Comment on Draft Recommendation: Adaptive Phased Management

J. Franta, 26 May, 2005

Regarding NWMO's *Draft Recommendation: Adaptive Phased Management*, I would like to point out a technical misunderstanding apparent in Appendices 8 and 9, concerning certain important attributes of used nuclear fuel.

According to **APPENDIX 8** / REPROCESSING, PARTITIONING AND TRANSMUTATION,

" *Reprocessing ....potentially separates out **weapons-grade material (plutonium)** in the course of the process..... As is the case for reprocessing, there would be further risk of spreading technology that could be used for production of **nuclear weapons material**.*"

Similarly, according to **APPENDIX 9** / METHODS SCREENED OUT,

"*Reprocessing....potentially separates out **weapons usable material** in the course of the process.*"

Both statements misrepresent plutonium in spent nuclear fuel (as “weapons-grade material”), and its usability in nuclear weapons.
Provided here are a few references that help dispel the misunderstanding.

According to a statement quoted by Pugwash in www.pugwash.org/publication/pb/sept2002.pdf

"Most people seem unaware that if separated U-235 is at hand it's a trivial job to set off a nuclear explosion, whereas if only plutonium is available, making it explode is the most difficult technical job I know."
Luis W. Alvarez, a key participant in the construction of the first US nuclear weapons and recipient of the Nobel Prize in Physics, 1987; see Luis W. Alvarez, Adventures of a Physicist (Basic Books, 1988), p. 125.

and,

"While the availability of plutonium certainly poses a risk with respect to the possible acquisition of nuclear weapons by States, it does not pose a risk comparable to that of HEU for the possible clandestine manufacture of a nuclear explosive device by a subnational terrorist group. The reasons for this have to do with the far more demanding technological expertise required to manufacture a nuclear explosive device based on plutonium (including experimentation with very sophisticated conventional explosives and electronic equipment).
Moreover (albeit less importantly) handling plutonium entails much greater health hazards than does HEU, and transporting it clandestinely is more difficult (because of its more pronounced radiation signature). Hence, plutonium nuclear explosive devices are much less likely to fall within the competence of any subnational terrorist group, and in any case their yield is unlikely to be comparable to that of an HEU device."

Additional technical details are provided by GLOBAL SECURITY, at
http://www.globalsecurity.org/wmd/world/iran/bushehr.htm

"Normally for electrical power production the uranium fuel remains in the reactor for three to four years, which produces a plutonium of 60 percent or less Pu-239, 25 percent or more Pu-240, 10 percent or more Pu-241, and a few percent Pu-242. The Pu-240 has a high spontaneous rate of fission, and the amount of Pu-240 in weapons-grade plutonium generally does not exceed 6 percent, with the remaining 93 percent Pu-239. Higher concentrations of Pu-240 can result in pre-detonation of the weapon, significantly reducing yield and reliability. For the production of weapons-grade plutonium with lower Pu-240 concentrations, the fuel rods in a reactor have to be changed frequently, about every four months or less." [whereas a typical commercial nuclear reactor refuelling outage is a complex, month-long affair conducted every 18 months or longer]

The question of explosive yield is really a problem of the very high neutron background from Reactor-Grade Plutonium (RGPu) -- a gun assembly type of device is too slow relative to the amount of time available between two randomly appearing neutrons (the time needed for the two RGPu components to come together as close as possible before the explosion is initiated by a neutron, in order to achieve the highest possible multiplication factor "k" and explosive yield "Y"...):

The per-unit-mass neutron rate for RGPu is on the order of 340,000 neutrons/kg/sec.
If the supposed explosive device comprises, say, 6 kg RGPu (combined mass of the two components), that comes to 1,700,000 n/sec. That much RGPu will also exhibit a significant subcritical neutron amplification factor - anywhere from 10 to 100+ times the basic per-unit-mass rate (depending on details of the design).
.....the fission burst starts as soon as the approaching masses reach a configuration with a combined k0 > 1, AND the first neutron appears; .....this combination of relatively slow approach speed and a background rate of tens of millions of neutrons per second, means that the chain reaction would start as soon as k is just slightly above unity and, since fast-neutron generation times are very fast too (about 0.01 micro-sec), the burst would be over (i.e. thermal expansion & dispersal of the two solid masses) long before they approached significantly closer, and before k got much higher.

Specifically, from the above example of RGPu, a total background rate of something like 70 E+6 n/sec will be present, and the average time between background neutrons will be 0.014 microseconds. If the gun propels the pieces together at a brisk 1,500 km per hour (926mph -- for the sake of this example), or 417 m/sec, then the two components will only approach each other by about (417m/sec x 0.014 E-6 sec =) 6 micrometers more than the separation distance at which critical configuration is achieved (i.e. multiplication factor = 1.000), before the chain-reaction diverges (6 micrometers BTW, is 60,000 Angstrom units, or about ten times the wavelength of visible light...).

Since thermal expansion & dispersal of the two solid masses also proceeds quite a bit faster than the 417m/sec approach speed (more like 4 to 8 thousand m/sec at least - similar to the speed of sound in the metal), the k factor will tend to drop back below unity, rather than continue

increasing. The explosive yield will likely be little more than that which sufficed to disperse the approaching RGPu components.

Its possible to do some calculations using an explosive yield equation (semi-empirical, combining basic physics with fitting of data from experimental nuclear fast-burst curves - i.e. peak fission rate multiplied by pulse half-width....) :

Y(tTNT) = 7.246E-27 * exp (4 * ln (k0 * x ^ (-2/3) - 1) + 74),

....where x is the density ratio (1 in this case, since a simple assembly doesn't involve any compression), and k0 is the "initial" multiplication factor (in this case the same as the "final" multiplication factor k, achieved at the time that the chain reaction begins in the two approaching RGPu components - which in this gun-assembly example is at some distance greater than zero (contact)).
Using the above formula, some results for various values of k0 with zero compression are :

Y(tTNT) = 7.246E-27 * exp (4 * ln (k0 - 1) + 74)

k0	Yield (in mass of TNT equivalent)
1.001	0.001 kgTNT
1.002	0.016 kgTNT
1.005	0.62 kgTNT
1.007	2.4 kgTNT
1.01	10 kgTNT
1.04	2550 kgTNT
1.1	100 tTNT
1.2	1.6 ktTNT
1.3	8.1 ktTNT
1.4	25.5 ktTNT

.....a 10kgTNT explosion is probably more than enough to vaporize the two approaching RGPu components, with a very fast shockwave dispersing them and preventing them from reaching multiplication factors greater than ~1.01, due to the low approach speed relative to the fast nuclear reaction rate.

Note that you would get the same, mediocre result if instead of a gun assembly, you simply had one large RGPu mass with a shut-off rod in the middle, which you then expelled rapidly -- low yield explosion & disassembly would follow quickly, as soon as the shut-off rod was far enough out to raise k just slightly over 1.000.

One excellent discussion of the proliferation topic may be found in Dr. J. Whitlock's web-posted text, "How easily can an atomic bomb be made with spent CANDU fuel?", on The Canadian Nuclear FAQ, www.nuclearfaq.ca/cnf_sectionF.htm#x2

quote :

The only publicly known US test of a reactor-grade device was a 1962 explosion, partially declassified in 1977. However, in 1962 the term "reactor-grade" included any purity less than 93% Pu-239 [14].
The plutonium for the 1962 test came from a British MAGNOX reactor (a dual-purpose electricity/plutonium-production design), and is suspected of being in the range 80-90% Pu-239, although this fact remains classified [15,16].

[14] DOE Facts, "Additional Information Concerning Underground Nuclear Weapon Test of Reactor-grade Plutonium", Washington, D.C., http://apollo.osti.gov/html/osti/opennet/document/press/pc29.html , June 1994.

quote from [14] :

Prior to the 1970's, there were only two terms in use to define plutonium grades: weapon-grade (no more than 7 percent Pu-240) and reactor-grade (greater than 7 percent Pu-240). In the early 1970's, the term fuel-grade(approximately 7 percent to 19 percent Pu-240) came into use, which shifted the reactor-grade definition 19 percent or greater Pu-240.
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[15] A. DeVolpi, "A Cover-up of Nuclear Test Information?", Physics and Society, Vol. 25, No. 4, http://www.aps.org/units/fps/newsletters/1996/october/aoct96.cfm#a2 , October 1996.

quote from [15] :

The 1962 detonation involved plutonium of a quality below that of weapons grade. To reinforce its 1967 announcements that "high-irradiation level reactor-grade plutonium can be used to make nuclear weapons," the US government added in 1977 that "a nuclear test was conducted using reactor grade plutonium" and "it successfully produced a nuclear yield." As a result of the Openness Initiative formulated by Secretary O'Leary, DOE announced in 1994 that the plutonium was "provided" by the UK and the upper limit of explosive yield was 20 kt. [1,2]
<snip>
In fact, the missing data are likely to be quite discouraging to potential proliferators, thus fortifying existing perceptions about inherent difficulties in weaponization of civilian plutonium.
<snip>
Fresh disclosures from London indicate that the plutonium could not have been what we now consider to be reactor-grade[3]. DOE now implies, but doesn't assert, that the plutonium was fuel grade.
Meanwhile, other nations have publicized their disagreement with the DOE "spin" on declassified test information. In fact, the French "scorned the US government affirmation that it successfully exploded a weapon made with 'reactor-grade' plutonium."[4] During the 1950s the British carried out two tests with sub-grade plutonium that they considered disappointing. Based on these results, they went on to make weapons only from high- grade materials.
Although the results of the tests were reported in an official UK book, the information is considered classified in the US. This British data is not consistent with the 1962 test conclusions reported to the American public.

<snip>
The glaring shortfall in data and information released about the 1962 test is cause for suspicion about the quality, origin, or success of the experiment. The unreleased information can hardly be of more proliferant value than the specific data already divulged for other nuclear-explosive experiments. In fact, the missing data are likely to be quite discouraging to potential proliferators, thus fortifying existing perceptions about inherent difficulties in weaponization of civilian plutonium.

<END QUOTE>

Another often cited reference is,
J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," Science & Global Security, Vol. 4, pp. 111-128, 1993

His conclusions include the following:

1. Reactor-grade plutonium with any level of irradiation is a potentially explosive material.

2. The difficulties of developing an effective design of the most straightforward type are not appreciably greater with reactor-grade plutonium than those that have to be met for the use of weapons-grade plutonium.

J. Carson Mark was the director of the Theoretical Division at Los Alamos National Laboratory (1947-1972)

....but R. Rhodes & D. Beller wrote in their Jan/Feb. Foreign Affairs article, "The Need for Nuclear Power," page 41:

Weapons made from reactor-grade plutonium would be hot, unstable, and of uncertain yield.
<END QUOTE>

They might have added "suicidal."

Jacques Read (US DoE) also stated (Radsafe, Wednesday August 16, 2000 1:24 PM) that "It is theoretically possible to drive any fissile material to super-criticality if you use enough chemical high explosive to compress it, but the fission density suffers and the resulting object doesn't give a big multiplier over the same weight of TNT."

He said further that "High 240Pu would have a very high dud-rate -- a very good chance it wouldn't light at all, and a very low fission efficiency. As a weapon, it might easily be preferred to just send a dozen or so aircraft or rockets to deliver chemical explosives.
Although there are a lot of amateur designs for simple nuclear bombs on the web, none would be likely to work with reactor-grade Pu."

Then there is the self-heating problem due to radioactivity.

The fact is that Mark's claim that RG-Pu heating problems may simply be overcome using a "thermal bridge" are bogus. That "thermal bridge" would also act as an excellent "shockwave bridge" (due to the higher density of the metal) and ruin the geometry of the implosion.

Spent fuel from commercial nuclear power plants typically yields plutonium with a Pu-239 fraction between 55% - 70% (depending the burn-up of each specific type of reactor, measured in "megawatt-days per tonne of fuel" or "MW-d/tonne").
This is useless for weapons.

In his book, "Proliferation, Plutonium and Policy," Alexander DeVolpi gives the following numbers (mass of various Pu isotopes per tonne of spent fuel) in Table B-3, p.218, for LWRs with 33,000 MWd/t burnup :

Pu-238 0.13 kg/t
Pu-239 5.0 kg/t
Pu-240 2.3 kg/t
Pu-241 1.2 kg/t
Pu-242 0.46 kg/t

Total Pu 9.09 kg/t ----> 0.9%
fissile Pu 6.2 kg/t ------> 0.6%

Table II-2 of DeVolpi's book (p.65) includes a list of heat rates for various actinide isotopes, in the last column.
Here's what he put for the Pu isotopes:

Pu238 567. W/kg
Pu239 1.9 W/kg
Pu240 7.1 W/kg
Pu241 3.4 W/kg
Pu242 0.15 W/kg

So, for 10 kg of delta-phase RGPu (PWR SNF) with 55% Pu239, 25.3% Pu240, 13.2% Pu241, 5.1% Pu242 and 1.4% Pu238 (Table B-3, p.218, 33,000 MWd/tU), the total heat rate will be 5.5 x 1.9 + 2.53 x 7.1 + 1.32 x 3.4 + 0.51 x 0.15 + 0.14 x 567
= 10.45 + 17.9 + 4.49 + 0.077 + 79.38
= 112.3 Watts.

Note that the heat rates do not include fission of (hopefully) subcritical mass due to amplification of the background spontaneous fission rate.... Depending on the design, that could easily be several times 100W, if no thermal neutron poison is used to suppress it (critical mass is much less for thermal neutrons than fast ones ! ...high explosive material makes good moderator)
For a 4.5 kg alpha-phase Pu bomb core made of near-pure Pu-239, the heat rate will only be about 10 - 20 W.

According to DeVolpi (Fig. A-3 on p.206), for spheres reflected with a 15 cm layer of NU, the critical mass for HEU is about 16.5 kg, while for a similar arrangement with Pu from PWR spent fuel (57% Pu-239) and a 10 cm layer of NU, its about 18.0 kg for the delta phase of the metal (15.8 g/cc) and 11.5 kg for the alpha phase (19.5 g/cc).
Since it would be difficult to maintain this kind of (hot) Pu in the alpha phase, the amount of Pu required would actually be ~ 10% MORE than that of HEU (18.9 g/cc).
Weapons-grade Pu is stabilized in the alpha phase using gallium, but the situation is far worse for reactor-grade Pu, with much more self-heating.

DeVolpi's Table A-1 (p.202) gives critical masses for alpha- and delta-Pu spheres reflected by 10 cm NU shells, with all four Pu isotopes included.
For example, for an RGPu ("reactor-grade Pu") material with 70% fissile fraction (Pu239+241), there is 29.4% Pu240 and 0.6% Pu242, and the critical masses are 6.0 kg and 9.9 kg for alpha- and delta-Pu respectively (and slightly more for the more accurate ~69% fissile fraction typical of high-burnup PWR RGPu and ~68% fissile fraction typical of CANDU RGPu).

As one might guess - due to the low Pu242 fraction - the 9.9 kg point does in fact fall just slightly above the curve for Pu240-diluted delta-phase Pu.

DeVolpi adds, just below the table, that "Although weapons with a high fissile fraction are fabricated with alpha-phase plutonium metal, inherent radiation heating is likely to cause a jump to the delta phase (115 deg C) when the fissile fraction is highly degraded (Fig. II-3). It is thus reasonable to assume that, for denatured material diverted from LMFBR and LWR reactors, practical fission-explosives would have to be made from delta-phase plutonium."

What DeVolpi doesn't say, is that even with WGPu the heating rate and insulation of surrounding tamper and HX materials is apparently great enough to oblige manufacturers to employ gallium-alloying phase-stabilisation in order to maintain the Pu in the dense alpha phase.

The 112.3 Watt RGPu heating rate calculated above is slightly more than your typical 100-watt household incandescent lighbulb.
From experience, these get pretty hot, even without any insulation to cut off the convective & radiative heat transfer.
If we include fission heating due to subcritical amplification of the background spontaneous fission rate, my guess is it would be tricky to keep the bomb core from melting (639°C), never mind below the 115°C phase transition point....
Explosives tend not to react pleasantly, when you cook them at several hundred °C.
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