Pu MOX-fueled LWR, the Cs inventory remains essentially the same, while the Cm inventory increases by a factor of approximately 4. This implies that the number of latent cancers due to the Cm release from a W-Pu MOX-fueled LWR would be about 40% of those due to Cs release. For plutonium isotopes, a similar calculation shows that the approximately three-fold increase in Pu release from a MOX-fueled reactor would result in a number of latent cancers about 80% of those due to Cs release.

On the other hand, the decrease in Np would only translate into a few-percent decrease in the number of latent cancers. Because Cs release is the major contributor to latent cancers following an LEU-fueled LWR accident (typically 60% or greater), the Sandia result implies that the increased Cm and Pu releases from a severe accident affecting a W-Pu MOX-fueled LWR could result in a 50% increase in the total number of latent cancers as compared to an LEU-fueled LWR. (For R-Pu MOX, the increase would be significantly larger).

ii) Beyond design-basis accident probabilities

The DPEIS asserts that the substitution of MOX for LEU in LWRs would have no effect on the spectrum of accident probabilities. The document provides no evidence of this, nor does it even discuss a single safety-related issue associated with MOX use. Instead, it again refers the reader to vendor studies, which claim to demonstrate "substantial margins against limiting conditions" for transients involving MOX cores.

However, the situation is not nearly as straightforward as the DPEIS suggests. There are significant outstanding safety issues associated with the utilization of MOX in LWRs, even with partial-core, reactor-grade MOX, which is the only case for which there is industrial-scale experience. *In the case of full-core, weapons-grade MOX, for which there is no industrial experience, numerous additional technical uncertainties with serious implications for safety would arise.*

GESMO, the Generic Environmental Impact Statement on the Use of Mixed-Oxide Fuel in Light-Water Reactors, contained a brief discussion of some of the safety issues associated with partial-core, reactor-grade MOX. However, the document is completely out-of-date and many of the reassuring predictions it made concerning the viability of MOX have not been borne out in practice. For instance GESMO claimed that the issues of plutonium segregation and greater fission gas release in MOX fuel would not be significant; however, today they are major stumbling blocks for the qualification of MOX fuel for high burnups. The increased fission gas release from MOX fuel elements has led the French safety authority, DSIN, to limit burnups of MOX fuel in PWRs to 33 MWd/kgHM, well below that now achieved with LEU fuel, which imposes an economic penalty on the use of MOX in France.22

The DPEIS must include, at a bare minimum, a discussion of these issues at the same level of detail as GESMO, fully updated and with a candid discussion of the remaining uncertainties associated with MOX use in LWRs in the context of W- Pu disposition.

Relative to an LEU core, a MOX core is characterized by the following features: more negative moderator temperature and void coefficients, smaller delayed neutron fraction and prompt neutron lifetime, reduced control rod and soluble poison worths, reduced shutdown margin and greater inhomogeneities in fuel microstructure. Each one of these changes separately can have an adverse effect on safety. In addition, one can posit scenarios in which these changes interact synergistically to greatly amplify their individual effects.

The overall deleterious interaction between these elements can be understood in the following way. The decrease in reactor period associated with the smaller delayed neutron fraction and prompt neutron lifetime is perhaps the most serious issue, since this can result in a significant reduction in the time available for an operator to respond to transients. Because of the relatively small percentage of Pu-241 it contains (which has a larger delayed neutron fraction than Pu-239 and Pu-240), this problem is more severe for weapons-grade plutonium than for reactor-grade, especially at the beginning of cycle, when there is a nearly three-fold reduction in delayed neutron fraction.

For transients associated with an increase in coolant temperature (undercooling transients), such as those initiated by the loss-of-heatsink accident (LOHA) in PWRs, this decrease in stability may be compensated for by the greater negative temperature feedback associated with the greater magnitude of the power temperature coefficient.

However, because of the greater magnitude of the moderator temperature coefficient, the increase in core reactivity associated with a decrease in coolant temperature or increase in coolant density (overcooling or overpressure transients) will be more rapid for a MOX core than for an LEU core. In these events, the change in feedback behavior of a MOX core will aggravate, rather than compensate for, the reduced reactor period, so that the severity of overcooling/overpressure transients will increase. In particular, the reactivity insertion associated with the PWR main steam line break is rapid enough (a minimum of 5�$^{-4}$ /sec for the full MOX case) so that progression of the event is sensitive to the size of the delayed neutron fraction. The rate of reactivity insertion (measured in cents per second) for a full W-Pu MOX core can be ten to fifteen times greater than for an LEU core. The reduced worths of control rods and soluble poisons also increases the risk that the transient will result in a return to power after trip.

The third coupled safety issue is related to the differences in the microstructure and irradiation behavior of MOX as compared to uranium fuel, including inhomogeneities in the distribution of fissile particles in the fuel and significantly higher fission gas release. Current methods of MOX fabrication, such as the MIMAS process in use at the MELOX plant in France, produce inhomogeneous fuel that contains macroscopic plutonium clumps. Furthermore, during irradiation plutonium tends to migrate to the periphery of the central void region.23

This clumping phenomenon, which is very difficult to model, can lead to the formation of "hot spots," which may affect the ability to accurately calculate parameters such as the maximum cladding temperature reached during reactivity insertion accidents (RIAs), and derived thermal-mechanical limits, such as the maximum linear heat generation rate and the fuel rod failure enthalpy. Increased fission gas buildup may also result in decreased failure thresholds for MOX fuel rods during RIAs. Additional uncertainties result from the lack of fabrication and irradiation experience with MOX fuel containing integral burnable absorbers (such as gadolinium), which would be required in MOX fuel for U.S. Ex-LWRs. The effect of gadolinium addition on the microstructure of MOX fuel both before and during irradiation is not known.

At least two of the vendor documents (the only ones we have reviewed) cited indirectly by the DPEIS do not address the issue of determining MOX-specific thermal-mechanical limits, and explicitly assume that they are the same as for LEU fuel.24 This renders its conclusions regarding the acceptability of MOX core response during transients untrustworthy. For instance, the Westinghouse PWR study employs a limiting fuel pellet enthalpy of 200 cal/g in its safety analysis, which is based on a 20-year old study of UO_2 fuel. This limit is considered by Westinghouse "to contain sufficient conservatism to allow [its] application to the MOX fuel." This statement ignores both the fact that the enthalpy limit for irradiated MOX fuel is likely to be smaller than that of uranium fuel at a given burnup, and the fact that the 200 cal/g criterion has recently been called into question even for uranium fuel at high burnups.25 This point is underscored by the fact that the DPEIS, as well as the vendor references, assume that MOX fuel burnups will be significantly higher (e.g. 43 MWd/kgHM for PWRs) than those currently allowed in France.

The magnitude of the increase of overall risk of core damage and catastrophic release if MOX is substituted for LEU in an Ex-LWR is highly plant- specific, as is the relative contribution of various initiating events to core damage in LWRs. In order to get a sense of the issues involved is instructive to look at a few specific cases.

PWRs: Examination of the Westinghouse study on use of MOX in existing PWRs, which is one of the documents upon which the DPEIS bases its assertions regarding MOX safety, reveals that *none* of the safety analyses (e.g. control rod ejection, main steam line break) was carried out for a full MOX core, but only for a partial MOX core. Therefore, the DPEIS is incorrect when it infers that `substantial margins against limiting conditions have been demonstrated' by the vendors for full MOX cores in existing LWRs. For Westinghouse PWRs, this has not been done.

In lieu of an analysis of full core MOX safety, the Westinghouse document provides unconvincing hand-waving arguments for extending results obtained for partial MOX cores to full MOX cores. For example, in the analysis of control rod ejection, Westinghouse claims that that the transient is less severe for a partial MOX than for an LEU core, because the reduced worth of the ejected control rod and the more negative reactivity coefficients more than compensate for the smaller delayed neutron fraction. The report then argues that the full MOX core `would be expected to behave much like a conventional full UO_2 core during a [rod] ejection transient.' However, the full MOX reference case utilizes "hybrid" control rods with enriched boron, which do not have reduced worth compared to the LEU core and therefore do not provide a compensatory effect. Therefore, it is not at all clear that the partial MOX core results can be extended to the full MOX core, which has a smaller delayed neutron fraction than both partial MOX and LEU cores.

Westinghouse does not seem to have solved the problem of reduced shutdown margin in PWRs with full MOX cores. Even with enriched boron hybrid control rods (the reference design), the excess shutdown margin of the full MOX core is significantly smaller than for the LEU core. Westinghouse also appears to have adjusted the minimum shutdown margin requirement for convenience. In its analysis of a full MOX core advanced PWR, which has a shutdown margin of around 4% $\Delta\rho$, it imposes a 1.6% $\Delta\rho$ minimum shutdown margin criterion. For the existing PWR, however, it imposes a minimum shutdown margin of only 1.3% $\Delta\rho$. The reason for this discrepancy is clear: at EOL, neither of the partial MOX core designs would be able to meet the 1.6% $\Delta\rho$ criterion, and the excess margin for the full MOX reference design would be a mere 0.02% $\Delta\rho$, compared to the LEU excess margin of 0.5% $\Delta\rho$. Because of the uncertainties associated with fuel and control rod depletion during full MOX core operation, substantial excess shutdown margin should be a design requirement.

Perhaps the most troubling consequence of the use of MOX in PWRs is the fact that one of the classes of events which are more severe for MOX cores than LEU cores, the overcooling transients, is also the same class which has the potential to cause one of the most dangerous and poorly understood safety phenomena associated with PWR operation, pressurized thermal shock (PTS) failure of the reactor pressure vessel (RPV).[26]

PTS is a phenomenon in which the reactor vessel can undergo catastrophic failure if the vessel remains pressurized during (or repressurizes immediately following) a sudden and significant drop in reactor temperature. In the worst case, this event, can result in a simultaneous failure of all the barriers (the fuel cladding, the RPV itself, and the containment building) to release of radionuclides into the environment.[27] Early containment failure can occur as a result of missile attack from fragments of the exploding RPV or from direct containment heating (DCH) in accident sequences in which partial melting of the fuel occurs prior to RPV failure. Such events are also associated with significant releases of low-volatile radionuclides to the environment, as discussed in the previous section; *thus the substitution of MOX for LEU in Ex-LWRs may result in an increase in both the probability and the consequences of this class of accidents.*

PTS transients can result directly from a large variety of initiating events, including main steam line breaks, small-break LOCAs (e.g. Three Mile Island) and steam generator tube ruptures (SGTRs).[28] Other events, such as instrumentation malfunctions or turbine trip due to loss of offsite power (LOOP), can initiate sequences resulting in PTS as well.[29] In many of these sequences, the time available for initiation of operator action is an important parameter.[30] Since the reduced response time to overcooling transients associated with the substitution of MOX for LEU increases the risk of inadequate or incorrect operator action, the risk that one of these initiating events will progress to PTS may increase as well.

The susceptibility of a reactor vessel to PTS increases with irradiation time as a result of fast neutron embrittlement of the reactor vessel; the PTS risk increases sharply with reactor age. The approach used by the NRC for limiting the risk of PTS in the aging fleet of U.S. PWRs has been to restrict the extent of RPV embrittlement permissible in operating reactors before plant- specific evaluation is required. This is done by comparing PTS "reference temperatures" for base metal and welds, which provide a rough measure of the PTS susceptibility of the RPV with respect to the spectrum of identified overcooling transients, to "screening criteria" defined by NRC. Because of the large uncertainties characterizing initiation and progression of the PTS phenomenon, however, the actual level of risk of core damage and radionuclide release corresponding to the screening criteria, which were set in 1982 and have remained unchanged, is unclear.31

The NRC concluded in 1994 that only two U.S. PWRs would exceed the PTS screening criteria before the end of operating life. However, since that time NRC has apparently lost confidence in the adequacy and completeness of data it has received from operators in support of their compliance with the PTS rule. Reasons for this include new indications of greater uncertainties in the chemical composition of welds than was previously assumed and greater sensitivity of PTS reference temperature to variability of weld composition. Also, accurate analysis of PTS risk is seriously impaired by gaps in the data supplied by operators that result from withholding of information based on proprietary considerations.32

Because of the large uncertainties associated with the PTS phenomenon, the baseline PTS risk of Ex-PWRs is very difficult to assess accurately. The spectrum of initiators includes events of relatively high probability, such as SGTRs (approximately 0.005 per reactor-year) and small steam line breaks (0.02 per reactor-year), which have consequences that depend strongly on operator intervention and therefore may be more likely to progress to PTS in MOX cores than in LEU cores. Moreover, the increased flux of fast (> 1 MeV) neutrons associated with the substitution of MOX for LEU (approximately 6%) can accelerate RPV embrittlement. This suggests that *the overall risk of PTS may be substantially greater in MOX cores. Therefore, the PTS screening criteria now in use may not be appropriate for MOX cores and will have to be reevaluated. Determination of the impact of MOX fuel on the risk of PTS will require detailed, MOX-specific analyses of PTS precursor events.*

BWRs: In BWRs, the PTS risk is believed to be considerably smaller than that in PWRs. However, there are BWR-specific safety issues associated with MOX use as well. Probabilistic risk assessments such as NUREG-1150 have shown that core damage in typical BWRs is dominated by station blackout events. In this category is the turbine trip without bypass event, a loss-of-heatsink accident (LOHA) associated with overpressure transients and void collapse. This is one of the most limiting transients that can affect a BWR, and it is also one which is more severe for a MOX core, as discussed above. Thus *the overall risk of core damage in BWRs will increase if MOX is substituted for LEU.*

iii) The role of economics in safety assessment

An accurate assessment of the PTS risk associated with MOX use in Ex-PWRs is also closely related to reactor-specific economic issues, which are not addressed in the DPEIS. For instance, the risk may be reduced by annealing the reactor vessel, a procedure that is not anticipated to be very costly (about $20 million) but which nonetheless has been resisted to date by the PWRs identified as being of greatest PTS risk, such as the Palisades plant in Michigan. If DOE decides that the PTS risk should be mitigated by annealing the RPVs of Ex-PWRs chosen for Pu disposition, both the cost and the associated worker radiation exposure will probably have to be borne by the disposition program.

The degradation of steam generators (SG) in PWRs raises a similar issue. Some of the utilities which have responded to DOE's solicitation of Expressions of Interest have offered the use of PWRs which are known to be operating with severely degraded steam generators (Kewaunee). The operator of Kewaunee has opposed steam generator replacement (at a cost of approximately $100 million) on economic grounds. However, given the large contribution of SGTR events to overcooling and PTS transients, it would be unwise to pursue MOX disposition in these reactors without SG replacements. Again, the cost would probably have to be charged to disposition, since plants like Kewaunee are determined not to replace their steam generators. Charging the occupational exposure of SG replacement, typically about 150 person-rem, would increase the total incremental occupational exposure associated with the Ex-LWR MOX option of 27.2 person-rem per reactor listed in the DPEIS (Vol. II, Table 4.3.5.2.9-2, p. 4-690) by a factor of greater than five.

Another area in which safety and economics interact concerns the allowable MOX fuel burnup. *Utilities are going to expect to be compensated for MOX- related issues that impair the reactor performance. Restriction of MOX burnups to well below LEU burnups, as is the case now in France, will have economic consequences and affect the cost of the MOX option. The calculus that will be used to balance the safety issues associated with high MOX burnups and the economic penalty is not addressed in the DPEIS.*

3. Conclusions

The DPEIS does not contain sufficient information to consistently compare the occupational and public health and safety impacts of the immobilization and MOX options. To correct this problem, the final version should include:

A full evaluation of the incremental health and safety impacts of the can-in- canister (CIC) immobilization options, both for routine operation and for accident conditions.

A full evaluation of the incremental health and safety accident impacts of the existing LWR and CANDU MOX option, taking into account the specific properties of full-core, weapons-grade MOX fuel and potential differences in the probabilities and consequences of accidents relative to LEU fuel, as well as specific issues (e.g. pressure vessel embrittlement) pertaining to the physical condition and operating history of existing reactors which are candidates for the program.

A revision of the accident impact analysis of the evolutionary LWR option, taking into account the specifics of MOX fuel as described above, and using a more realistic source term for loss-of-containment accidents.

In all parts of the analysis, outstanding uncertainties should be clearly identified and their magnitudes estimated.

End Notes

1. *Storage and Disposition DPEIS*, Attachment B, Pg. S-150. Back to document

2. *Storage and Disposition DPEIS*, Section M.5.1.1.2, p. M-226. Back to document

3. *Storage and Disposition DPEIS*, Section M.5.1.1.1, p. M-225. Back to document

4. DPEIS, Volume II, pg. 4-690. Back to document

5. Personal communication with General Electric executive, September 1995. Back to document

6. DPEIS, Volume III, Appendix M, Table M.5.3.8.1-2, p. M-361. Back to document

7. LLNL 1996g, op. cit, Table 8-1, p. 8- 10. Although the Cs-137 value cited above is reasonable, one should note that this table is otherwise unreliable, with some entries clearly wrong (e.g. a core inventory of 5.4 105 Ci, or 8.7 MT, of Pu-239, is given for a LEU-fueled Ev-LWR), and others inconsistent with values given in the DPEIS (for instance, a release of 4.4 106 Ci of Kr-85 is postulated in the DPEIS, whereas the core inventory in Table 8-1 is only 1.2 106 Ci). Inconsistency among the various source documents is a general feature of the DPEIS. Back to document

8. LLNL 1996g, Table 8-5, p. 8-14. Back to document

9. Although one of the main references for the DPEIS section on Ev-LWR safety is a document (Evolutionary/Advanced Light Water Reactor Data Report, UCRL-ID- 123411, February 1996), which does contain some discussion of the differences between MOX and UO2 source terms, this information is apparently not used in the DPEIS for the development of accident risk values. Instead, data from two other documents which refer exclusively to UO2-fueled LWRs are used. Back to document

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11. L. Devell et al. "The Chernobyl Reactor Accident Source Term: Development of a Consensus View," OECD/NEA, OECD/GD(96)12, November 1995. Back to document

12. US Nuclear Regulatory Commission, NUREG-1150, 1987. Back to document

13. U.S. Nuclear Regulatory Commission, "Accident Source Terms for Light-Water Nuclear Power Plants," NUREG-1465, February 1995. Back to document

14. H. Nourbaksh, "Estimation of Radionuclide Release Characteristics Into Containment Under Severe Accident Conditions," U.S. Nuclear Regulatory Commission, NUREG/CR-5747, Nov. 1993. Back to document

15. US NRC Advisory Committee on Reactor Safeguards, letter to NRC Chairman Ivan Selin, September 20, 1994. Back to document

16. U.S. Nuclear Regulatory Commission, "Proposed Issuance of Final NUREG-1465," SECY-94-300, December 15, 1994. Back to document

17. D. Osetek, "Low Volatile Fission Product Release During Severe Reactor Accidents," Los Alamos Technical Associates, Inc, Albuqurque, NM, prepared for the U.S. DOE Idaho Operations Office,DOE/ID-13177-2, October 1992. Back to document

18. M. Allen et al. "Fission Product Release and Fuel Behavior of Irradiated Light Water Reactor Fuel Under Severe Accident Conditions: The ACRR ST-1 Experiment," NUREG/CR-5345, Sandia National Laboratories, November 1991. Back to document

19. Ibid. Back to document

20. DPEIS, Vol. 2, Sect. 4.3.5.2.9, pg. 4-690. Back to document

21. D. Alpert, D. Chanin and L. Ritchie, "Relative Importance of Individual Elements to Reactor Accident Consequences Assuming Equal Release Fractions," NUREG/CH-4467 (SANDIA85-2575), Sandia National Laboratories, Albuquerque, March 1986. Back to document

22. A. MacLachlan, "New French RIA Tests Suggest Better Resistance of High-Burnup Fuel," N*uclear Fuel*, September 11,1995, p.1. Back to document

23. A. MacLachlan, "French Working to Improve MOX Performance and Economics," *NuclearFuel*, November 6, 1995, p. 8.Back to document

24. GE Nuclear Energy, "Study of Plutonium Disposition Using Existing GE Advanced Boiling Water Reactors," NEDO-32361, June 1, 1994; Westinghouse Electric Corporation, "Plutonium Disposition in Existing Pressurized Water Reactors," DOE/SF/19683--6, June 1, 1994, p. 2.1-69. Back to document

25. Ann MacLachlan, "EDF, DSIN Square Off on License for Burnups Beyond 47,000 MWD/MT," *NuclearFuel*, July 29, 1996, p.9. Back to document

26. U.S. Nuclear Regulatory Commission, "Reactor Pressure Vessel Status Report," NUREG-1511, December 1994. Back to document

27. J. Collier and L. Davies, "Second Marshall Report Gives Grounds for Confidence," *Nuclear Engineering International*, May 1982, p. 30.Back to document

28. NRC, NUREG-1511, op cit., p. 4-2. Back to document

29. U.S. Nuclear Regulatory Commission, "Pressurized Thermal Shock," SECY-82-465, November 1982. Back to document

30. Ibid, p. 6-5. Back to document

31. Comments of David Okrent on SECY- 82-465, member of NRC Advisory Committee on Reactor Safeguards, October 14, 1982. Back to document

32. U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, NRC Generic Letter 92-01, Revision 1, Supplement 1: Reactor Vessel Structural Integrity, May 19, 1995.Back to document

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nci@mailback.com