# What Criteria Would Govern the Disposal of Immobilized Plutonium?

**Allison Macfarlane, Belfer Center for Science and International Affairs, Harvard University**
**Edwin Lyman, Nuclear Control Institute**
**Mycle Schneider, WISE, Paris, France**

**David Albright:** I have an announcement to make: We have changed the format of this panel from what was presented on our agenda. This idea put forth by the "ÖKO-Institute" has come up a number of times in this conference, and while we invited ÖKO representatives to come to this conference, they, unfortunately, were tied up with other matters, and expressed their regrets that they couldn't attend.

The original idea was that I was just going to say a few words about their immobilization proposal. I think, in a sense, it's a departure from what people think of when they think of immobilization. But what we've decided to do is to ask Mycle Schneider to briefly talk about it, and give some of his reactions to it.

Allison Macfarlane, who I'll introduce in a second, was also at the Jülich meeting, which we have heard about. She will give some of her reactions to it. This will all take place after Allison gives her primary address. But that is only one aspect of this panel, and we are going to try to cover a lot between now and 3:15 pm.

The first speaker, as I mentioned, will be Allison Macfarlane. She is currently a Science Fellow at the Belfer Center for Science and International Affairs at the Kennedy School of Government at Harvard University. There she specializes in the technical aspects of nuclear policy issues, particularly fissile material controls, disposition, and high-level waste management. Prior to joining the Belfer Center she was a professor of geology at George Mason University for five years. She has also held a number of fellowships.

Afterwards, we will hear from Ed Lyman. Ed has been Scientific Director at the Nuclear Control Institute since 1995. Previously he was a post-doctoral research associate at the Center for Energy and Environmental Studies at Princeton University. Throughout his career, his research focus has been on nuclear materials management and nuclear power plant operations.

The third person is Mycle Schneider, who is the chief editor of *Plutonium Investigation*, and the Director of WISE-Paris. For some 20 years he has worked on nuclear power issues, reprocessing issues, and is also published quite widely. And, given the short notice, I want to especially thank him for taking my place on this panel.

**Allison Macfarlane:** Thank you for the introduction, David. I am very happy to address this conference. However, I hate to burst everybody's bubble of expectation, but I think my talk is going to be a little anti-climatic. I come to report that the National Academy panel that I sit on, and that you're all waiting to hear the results of, has not issued its final report yet. So I can't tell you what's in the final report, because it hasn't gone through the review process. But I will go over what we're thinking right about now in terms of the interim report.

But that's just part of what I'm going to talk about today. One thing that I'm going to do is open up the conversation that we are having to include a discussion of other immobilization options as an

alternative to MOX for plutonium disposition. I also want to talk about the criteria for immobilizing plutonium in a larger framework than we've been talking about so far today.

So, with those remarks, let me begin by observing that when a nation plans to dispose of its stockpiles of separated plutonium—civil or military—it should have in mind criteria to distinguish among the different available options. I like to think of these criteria as divided into the short term and the long term. For example, if you have plutonium oxide stored in containers, the material poses very different security and safety risks than spent MOX fuel—over both the short term and the long term. So, I'm going to try to discuss methods to differentiate different disposition methods based on safety and security risks over both the short term and the long term today.

First, I define the short term as the next 100 years or so. This is the span of time in the future over which we can plausibly imagine scenarios playing out. Then there's the long term, which is very important as well. This is defined more in the geologic sense, and so here we're talking 1,000, 10,000, or one million years into the future.

In the short term, a nation's goal in disposing of its stockpiles of plutonium should be proliferation resistance—in addition to safe and cost-effective production, of course. But meeting the spent-fuel standard is only part of the picture, as I'll soon discuss. In the long term, a nation's goals should be to protect the population and the environment from radiation doses. A waste form is less likely to pose a radiation dose hazard if it's chemically durable and resistant to radiation damage, and I'll talk about that more in a minute.

So, first I'm going to talk about the short term, but I want to emphasize: It is of little use to plan for the short-term aspects of plutonium disposition only to find out that the plan you've chosen is a failure in the long term. In other words: You don't want to spend your money twice, so you better think about it all ahead of time.

So here we are in the short term. Now, we're going to talk about the spent-fuel standard as part of the short-term criteria for immobilizing plutonium. And, as I think Professor Pigford pointed out this morning, contrary to our wishes, it is basically impossible to immobilize plutonium in a form from which it could never be extracted and used again as bomb material. So, we need to follow some guidelines to make it as proliferation resistant as possible, but it's impossible to make it completely proliferation resistant.

In the fall of 1998, the National Academy of Sciences convened a panel, as requested by the Department of Energy, to clarify the spent-fuel standard, and to apply it to the Department of Energy's two prospective waste forms: spent MOX fuel and the can-in-canister immobilized plutonium option. The panel is to judge whether these options do, in fact, meet the spent-fuel standard. Here comes my apology to Bill Danker: I'm not going to give you formulas, and there are not going to be formulas in the final report, either. Unfortunately, this is not something where we can plug some numbers in and come out with an answer. I think that there are a lot of judgments involved.

But let me just go over the spent-fuel standard. You're probably all aware of it. The spent-fuel standard is basically to make plutonium—in this case, plutonium from weapons—roughly as inaccessible for weapons use as the much larger and growing stock of plutonium in civilian spent fuel. The spent-fuel standard does not ensure proliferation resistance, but instead it ensures that plutonium that meets

the spent-fuel standard poses no additional risk to that already posed by the plutonium in spent fuel. John Holdren, the chair of the NAS panel, likes to use this image of an outcropping of military plutonium relative to plutonium that's in spent fuel, and the spent-fuel standard just ensures that that outcropping is gotten rid of, and that we're all at the same level.

The spent-fuel standard does not provide adequate protection for spent fuel itself, or for the other waste forms that meet it. Just because something meets the spent-fuel standard does not mean that it's adequately protected. Plutonium in spent fuel isn't the end point here.

Another point to make is that handling and processing of plutonium to forms that satisfy the spent-fuel standard may entail greater proliferation risks than posed by the final form. You need to judge whether or not the end form is worth the risk of getting there.

Finally, the point that we really want to re-emphasize in this report, and it'll be re-emphasized in the final report, is that the spent-fuel standard depends only on intrinsic properties of the immobilized waste form. In other words, engineered and institutional safeguards may be added—and in fact are very necessary—but they are not considered in determining whether or not a waste form meets the spent-fuel standard.

Next, I'm going to explain how we have formulated a matrix that will help us to determine whether or not a form meets the spent-fuel standard. In thinking about this, the panel decided that we would have to consider a number of different threats, and not just one general threat. So in our report we defined three different threats, looked at the properties of the waste form and the relevant characteristics of the plutonium waste form, and judged how these properties are different for each of the kinds of threats.

So, as you see, we have three threats: host nation, proliferant state, and proliferant group (figure 1). We assume, for a host nation case, that they would be interested in getting a large amount of plutonium. For a proliferant state case, they would be interested in a moderate amount, and for a proliferant group they would be interested in a small amount of plutonium.

**Figure 1: Criteria for Meeting the SFS -- Potential Threats**

| Host Nation | Proliferant State | Proliferant Group |
|---|---|---|
| Large amt. of Pu | Moderate amt. of Pu | Small amt. of Pu |
| No limits on access to waste forms | Steal material by stealth or force | Steal material by stealth or force |
| High capability to extract Pu | Moderate capability to extract Pu | Mod-low capability to extract Pu |
| High performance requirements for weapons | Moderate preformance requirements for weapons | Low performance requirements for weapons |

For the host nation, there would be no limits on the access to the waste forms. They could take them quite easily. For both proliferant states and proliferant groups, they would have to steal materials by stealth or by force.

A host nation would probably have a high capacity to extract plutonium, a proliferant state would have a moderate capacity, and a proliferant group would have a moderate to low capacity.

In terms of the weapons that would be made from this material, we assume that a host nation would have high performance requirements for the weapons, a proliferant state would have moderate performance

requirements, and a proliferant group would have low performance requirements. So these are the definitions that we're starting with.

So now that we've defined who the threats are, we want to look at the barriers to those threats, depending on the step in the proliferation process. The barriers will be different depending on the threat. Very briefly, I want to run through these barriers for different steps in the process, and highlight those that we think are very important for different threats. If you want to know what we think about all the threats, you can look at the matrix that we published in the interim report; it is available on the National Academy's website.

First, we have barriers to the acquisition of the waste form at the storage site. These would be the mass of the item—and by "the item" we're referring to the waste form, itself. Other barriers are: the dimensions of the item, the concentrations of the plutonium in the item, the radiation barrier of the item, the difficulty in separating the waste form from the bulk of the item and detectability—in other words the chemical, thermal, or nuclear signatures given off by the item.

We've judged that the concentration of plutonium in the item is important for both proliferant states and groups. The difficulty in separating the waste from the bulk of the item is also important for proliferant states and groups, and detectability is also important for proliferant states and groups. So those are the most important factors in this particular step in the process of getting plutonium.

The next set of barriers concern the separation of plutonium from dilutants and fission products in the waste form. These barriers include: the amount of material to be processed, the technical difficulty of physical disassembly, the technical difficulty of dissolution, the technical difficulty of chemical separation, radiation criticality and toxicity hazards, and again detectability—the chemical, nuclear and thermal signatures.

We have judged that the amount of material to be processed would be important for all threats, the technical difficulty of dissolution and of chemical separation would be important for a proliferant group, and detectability would be important for proliferant states and groups.

Finally we have a barrier to the use of plutonium in weapons—namely, the isotopic composition. We have not judged this barrier to be highly important for any particular group.

Now, I'm going to just run through what we're using as our basis for comparison. Since this is the spent-fuel standard, our basis is spent fuel. In particular, it is your average spent LWR fuel assembly. So for a boiling water reactor, this would be something that's four meters in length, 15 centimeters on a side, and a mass of about 250 kilograms. For a pressurized water reactor, we're talking about something that's four meters in length, 25 centimeters on the side, and a mass of about 670 kilograms.

Determining the radiation barrier that we're using for comparison is a little complicated. The original idea was to look at fuel assemblies about 30 years after irradiation, because we figured that the immobilized waste forms would not be produced until about ten years from now. And if we look at when that waste form is about 10 years old, that would correspond to when the bulk of the U.S. spent fuel would be about 30 years old. For 30 year-old spent fuel that was irradiated to 33 GW-days per tonne, the gamma ray dose at one meter from the midpoint would be about 800 rem per hour. The plutonium content for that kind of spent fuel would be about 2.5 kilograms for boiling water reactors, and about 6 kilograms for pressurized water reactors.

The idea is that we're going to make a matrix, with all these different barriers, list these different conditions here for these quantities for spent fuel, and compare these to the quantities for the waste form, whatever the waste form is.

So now for the burning question: Do the DOE waste forms meet the spent-fuel standard? I'm not going to give you a solid yes or no on anything here, except to say that perhaps MOX light-water reactor fuel appears, for the most part, to meet the spent-fuel standard. The one thing that may not meet the spent-fuel standard is CANDU MOX, because currently it is small, light, and does not have a very high radiation barrier. However, this option is still under discussion for the final report.

Does the can-in-canister form meet the spent-fuel standard? Since the interim report was released, we've acknowledged—this is a little view into the final report—we've acknowledged that the DOE has made a newer, hardened design of the canister. But as we say in the interim report, we still don't have any experimental evidence over the difficulty of extracting plutonium from the can-in-canister design using an energetic attack, because there's no experimental data on that.

The panel has discussed possible fixes to the can-in-canister design. I've included these possible fixes—not because they'll be in the final report, and not because the Academy is necessarily going to recommend any of them—just to open up a discussion of alternative waste forms, because we are talking about civilian plutonium at this conference. We haven't decided as a panel whether any of these different forms would meet the spent-fuel standard certainly, so I'm just throwing these out there as alternative ideas.

One fix is to decrease the plutonium concentration in the waste form. This really isn't an option for the Department of Energy, because this would increase the costs greatly.

Another possible fix is to add cesium directly to the pucks. That wouldn't happen for the DOE because it would greatly increase the cost and time over which you would create this material.

Something that might be considered by other countries, if they're going to consider the can-in-canister option, would be making ceramic pellets and putting them in a mesh, rather than doing cans in canisters. Alternatively, you could try to add some material that would enhance the detectability of this.

Now, I want to turn to other criteria that should be considered in the short term for immobilizing plutonium. These already have been discussed today to some degree. First, the maturity of the production technology is important, as are cost and safety. These were important factors in the DOE decision between glass and ceramic. In addition, other criteria are radiation doses to workers, criticality issues, transparency and verification issues, and—I've added one of my own—the flexibility of the waste form.

What I mean by flexibility is that a lot of waste forms, including can-in-canister, lock you into one line in the end; you're not going to do anything with that plutonium except probably throw it into a hole in the ground. However, there are other waste forms out there that you could actually burn in a reactor if you wanted to at some later date, like inert fuel matrices, which I'll talk about more in a minute.

So let's turn to the long term, where I'm looking at repository issues for the most part. Again, although I think its absolutely essential that we pay close attention to short-term considerations on proliferation risks posed by immobilized plutonium, I think it would be a waste of money and effort to design a proliferation-resistant waste form only to discover, once in the repository, the plutonium

leaches from its waste form relatively rapidly and contaminates the ground water. I think we should use the insight we have available to us at this time—and, I must say, I think it's quite substantial—on the long-term performance of waste forms.

So I think that there are three criteria that we should really pay attention to in the long term. The first is criticality in the repository. Plutonium 239, as you know, decays to uranium 235. If enough uranium 235 migrates to an area in a repository, and there's enough water around, you could have a criticality event, which would disperse fission products into the ground water. This problem is solvable by adding uranium 238 to your waste form. Now, to do this, your waste form has to be able to accept a lot of uranium; this is one of the problems with the types of glass that DOE was considering—they couldn't incorporate enough uranium.

Radiation damage is another criterion that is very important. Radiation damage—basically, in a crystalline material, alpha particles disrupt the crystalline structure. In a non-crystalline material, it's not exactly clear what alpha particles do, but they do create helium bubbles. In the end, for both crystal and non-crystalline materials, you get a volume increase, which will cause cracking, an increase in surface area, and lead to a more rapid leaching of material. So you want to avoid a material that's damaged by radiation.

Finally—and I think it is most important—you want a material that is very chemically durable, that is not going to break down over a short period of time. You don't want radionuclides leaching rapidly into the ground water.

So, let me just present you very briefly, in the last few seconds here, with my favorite suggestion of the month—inert matrix waste forms. By that I mean materials such as zircon, zirconia, apatite, monazite, pyrochlore, or zirconolite. I'm going to focus here on yttria-stabilized zirconia. These are stable waste forms that can also be used as reactor fuel—not plutonium-producing reactor fuel, but actually plutonium-burning reactor fuel. Now, if you don't want to use this waste form as reactor fuel, you don't have to. All you have to do is add neutron poisons, such as gadolinium or hafnium, which this waste form will readily accept. So you can choose to do whatever you want to do with it.

Figure 2 on the facing page compares MOX and zirconia as immobilized waste forms for plutonium disposition.

You can definitely add neutron poisons to zirconia; in fact, natural zirconia exists with a lot of hafnium in it. It's not clear whether you could add these neutron poisons to MOX, if you want to make sure if a MOX form cannot be used in a reactor. In terms of method of production, MOX, of course as we've heard, and we all know, is very mature, and is produced by the cold-press-and-sinter method. Zirconia could be produced by a number of different methods, including cold-press-and-sinter. It is not mature at an industrial scale, but I think that it would be quite possible to adapt existing MOX facilities to make zirconia by the cold-press-and-sinter method.

In terms of proliferation resistance, and here I mean ease of chemical extraction of plutonium, its more difficult to extract plutonium from MOX than it is to extract it from spent fuel, but of course, how to do this is available in the literature. Extraction of plutonium from zirconia is less straightforward than MOX. Again, this material is in the literature, so it provides maybe a little more proliferation resistance.

Finally, in the long term, the problem with MOX is that it oxidizes. As we've heard earlier, although you may have a reducing environment for your geologic repository, you still may have localized oxidizing conditions. Thus, the material may oxidize, and thus MOX is not a good long-term waste form. In contrast, zirconia is very resistant to oxidation, and it is the most chemically durable of all the waste forms that we know of.

**Figure 2: Comparison of MOX and Zirconia**

| | MOX | Zirconia |
|---|---|---|
| ***Short Term Considerations*** ~~ | | |
| Chemical formula | $UO_2 + PuO_2 + U_3O_8$ | $(Zr, Y, Pu, U, Gd, Hf)O_2$ |
| Neutron poisons | Add Hf, GD to $PuO_2$; requires research | Hf, Gd |
| Method of production | Cold Press and Sinter | Hot Isostatic Pressing; Cold Press and Sinter; Sol-Gel Press |
| Maturation of production technology | Mature on an industrial scale | Not mature on an industrial scale |
| Ease of chemical extraction of Pu | More difficult than simple PUREX process, but procedures readily available in open literature | Less straightforward than extraction from MOX, but not unkown; procedures are available in the open literature |
| ***Long Term Considerations*** ~~ | | |
| Oxidation under repository conditions | $UO_2$ and $U_3O_8$ will oxidize; $PuO_2$ is fairly resistant | Resistant to oxidation |
| Chemical durability | Not durable if oxidized | Very durable |
| Radiation Damage | Very resistant to radiation damage | Very resistant to radiation damage |
| Natural Analogues | Uraninite | Baddelyite |

So, in conclusion, just my plug for zirconia here, I think that it may be as easy to produce as MOX, it is slightly more proliferation resistant than MOX, it's more chemically durable than MOX, and it's more flexible than MOX. If you don't want to lock yourself into throwing this material away, don't add neutron poisons to it, and you can keep it around and store it. If you store this material for a while, and you decide that you need to use the energy potential of plutonium, you could do so, you could burn it in a reactor. If you decide that the radiation barrier surrounding the plutonium is not adequate anymore, you could also burn it in a reactor. So, this waste form offers you flexibility.

And I'll end there.

**Ed Lyman:** I was asked to comment on criteria, but since this is my only chance at the podium, I would like to make some more general comments as well. I don't think that it has been driven home that we do need an immobilization alternative for civil plutonium stockpiles. In a sense, I think that Sandy Spector made the case for it, but I'd just like to drive home that the MOX industry has a big credibility problem right now, stemming from the collapse of the BNFL MOX producing dynasty and the resignation of its CEO, the suspension of Japanese MOX contracts with BNFL, and the shut down of a reactor in Germany to unload BNFL-produced MOX fuel. There is a big risk, I think, that the so-called MOX solution to the reduction of these ever-growing stockpiles is going to be viable in the near term, and an alternative really is needed.

I'd just like to make one other point: Why is quality control so essential? Well, it is really tied to the operating safety of the reactor. I'd just like to briefly show the results of a study I did.

**Figure 1: Consequences of Severe Accidents at the Takahama Plant (Pu RF=plutonium release fraction)**

| | LEU | RG-MOX | | RG-MOX/LEU Ratio | |
|---|---|---|---|---|---|
| Source term: | | full core | 1/4 core | full core | 1/4 core |
| Pu RF=0.01 | | | | | |
| Latent cancer fatalities | 11,700 | 56,800 | 24,200 | 4.85 | 2.09 |
| Prompt fatalities | 75 | 265 | 133 | 3.53 | 1.77 |
| Pu RF=0.035 | | | | | |
| Latent cancer fatalities | 31,900 | 155,000 | 70,700 | 4.86 | 2.22 |
| Prompt fatalities | 417 | 2,420 | 827 | 5.80 | 1.98 |
| Pu RF=0.0014 | | | | | |
| Latent cancer fatalities | 6,090 | 15,900 | 8,630 | 2.61 | 1.42 |
| Prompt fatalities | 40 | 64 | 44 | 1.60 | 1.10 |

Here (figure 1) I evaluated the consequences of a severe loss-of-containment accident at a pressurized-water reactor fueled with reactor-grade MOX, and compared it to the consequences if only low-enriched uranium fuel were used. I looked at a range of possible release fractions, depending on the severity of the accident. We see that, generally speaking, for a one-quarter core—as at the Takahama Plant, which is the first plant in Japan that was supposed to have MOX fuel loaded—the results of my calculations show that there is more than a doubling of the number of latent cancer fatalities that would result from a loss-of-containment accident. In Japan, which is densely populated, this corresponds to additional tens-of-thousands of cancer deaths. In addition, the number of prompt fatalities would roughly double for two of the cases. This corresponds to dozens of additional prompt fatalities, similar to the terrible death suffered by Mr. Ouchi after the Tokaimura accident on September 30, 1999.

This is due to the greatly increased actinide inventory in a light-water reactor fueled with MOX. For these reasons, I really do believe that we need an alternative that does not involve irradiating MOX in a reactor, and thus avoids these potential risks.

Now, on the question of the spent-fuel standard. We've heard two different perspectives on different immobilization options. One is the interim report of the National Academy's opinion of the can-in-canister method. I believe that their opinion is not going to be changed at the time of the release of their final report. The NAS is concerned by the absence of experimental evidence that the can-in-canister waste form is robust enough to withstand certain types of scenarios, in which a diversion could occur at the storage site by separating the highly radioactive matrix from the inner cans, which themselves do not have intrinsic fission-product barriers. So on the one hand, we see a really stringent criticism of can-in-canister, which, as Mr. Danker pointed out, resulted from a trade off between getting a system up and running, by using existing facilities to cut costs, and having a rigorous and intimate mixture of fission products and plutonium.

On the other hand we have a proposal that came out of Germany. The "ÖKO-Institute" proposal is based on the presumption that the spent-fuel standard is not an essential objective of long-term storage and final disposal. The proposal makes no attempt to try to integrate plutonium—the so-called "storage-MOX rods"—with fission products. There are two different options: One is simply storing spent fuel assemblies next to the storage-MOX assemblies, in which case there is no technical barrier to separating the unirradiated material from the irradiated forms. The other option is to take a spent fuel assembly and actually substitute some pins with storage-MOX into it. In this way, you

could have a waste form that's harder to disassemble, but still not impossible—you could use the same equipment for disassembly that you used for assembly.

So we have two really different points of view. One is a criticism of can-in-canister, in which some analysts claim—in spite of the fact that the cans of plutonium are fused to highly radioactive glass inside a very large heavy waste form—that a terrorist could break them apart with ease at a storage site. The other view is based on a much more liberal interpretation of the spent-fuel standard, where simply storing spent fuel and plutonium together in a cask provides adequate self-protection.

So where is the truth in this? My own opinion is that it's somewhere in between. In other words, I think the can-in-canister option does provide adequate proliferation resistance, and does not really require any further experimental testing. On the other hand, I do not think that the "ÖKO-Institute" proposal, while interesting at this point, provides adequate long-term proliferation resistance.

I think the spent-fuel standard is a good idea and should be maintained. Considering to the issue of can-in-canister, scenarios were identified by Sandia National Laboratory in which someone could apply shaped charges to these high-level waste canisters, blow them apart, and then somehow scurry after and pick up the plutonium cans and run away with them. Then, since the cans have been freed from the radiation barrier, one can process them with minimal shielding. Disassembly of the waste form at the storage site was referred to by Professor Macfarlane as a high barrier for both subnational groups and terrorists who are working in the interests of other states. This was regarded as a high barrier—the physical inability to actually go into a storage area and somehow separate the plutonium you want from the fission products. But my question has always been: Have they really identified credible, realistic scenarios where you could actually do this in a storage facility? Can you really expect that a terrorist would be able to unload high-level waste canisters with a very high radiation dose-rate, apply shaped charges to the surface of the canisters, detonate them, thereby scattering highly radioactive glass dust and volatilized cesium into the storage area? I mean, the ambient radiation in this building would reach dangerous or even disabling levels. It is hard to see why this would be considered a more credible thing to do than to try to reprocess spent fuel with hand tongs.

I think that Lawrence Livermore National Laboratory—which has a stake in this of course, since they were the designer of this approach—feels that Sandia never really defined credible or realistic scenarios, and I'd have to concur with that. I think that it is harder than they give it credit for.

On the other hand, by the same logic, if you look at this one barrier, which is the difficulty of mechanical disassembly at the storage site, we can see that the storage-MOX idea certainly does not meet it in a very robust way. I think that can-in-canister actually provides a more viable model for the disposition of civil plutonium stockpiles—for instance, for the foreign owned plutonium that's accumulating in France, which is reaching 40 tonnes. I would then consider that, and start to seriously examine options by which the can-in-canister approach could be implemented in France using the R7 and T7 plants, and additional MOX fabrication capacity, which could be modified to produce pucks containing plutonium. There are a number of varieties that can be considered. For example, you could either make storage-MOX, and then combine that with the can-in-canister, you could use different types of ceramic formulations, and you could modify the processes to some extent. There are a number of things that can be considered. One thing that all of them would have in common is that you would need to construct a frame—you would have to modify the R7/T7 process so that you could introduce a frame and load the plutonium pucks into the canisters.

The one modification that would be needed is that operators would have to be able to handle plutonium materials at the site where the high level waste canisters are filled and welded. Based on the U.S. experience, something like 15 percent of the volume of a high level waste canister could be displaced by the frame and the inner plutonium canisters, without affecting the pouring of the glass. Based on that observation, and on the 10 percent plutonium loading in the ceramic, you could get about 15 kilograms of plutonium in an R7/T7 high-level waste canister. Since about 400–450 of those are produced each year at R7 and at T7, you could immobilize about six tonnes a year in the existing plants.

Some have raised the issue of whether or not there is enough separated cesium around to immobilize the world's stockpile of excess civil plutonium. Do we have to reprocess spent fuel to produce cesium to immobilize separated plutonium elsewhere? It seems senseless, but in this context it may make sense, because France is separating plutonium owned by foreign customers and the French domestic utility, so at least the foreign customers can make their own business decisions about what they want to do with the plutonium that they may not be able to incorporate into MOX. And assuming that France will continue its own plan and reprocess at UP2, that high-level waste could be used to immobilize the surplus plutonium that the foreign customers no longer want in the form of MOX.

This proposal could actually save money, given that you're trading off the storage costs, which range from like $1–4 per gram per year. These costs add up when you're talking about a 40-tonne stockpile. There are also reduced transport costs. Now, all the countries that have reprocessed spent fuel in France and the UK have to bring back both the plutonium and the high-level waste. If you combine the two you're going to reduce the number of shipments, so that's another cost saver.

My final candidate for a pilot project for can-in-canister would be the eight fuel assemblies which are now stuck in Japan that were due to be loaded in the Takahama plant. Japan wants to send the assemblies back to the UK, but the UK would rather not have to repeat, in reverse, the very high-profile, expensive shipment to Japan, which involved two ships, each equipped with machine guns riding shotgun. They prefer not to have to do that.

So, I would propose that these assemblies be used as a pilot project. The eight fuel assemblies could be disassembled at one of the fuel production plants at Tokai, and the Tokai vitrification plant—which I believe has accumulated backlog of high-level waste because it hasn't been operating steadily—could be used to test the viability of the can-in-canister for this material, thus solving the problem that both Japan and the UK have right now.

Thanks.

**Mycle Schneider:** Thank you, David. Again, I'm just jumping in, so this is not a prepared presentation. I just quickly want to give you an idea about the "ÖKO-Institute's" concept (figure 1).

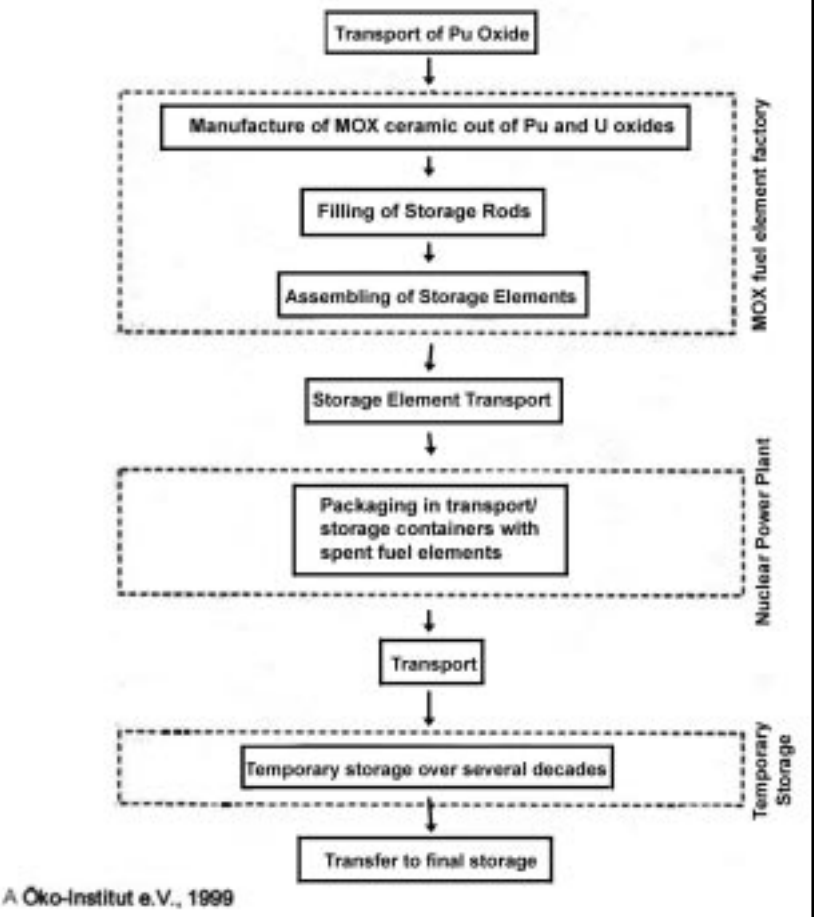
The basic idea is to make storage pins or storage rods of plutonium for final disposal. The basic steps are very much the same as the normal process in a MOX fabrication facility. Your output is a ceramic of plutonium and uranium dioxide—preferably depleted uranium. You have pellets that would be introduced in rods, and then you assemble the storage rods as elements—storage elements. These steps would take place in an existing MOX fuel fabrication facility.

Then the elements would be transported to a nuclear power plant where they would be loaded into transport and storage casks, and mixed with spent fuel elements to present a radiological barrier. The

casks loaded with storage elements and spent fuel then would be shipped to an intermediate storage facility, and eventually to a final storage facility, along with spent fuel.

There were some questions raised at the workshop in Jülich in January 2000, some of which have been raised by Allison already. Proliferation resistance is one point, of course. However, the shipments of the storage elements are essentially comparable to fresh MOX, so you would have to apply similar physical protection measures as in the case of fresh MOX. Regarding interim storage, it really is a bit questionable as to whether or not this storage would be dry or wet. If you bring the storage elements back to the nuclear power plant, the question is: Would they be stored in the pools, or would they be stored in dry storage? It wouldn't be exactly the same analysis for proliferation resistance. I would be curious to get a few comments out of this audience on that question.

**Figure 1: Storage Rod Procedure with Manufacture of Storage Elements [1]**




[1] Original appears in Keuppers, Liebert and Sailer, "Alternative Measures for Processing Plutonium," paper prepared for the plutonium workshop, Jan. 13-14, 2000, Jeulich, Germany; translated by Schreiber Translators, Bethesda, MD.

Of course, for the final storage, to me it became clear during the Jülich workshop that there might be a preference to mix storage rods with irradiated fuel pins (rather than mixing elements), so it would really be a preparation for final storage in the form of pins, for example in a POLLUX type cask. The other question which came up, and has been mentioned here, is the availability of installations. The basic idea, of course, is to do this in existing MOX fuel-fabrication facilities, and not to build new facilities to do it.

In fact, there is exactly as much availability to do storage pins as there is for MOX production. It's a matter of choice whether or not a given facility is used to produce MOX or storage pins. In fact, the capacity for storage pins would increase if you increase the percentage of plutonium beyond the 5–8 percent, which is currently in MOX fuel. So, you would actually be able to immobilize more plutonium in existing MOX fabrication facilities than if you go down the MOX route.

That's another question, which of course is very important: What is the limit in terms of plutonium content? Is it 10 percent? Is it 15 percent? What are the criteria here, and what are the limitations?

The economics of the process depend, to a large extent, on the amount of plutonium per rod. This is the single most sensitive criteria affecting the cost. It's obvious that, overall, the process is much

cheaper, because you don't have to qualify the rods for use in a nuclear power plant. This is in contrast to what Allison said—it is not a choice anymore. Once you have a storage rod, you can't change your mind afterwards, because it hasn't gone through the technical specifications in the same way as MOX fuel does.

Another question was whether or not an existing MOX fabrication facility could be used to produce MOX and storage pins—either simultaneously or alternatively. It's a question to which I haven't gotten a clear answer so far. It would be interesting to hear what the MOX fabricators at this conference think about it.

Finally, the process is actually being carried out. Siemens is currently, as they say, "running empty" the old Hanau MOX fabrication facility. They are immobilizing, in storage pins, approximately 0.6 tonnes of plutonium. They started doing that in the beginning of 1999, and the forecast is that they will finish producing about 12 tonnes of storage elements by the end of this year. That's a fair throughput, taking into account that they're faced with various qualities of plutonium, including some scrap materials and even some quantities in liquid forms.

Thank you.

**David Albright:**Thank you. Are there any questions or comments for our panelists? Allison, did you want to add something?

**Allison Macfarlane:** Thank you, yes; just a couple brief comments. First of all, I don't want to leave you with the impression that the National Academy thinks that the can-in-canister has failed the spent-fuel standard. That's not what we think and that's not what we say. Point number one.

Point number two. I just want to point out that the can-in-canister isn't necessarily the only answer for plutonium immobilization that meets the spent-fuel standard. Although it doesn't appear that a storage-MOX form necessarily meets the spent-fuel standard, especially in terms of a host-nation threat, it's harder to imagine proliferant groups of states being pretty successful extracting it.

I think there are potential fixes to their proposal. I'm not going to go into detail now, but Frank von Hippel and I are actually working on a paper that looks at potential fixes that would use the basic "ÖKO-Institute" plan, but would meet the spent-fuel standard at the same time.

**Q:** This is a question mainly to Professor Macfarlane. First of all, you have my sympathy to be part of a panel that's tasked with evaluating the relative ability of two processes to achieve a standard, which is neither defined nor constant over time. I know this has been a very hard task and it has been full of both technical and political complexity.

But there were a couple of points that you made that confused me a little bit. I've seen the interim report—I've only skimmed it—but I was a little confused on some of the points you make early in your talk.

You mentioned that the process of getting to the spent-fuel standard can have as many intermediate stages that can be as important to evaluating the overall proliferation resistance as the final stage. But then I think you said that the NAS was not tasked to evaluate the external or institutional factors, or controls that surround the final end-state. That confused me a little bit: what was the tasking, and what was your own personal view of the tasking?

But then, as you continued in your talk, you broke down the individual criteria for defining the spent-fuel standard. You had detectability: Now, there certainly can be intrinsic properties of materials that lead to the detectability that these materials are being reprocessed or extracted, but certainly when you introduce detectability you intrinsically connect it to an externality, because the amount of safeguarding, the distance from accessibility, controls, monitoring, transparency, etc.— all these have to do with detectability of reversing the spent-fuel standard.

So, my question first is a factual one: What is your direct tasking as a member of the NAS panel, and is your tasking to either include or ignore certain factors in evaluating proliferation resistance? Second—this is more of a personal view that I'm asking—where do you see the objective of this study, given the timing that it was tasked in 1998 and is still writing the final report? What is the objective, in the context where it's most applicable, that is, the disposition program for United States?

**Allison Macfarlane:** Thanks for that question. First of all, I am sorry if I was confusing. What I was trying to say, when I was talking about points on the way to the spent-fuel standard, was that sometimes during the processing of making your plutonium waste form, you may not actually meet the spent-fuel standard. For example, you're dealing with plutonium oxide, and you may have to transport it somewhere—we're going to go from Pantex to Savannah River in the United States—and at that point in time, that waste form does not meet the spent-fuel standard.

What we're going to judge is the final waste form, period. We're not going to judge those intermediate processes. What we're saying is that it's up to individual countries to decide whether or not those processes entail risks that are too great to go forward with the final form. We're not going to judge that.

Second of all, we are only looking at intrinsic properties of the waste form itself. We are not going to consider engineered and institutional safeguards. So, in terms of detectability—as you've brought up—we are only going to look at detectability issues that are intrinsic to the waste form. So, for example, if someone blows up the waste form, does it give off some kind of chemical or nuclear signature? Can you detect whether or not you still have this material in a pool, if it's in a pool? That kind of thing.

We are not going to judge the amount that you would use in detection, we're just judging whether this material has some kind of detectability property that you could use, if you wanted to. Does that make more sense?

**Q:** Can I just follow up on that question? I don't want to pretend that I'm privy to the deliberations, but my impression was that it was really the personal insistence of the chairman that institutional barriers not be considered, but that had been a topic of discussion in deliberation of the panel. Is that not true?

**Allison Macfarlane:** We talked about it, yes, as a panel, and I'm not going to name any names, but we decided as a panel to only look at the intrinsic properties.

**Q:** A question to Dr. Ed Lyman: Dr. Lyman, you're very famous worldwide for your technical argument on the vulnerability and dangers of vitrified waste transportation—by the way, waste with no plutonium inside. On the other hand, you are supporting this can-in-canister approach, which, as I understand, does include vitrified waste inside. How do you rationalize your transport argument with your support for the can-in-canister issue?

**Ed Lyman:** There is a very short answer to that. Any time you transport nuclear radioactive material, there is a cost-benefit, risk-benefit equation. The first part of my answer is that I'm more persuaded that the risks of transporting vitrified waste may be justified when there's actually a benefit. When there's no benefit, for instance in the commerce between Japan and Western Europe, in that case I only see risk and no benefit.

The other point, which I haven't really addressed, is that we do believe that during any transport of radioactive materials, there have to be increases in the physical protection of those materials to guard against a more robust sabotage threat. I would be consistent in applying those systems for whatever the purpose.

**Q:** In previous years, you never expressed risk-benefit argument in opposing vitrified waste transport. So, from now on, you will argue that there's a risk-benefit analysis? You never articulated that, by the way, before.

**David Albright:** Are there other questions?

**Q:** I had a question for Allison Macfarlane regarding zirconia. You talked about it being more flexible, and that it could be used as a reactor fuel at a later time. I'm wondering if you had any data or information about the performance of that material if it were to be used in a power reactor. I'm assuming that a decision to use that material as a fuel would be based on some kind of economic cost-benefit analysis. Thank you.

**Allison Macfarlane:** That's a good question, and no, I don't have any information. I think that only experimental work has been done.

**Ed Lyman:** I think the Doppler coefficient of those fuels is close to zero, or even positive, so it lacks a critical safety feature of uranium based fuels.

**Q:** A question to Allison. You said that the spent-fuel standard concerns only the intrinsic property of the waste form. But when the spent-fuel standard was originally proposed, it defined proliferation resistance in terms of civilian spent fuel. One of the characteristics of civilian spent fuel is that it's safeguarded by the IAEA. So, I think the spent-fuel standard should consider IAEA safeguards, not just monitoring by the host nations.

**Allison Macfarlane:** Thanks for another opportunity to clarify this extrinsic/intrinsic question. The first few NAS reports on this actually emphasized—as Dr. Pigford, I think, said this morning—that the Academy was just looking at the intrinsic properties. And as you say, spent fuel has IAEA safeguards. But not all spent fuel is under safeguards; the spent fuel in the United States is not under IAEA safeguards, for instance, nor is spent fuel in Russia. This is why we want to only look at the intrinsic properties of the waste form itself. Different countries, at different points of time in the future, may apply different amounts of safeguards on the material. That is something that's more difficult to standardize. So, if you want to just look at the barebones situation, its better just to look at the intrinsic properties of the waste form itself, and compare it to the intrinsic properties of a spent fuel assembly.

**Q:** I have two small comments. First: during the process of converting plutonium metal to MOX and irradiating it in reactors, there are varying levels of attractiveness. On the one hand, plutonium metal

is very attractive. At the other end, the spent-fuel standard has little attractiveness. I think that we are beating around the bush by talking about the spent-fuel standard's level of protection. We need to look at the conversion cycle. If I were a potential proliferator I will try to steal plutonium at intermediate steps, because to steal it at the end would be stupid. It concerns me that you never mentioned how to protect this technological cycle.

Another comment: This refers to the quality of plutonium needed to assemble an atomic bomb. Of course, to prepare a very effective weapon it is necessary to avoid spontaneous fissions, and so you want almost 100 percent plutonium 239. But if I were a potential proliferator, I will try to arrange a simple device using stolen plutonium. I have read one article, and there was a reference to Carson Mark, who formerly was the head of the theoretical department of the Los Alamos National Laboratory. He stated that there are no principal differences between weapon-grade and reactor-grade plutonium when preparing a simple nuclear device. Those are my comments.

**David Albright:** Before I take the next question, I would just like step outside of my role as chair for just a second, and interject the following point of view into this discussion.

I want to clarify something about the "ÖKO-Institute" report. Forgive me, I live in Europe for part of the year, so I sometimes take on a non-American perspective.

First of all, you have to put yourself in the framework as a non-nuclear weapon state that's already handling several tonnes of separated plutonium, and probably will have that for many, many years. If Wolfgang Kersting is right, maybe it's 10 years, but maybe it's 20 years.

In this context, when you bring in a discussion of the spent-fuel standard—something that was concocted in a nuclear weapons state, and that is independent of safeguards and physical protection—it comes across a little bit preposterous.

I'm just giving you an honest reaction. Because non-weapon states have to have the most advanced safeguards, now involving the protocol, which are meant to assure the absence of undeclared activities, and not just verify material balances. So, when they look at a storage-MOX arrangement, they say: "Well, let's evaluate this on standards we're used to talking about—IAEA safeguards, physical protection, proliferation considerations, or responsibilities or history—and not on intrinsic properties." Because they can say: "Look, we already have five tonnes at our vaults at Alkem, and at any time we can pull that out and make nuclear weapons."

Again, there's a disconnect here that I think we have to bear in mind. In a sense, that is what I'm hearing from the Germans, who are saying: "We're not a nuclear weapon state, we're also not in the United States, and we're looking at an alternative that we would like evaluated based on a set of criteria that we're used to dealing with. We're not used to dealing with a spent-fuel standard; we have no concept of that, in terms of our evaluation."

**Q:** Another interjection, actually. My Japanese colleagues have asked me to clarify the safeguards status of spent fuel in the United States. Technically, you are correct to say that the IAEA is not applying safeguards to spent power reactor fuel in the United States, however it does have the legal right to apply safeguards to virtually all power reactor fuel in the United States. It will likely have the legal right to apply safeguards to Yucca Mountain; we expect to make Yucca Mountain eligible for safeguards, whether it will be safeguarded or not is a different question. I was asked by my Japanese colleagues to clarify that.

**Q:** Just a small question to Dr. Lyman. You mentioned the risk of MOX burning in the event of a loss-of-containment accident. I'm not too familiar with this discipline, but the result that you show is derived from a probabilistic study. I think it is a consequence of the highly improbable accident. Would you tell me: What is the probability for your specific consequences?

**Ed Lyman:** For U.S. reactors—I don't know the figures for Japan—those types of accidents, according to probabilistic risk assessments range up to about $5*10^{-5}$ per reactor year. The average from the NRC's Independent Plant Examination program, for combined containment bypass and containment failure is around $1*10^{-5}$.

That's the average, but the point that I like to make is that, at least in the U.S. context, we're going towards a risk-informed regulatory process. In that context, there're going to be controls on the amount of additional risk that have to be incurred at nuclear power plants. There have been numerical guidelines for the additional risk that is considered to be tolerable in nuclear power plants. It turns out that the risk associated with a doubling of consequences, say, would actually lead to an unacceptable increase in risk. So it's really in that context, even though these are low probability accidents, the actual increase in risk could be unacceptable.

**Q:** In light of the NPT review conference, a number of non-nuclear weapon states are frustrated, basically, at the arrogance of the weapon states saying that the burdens of safeguards are too heavy. It's unbelievable. For example, Japan is receiving 20 percent of all IAEA safeguards, and still some of the people cast doubt on our nuclear activities. Now, Allison, you mentioned that institutional safeguards may vary among counties. But in doing so, I think that you are going to turn off many of the non-nuclear weapon states. I think you need to take that into account very much.

**Allison McFarlane:** I'm sorry, I think you're entirely misunderstanding me. I'm not trying to say that the United States deserves different kinds of safeguards than any other countries. I'm not trying to have a discussion about safeguards at all.

We're talking about immobilized plutonium here. Say, for example, that China one day in the future decides to immobilize some of its plutonium. China may not have the same kind of physical protection, the same kind of extrinsic characteristics. Their immobilized plutonium may not necessarily have the same kind of extrinsic properties as other countries. That's the only reason why we're looking at intrinsic characteristics, that's all.

**David Albright:** Let's take a break now, we'll reconvene in about ten minutes.