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Nuclear weapons and power-reactor plutonium

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With modest design sophistication, high-burn-up plutonium from power reactors can produce powerful and predictable nuclear explosions. There is no way to 'denature' plutonium. Power reactors are not implausible but rather attractive as military production reactors. Current promotion of quasi-civilian nuclear facilities rests, dangerously, on contrary assumptions.

NUCLEAR policy, especially in Europe, has often been justified by the belief[1-10] that for making nuclear bombs, 'reactor-grade' plutonium produced by the normal operation of uranium-fuelled power reactors is necessarily much inferior to specially made 'weapons-grade' Pu: so inferior in explosive power or predictability that its potential use by amateurs is not a serious problem and that governments would instead make the higher-performance weapons-grade Pu in special production reactors.

Although that belief is false it was vigorously asserted during 1978–79 by responsible Ministers or by Prime Ministers in at least three high-technology nations. This was apparently because some of their nuclear experts did not know differently, and rejected contrary official US statements as being exaggerated or even politically motivated; or because those experts who did know were not asked; or because correct technical advice was lost, oversimplified, or garbled in transmission through advisors who did not understand the physics. Here I attempt to clarify the properties and performance of various grades of Pu, outlining the physical logic explicitly enough to ensure understanding although discreetly so as not to help the malicious: certain details and technical references have, therefore, been omitted and some calculations treated in conclusory fashion.

The possible military utility of power-reactor Pu has caused widespread professional confusion since 1946. Although some leading scientists appreciated even then[1,11] that it was useable in bombs or might become so, the contrary assumption (admittedly hedged) was made in the Acheson-Lilienthal report[12,13]. This recommended that certain nuclear activities could be classified as 'safe' because the Pu they produced could not be converted without timely warning into weapons-useable form, and that these activities could thus be carried out by nations if under strict and enforceable international controls. With the radical 1953 Atoms for Peace initiative, the report's finding that international inspections and treaties could not stop proliferation was forgotten, and US nuclear knowledge and materials were distributed worldwide with increasing enthusiasm and decreasing care[14]—apparently on the assumption that power-reactor Pu was, or could be made, unsuitable for use in bombs ('denatured'), despite the US Atomic Energy Commission's refutation of this notion[15] in 1952. With this in many signatories' minds, the Non-Proliferation Treaty (NPT) was negotiated in 1967: an important fact to recall when construing the NPT today, even though its text and the International Atomic Energy Agency (IAEA) do not distinguish in quality between Pu made in power or in military production reactors.

Beginning publicly in the early 1970s in the US (earlier in the Soviet Union and France[16]), the assumption that power-reactor Pu was unsuitable for bombs was questioned with increasing force[17,18]. By 1974, authoritative reports[19,20] had concluded that reactor-grade Pu could be used even by amateurs to make effective fission bombs, albeit of somewhat reduced and uncertain yield[21-25]. Further analyses during 1976–77, mainly at the US weapons laboratories, revealed a still wider spectrum of technical possibilities, and in 1977 the US announced that it had successfully tested a bomb made from reactor-grade Pu[26,27]. Yet the earlier finding that this material, though useable, was inferior if used in relatively crude bomb designs was widely and wrongly supposed to apply to all designs. In particular, reactor grade Pu was alleged to be inherently:

—far more hazardous than weapons-grade Pu to people dealing with it; or
—far more likely to cause unintentional explosions; or
—incapable of exploding violently enough to do much damage, or, at worst, to accomplish most military aims; or
—too unpredictable in explosive yield to be acceptable to its users.

Each of these assumptions contains, in certain circumstances, some truth; but each is generally, or can by plausible countermeasures be rendered, false. Their implication that reactor-grade Pu is not very dangerous, or unlikely to be attractive to governments, is wishful thinking, and causes the proliferation risks of 'civil' nuclear activities to be gravely underestimated.

In recent years, advocates of commercial Pu use, in referring to the bomb-making that might also result, have had to retreat "from the original concept of denaturing to the notion of making do with less than optimal material"[11]; yet the earlier myth lingeringly distorts policy[28]. To decide responsibly about nuclear power and nuclear fuel reprocessing, we must know exactly what "less than optimal" means, and hence must cautiously review published physical principles. The only thing more dangerous than discussing this subject is not discussing it; the lesson of Atoms for Peace may yet be that with Pu, we must get our assessments right the first time.

Plutonium production

All nuclear reactors fuelled with uranium[29] (notably the 0.7%-naturally-abundant species ^{235}U) produce ^{239}Pu by neutron-absorption in fertile ^{238}U. Some of the ^{239}Pu formed is fissioned; an increasing fraction absorbs successively more neutrons to form higher Pu isotopes, chiefly $^{240\text{-}242}Pu$, and transplutonic elements[30]; and some of the resulting $^{239\text{-}240}Pu$ (plus traces of ^{238}Pu and related species) survives until the fuel is discharged. Depending[19,24,25] on the type and detailed design of reactor, the composition of initial fuel, and the manner of operation, especially the burn-up (extent of exposure of the fuel to neutrons), the net Pu production of a I-GWe power reactor is typically several hundred kg yr^{-1}, for example ~210-240 kg yr^{-1} for a light-water reactor (LWR), the dominant commercial type.

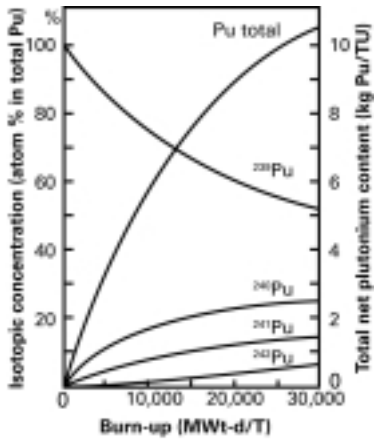

Fig. 1 Typical total amount and isotopic composition of plutonium in discharged fuel as a function of burn-up in a light water reactor[32]. The exact values depend in detail on reactor design and operation and on initial fuel composition. Higher isotopes of plutonium and transplutonics become more abundant in repeatedly recycled fuel.

For a given reactor, the isotopic composition of the discharged Pu depends predictably on burn-up. If each metric ton of uranium (TU) yields only a few gigawatt-days' thermal energy (GWt-d), neutron capture is so limited that nearly pure ^{239}Pu—'weapons-grade' Pu—is produced. It contains no more[1] than 7%[24] or 8%[11] ^{240}Pu, typically[31] around 6%; perhaps 0.5% ^{241}Pu; negligible ^{242}Pu and ^{238}Pu.

Higher burn-up, whether through leaving the fuel in the reactor longer or exposing it to a more intense neutron flux, produces a larger proportion of the higher Pu isotopes (Fig. 1). Low-enriched uranium fuel (the usual kind) left for the full 3–4 yr in a reliably operating LWR is usually designed for a nominal burn-up of 27–33 GWt-d/T. The latter corresponds[33] to discharge Pu containing ~58% ^{239}Pu and 11% ^{241}Pu (both fissile) plus 25% ^{240}Pu, 4% ^{242}Pu, and 2% ^{238}Pu. This composition is broadly similar for other thermal or fast reactor types, except for graphite-moderated reactors[34] ($^{240+242}$Pu ~20%) and fast breeder radial blankets[30] (~4%). In some circumstances the $^{240+242}$Pu fraction can rise from a nominal ~29% to as much as 49% (34% ^{240}Pu, 15% ^{242}Pu)[33] in equilibrium LWR Pu recycle fuel; this is unusually high and approximates a practical limit.

Power reactors also can, and often do, discharge fuel short of its full design burn-up. Mature US LWR cores routinely attain well below design burn-up[35]. Real or simulated malfunctions, such as leaky fuel cladding, may lead the operator to discharge fuel at very low burn-up[1]. Alternatively, manipulation of fuel rods can produce a core with high average burn-up but containing some rods of much lower burn-up. 'On-load-refueling' reactors such as Magnox and CANDU are suitable for clandestine introduction, brief exposure, and removal of small but adequate amounts of fertile material in a few fuel channels. Such methods are not necessarily easy to detect even if an inspector were continuously present, and would probably not be detected at all by present international safeguards[36].

Because burn-up, and hence isotopic composition of discharge Pu, can vary enormously between and within reactors and with time, 'reactor-grade Pu' is not a well-defined term. Weapons-grade Pu, which is fairly well-defined (supra), can be readily produced in any power reactor without necessarily and significantly decreasing efficiency, increasing costs, or being detected. But though that option is always open, we assume here that it is not–that power reactors will be used to produce only high-burn-up Pu. We also assume that 'reactor-grade Pu' implies a $^{240+242}$Pu content of ~30%; higher, even arbitrarily higher, even-isotope content will not affect the argument, while a lower content would strengthen it. On these conservative assumptions, the Pu discharged from power reactors will be shown to have major military potential.

Plutonium properties

Relevant nuclear properties of the common Pu isotopes are summarized in Table 1. The values given for m_c are not the quantities needed to make a bomb, as neutron reflection and implosion can reduce critical mass by a large factor. This factor has been officially stated to be ~5, consistent with the US[39] and IAEA requirement of strict physical security measures for quantities of Pu≥2 kg (independent of isotopic composition). Published data suggest, however, that with sophisticated design the factor may be > 5. For example, in its densest (α-phase) allotropic form, ^{239}Pu at normal density in a thick Be reflector has a reported critical mass as small as $m_c/4$, and large reflector savings are also obtainable with nonmoderating (and partly fast-fissionable) reflectors such as ^{238}U. Further, if the core and reflector are equally compressible and if the ratio of reflector thickness to core radius remains constant during compression, critical mass varies as the inverse square of core density. Densities 'several times' normal are said to be attained in military

Table 1 Some properties of plutonium[31,34,37,38]

	Decay properties				Fast-fission			Spontaneous Fission	
Isotope	Half life (yr)	Main emission (MeV)	Specific activity (Ci g^{-1})	Heat (W kg^{-1})	m_c* (kg)	$\bar{\nu}$†	σ_f‡ (barn)	Rate (n g^{-1} s^{-1})	$\bar{\nu}_{SF}$§
^{238}Pu	86.4	5.5 α	17.4	567	9	~3[‖]	2.5[‖]	2,600	2.3
^{239}Pu	24,390	5.2 α	0.061	1.9	10	3.1	1.9	0.03	2.9
^{240}Pu	6,600	5.2 α	0.23	7.0	40	3.4	1.3	1,020	2.2
^{241}Pu	13.2	0.021β	112	4.5	12	3.2	1.8	–	–
^{242}Pu	387,000	4.9 α	0.0038	0.1	90[¶]	3.3	1.2	1,670	2.3
^{241}Am#	433	5.5 α	3.43	106	114**			0.623	3.1

* Approximate bare-sphere prompt-critical mass at normal density; Pu is α-phase (ρ = 19.8 g cm^{-3}). For comparison, m_c for 93.5% ^{235}U (ρ = 18.8 g cm^{-3}) is 49 kg ^{235}U.

† Approximate gross neutron yield per fast fission (Argonne 16-group).

‡ Approximate fast-fission cross-section (Argonne 16-group). (The capture-to-fission ratios are also important, and tend to be high for even Pu isotopes.)

§ Approximate neutron yield per spontaneous fission.

[‖] Values cited by De Volpi[37], who gives the ^{238}Pu m_c as 7 kg (unpublished); the best value calculated for α-phase, however, is the m_c ~9.2 kg shown here (R. W. Selden, personal communication).

¶ Best Livermore estimate from the range 75-100 kg (R. W. Selden, personal communication). De Volpi[37] assumes ~95 kg (or 118 kg in Appendix H), but used ≳156 kg in earlier publications[45,46]. Calculated m_c is probably not finite for ^{242}Pu^{10}B$_2$, owing to threshold effects, but is ~350 kg for ^{242}Pu^{10}B$_2$ at ρ = 11.5 g cm^{-3} (R. W. Selden, personal communication).

Daughter of ^{241}Pu, important (like the trace isotope ^{236}Pu) mainly for its γ emissions.

**Approximate estimate by Clayton[38] for ρ = 11.7 g cm^{-3}, implying reactivity comparable with ^{240}Pu.

bombs[40] , and by means described in the open literature a slightly subcritical mass of α-phase ^{239}Pu in a U reflector can be compressed to 1.85 times its initial density, corresponding to a reactivity increase of ~3.4 times. The same method can yield even higher compressions. Although high compression is inconsistent with simultaneous high reflection, it may be possible to achieve significant supercriticality with initial ^{239}Pu masses under 2 kg. Regardless of the exact figure, the IAEA's 8-kg, 'significant quantity' design basis for detecting diversions[36] seems far too high.

Of the Pu isotopes in Table 1, only ^{239}Pu and ^{241}Pu are fissile, that is, fissionable by thermal (slow) neutrons. All Pu isotopes, however, are fissionable by the fast neutrons in a bomb: indeed, at energies > I MeV (69% of fission neutrons) the fission cross-section of ^{240}Pu is less than that of ^{239}Pu by a margin of less than 20%, so the amount of ^{239}Pu required to form a normal-density critical mass is remarkably insensitive to $^{240+242}$Pu content (Table 2). Published neutron transport calculations confirm that the even isotopes produce only minor changes in reactivity, neutron spectrum, and mean prompt-neutron lifetime. So reactive is ^{240}Pu that changing the $^{240+242}$Pu content from 6 to 30% increases m_c only from ~11 to ~13 kg[31]. No known fast-neutron absorber can make Pu of any practical composition incapable of forming a prompt-critical mass[31,42]: calculations[42] suggest that substituting the best fast-neutron absorber known, ^{10}B, for oxygen in reactor-grade crystal-density PuO_2 (m_c~ 35 kg) would increase m_c only to ~70 kg.

Fast-fission properties of Pu, then, are only slightly affected by ordinary changes in isotopic composition. The neutron background is, however, modestly affected. Spontaneous-fission neutrons (Table 1) provide typically[34] of the order of 100 n $g^{-1}s^{-1}$ in weapons-grade Pu, about 500 in reactor-grade Pu. A further contribution (at lower neutron energies) comes from (α, n) reactions with light-element impurities. In Pu metal this is not an important neutron source[34], but it can more than double the neutron background in PuO_2, as 1 Ci of α-emitter bombarding oxygen produces of the order of 5,000 n s^{-1}.

Neutron background from all sources is significant for weapons physics (infra) and makes reactor-grade Pu give somewhat higher radiation doses than weapons-grade Pu. For long-term commercial handling within the normal canons of health physics, shielding would be required. For clandestine weapons manufacture it would not, because the published total dose rates (mainly γ and X rays) are relatively modest—of the order of rem h^{-1} at the surface of a 1-kg fresh recycled PuO_2 sphere, < 1 mrem h^{-1} at 1 m. Even under extreme assumptions (18 1/2% ^{238}Pu, 30% $^{240+242}$Pu, 10-kg PuO_2 sphere with subcritical multiplication included), neutron dose rates (60 mrem h^{-1} at 1 m) "do not provide an effective deterrent"[44]. It is obviously not correct that "slight mistakes in the knowledge of exact [isotopic] composition.... may well pose extreme radiological hazards"[43], given normal precautions against inadvertent criticality.

The specific activity of reactor-grade Pu is typically[42] ~10 Ci g^{-1} as against 3 Ci g^{-1} for weapons-grade Pu, the neutron background (for metal) and the inhalation toxicity ~5 times higher, and the heat production ~10 W kg^{-1} (about the same as for 1-yr-old spent LWR fuel) as against 3W kg^{-1}. Only a difference of orders of magnitude in these quantities–the extent by which they all exceed the corresponding values for ^{235}U—would reflect differences in ease of handling that would be important in designing new bomb-making facilities[42].

'Thermal denaturing'[44-46] of reactor-grade Pu was recently proposed by A. K. Williams *et al*. (unpublished Allied-General Nuclear Services) and A. De Volpi[37]. The ^{238}Pu content would be increased from its normal 1–2% (nearly 5% in some recycle Pu[33]) to 10–15%, perhaps nearly 20%, chiefly by recycling ^{237}Np (itself a bomb material with m_c ~75-105 kg) with ^{232}Th rather than ^{238}U diluent[29]. The ^{238}Pu would increase heat production to 6–9 times normal. Some calculations[44] based on cores of high mass and high volume-to-surface ratio, in direct contact with non-thermally-stable explosives, suggest serious design problems. But realistic choices of geometry and materials can readily overcome these problems. Cooling does not even become an interesting design problem until the ^{238}Pu content approaches that of a thermoelectric heat source, and a much lower content, well over 20%, does not provide an effective deterrent even to most amateurs, though it would make safe and economic fuel-cycle operations hard to envisage[47]. Only in quite incompetent hands could the extra heat pose a danger of unplanned detonation.

Table 2 Critical mass of plutonium spheres in a ~10-cm natural uranium reflector as a function of plutonium isotopic composition [41*].

$^{240+242}$Pu (atom %)	^{239}Pu in critical mass (kg)	Total Pu in critical mass (kg)
0	4.4	4.4
10	4.5	5.0
20	4.5	5.6
30	4.6	6.7
40	4.7	7.8
50	4.8	9.6

*Assuming ^{240}Pu/^{242}Pu ratio similar to that shown in Fig. 1.

A second 'denaturing' proposal by De Volpi[37] would combine ^{238}Pu and ^{240}Pu with extra ^{242}Pu, which is a diluent in fast spectra and something of a neutron poison in thermal spectra[48]. Pathologically high ^{242}Pu content would increase m_c, though not by the ~30 times claimed by Olds[45] (compare Table 1); as all Pu isotopes have "reasonably small critical masses, this concept [of denaturing by dilution] is not applicable to plutonium"[44]. De Volpi states[46] that fuels made mostly of ^{242}Pu and with a fissile fraction as low as 18% are useable even in present fast reactors, but he does not analyze performance or economics, which apparently offer serious difficulties[48], and his analysis of weapons physics seems deeply flawed.

Synergisms are negligible, so the effect of each even Pu isotope can be dealt with separately: thermal 'denaturing' with ^{238}Pu above and neutronic 'denaturing' with all three isotopes below. Practicable dilution with ^{242}Pu cannot alter design constraints enough to affect the conclusions below.

Finally, nonmetallic forms of Pu must be considered. Reactor-grade Pu can be used directly in bombs without reduction to metal (though metal generally gives better performance). The oxygen in PuO_2 dilutes the Pu and lengthens the 'generation time' between fissions, reducing the yield, but it also slightly compensates by moderating the neutrons to lower energies where the fission cross-sections are higher. The dilution effect predominates and roughly doubles[42] the δ-phase metallic m_c. It also alters other design parameters. Nonetheless, the oxygen is not a neutron poison and does not prevent attainment of "large reactivity coefficients and short neutron life times"[18] even in the much less reactive $^{235}UO_2$. Indeed, the low initial density (ρ ~2.3 g cm^{-3} uncompacted, 4-5 g cm^{-3} moderately compacted) of PuO_2 powder relative to its sintered (≲11.2) or crystal (11.5) density, and its relative compressibility at crystal density, permit crude designs with a generous safety margin of initial subcriticality to achieve high supercriticality after implosion. It is, therefore, not surprising that PuO_2, has been uniformly agreed to be directly useable in formidable explosives[18,19,24,25,41]. A bomb made directly even from fresh LMFBR mixed-oxide fuel (15–25% Pu) is theoretically possible[49], though unwieldy.

Weapons physics and reactor-grade plutonium

A nuclear explosion results from a divergent chain reaction in a prompt-supercritical mass: that is, one which can support a chain reaction by virtue only of the prompt neutrons released immediately by fission. The fission neutrons in a bomb are fast, with energies in the megavolt range and velocities of the order of 1–2 x 10^{-9} cm s^{-1}. The fissionable material must be of sufficient

size and density that a neutron born within it is likely to cause a further fission within it. The critical masses discussed above imply that the mean distance between fissions is of the order of centimetres, hence that the mean time between fissions is of the order of 10^{-8} s. Roughly "40–50 generations of fissions are required to build up a fast chain reaction to an explosive level"[41]: e^{40}= 2.4 x 10^{17} fissions would release 1.6 x 10^{3} kcal, equal to the nominal energy release from ~1.6 kg of high explosive and thus approaching the energy density needed to disassemble rapidly a Pu core of nominal size. Only the last few generations in this exponential process provide appreciable energy yield. That energy builds up, in a few hundredths of a microsecond, temperatures of several hundred million ˚C of and pressures of the order of 10^{8} bar, causing the core to expand with a velocity of the order of 10^{8} cm s^{-1}. Expansion from the initial radius by a factor roughly equal to the sixth root of the number of critical masses present, that is, by ~1 cm, makes the mass subcritical and quenches the chain reaction. Once the explosion begins, then, only a few more generations of fission, producing most of the yield, are possible.

The designer seeks to assemble as supercritical a mass as possible (by 'inserting reactivity') as quickly as possible, and to inject neutrons to initiate the chain reaction at the optimal moment during that assembly—before the instant of maximum supercriticality, so that the bomb's tendency to fly apart is partly countered by the continuing forces of convergent assembly. The yield of the nuclear explosion depends strongly on the degree of supercriticality achieved when the chain reaction is initiated. If the neutron background is so large that preinitiation, before the optimal moment, is likely, then the yield varies[18] as (rate of reactivity insertion)$^{\sim 1\text{-}1.5}$.

Preinitiation reduces yield according to the Poisson statistics of neutron background, and can be counteracted by faster assembly. For a constant level of maximum reactivity insertion, the probability of avoiding preinitiation varies as 1/exp (neutron source strength x assembly time).

Preinitiation is a problem faced by any nuclear weapons designer using any fissionable material[31]. With ^{235}U (spontaneous fission rate 8 x 10^{-4} n g^{-1} s^{-1}), it is a mild problem, so assembly by the relatively slow 'gun' method at published rates <1 mm μs^{-1} (0.3 mm μs^{-1} in the Hiroshima bomb) suffices. But even weapons-grade Pu, with neutron background ≳60,000 times higher (just above ^{238}U), preinitiates unless assembled implosively by a convergent arrangement of chemical high explosives. The radial compression rate can then[32] exceed 2 mm μs^{-1}.

A reflected core of Pu metal, sufficiently subcritical that neutron multiplication can be neglected, will have a neutron background of the order of 0.5 x 10^{6} n s^{-1} if of weapons grade, several million n s^{-1} if of reactor grade. The former figure implies a mean time between neutrons of a few microseconds—half an order of magnitude longer than the duration of the fission chain. But the latter figure implies a mean time between neutrons that is short compared with the time required to complete the assembly of a highly supercritical mass, unless that assembly is extremely rapid, implying very high shock velocities and compression. This can in fact be achieved:

> "Plutonium of any feasible grade (weapons or reactor) is unsuitable for the gun-assembled systems because the neutron background and relatively long assembly time introduces significant preinitiation probabilities. This is not necessarily true for implosion types"[34].

Preinitiation, then,

> ". . . does *not* necessarily make an explosive unreliable. Preinitiation *does* result in a statistical uncertainty in the yield ... [that] is statistically distributed between predictable upper and lower limits which are likely to be more than a factor of 10 apart. For a *well-understood design properly constructed*, however, the most probable yield range could be predicted within much closer limits"[24].
>
> "In implosion devices, preinitiation probabilities may be lowered by various design techniques. Even relatively low technology designs, notwithstanding the variability in yield, *can produce effective, highly powerful weapons*"[34].

This can be achieved[41] even with a neutron source strength of the order of 10^{6} n s^{-1}. As was officially appreciated in 1944,

> "...[A] rough quantitative analysis of the assembly velocities attainable with very large charges of high explosive ... suggested that because of the strong focusing effect of the converging material, one could introduce a strong steady source of neutrons into the bomb (for example, by deliberately leaving the material in an impure state), and still beat the chain reaction and attain complete assembly".

Thus preinitiation "*...may mean a statistical uncertainty in the yield within a predictable range*. Increasing technological sophistication will reduce this uncertainty"[31].

Now, consider several several levels of "increasing technological sophistication" and their likely effects on the performance of implosion bombs made from reactor-grade Pu or other compositions[37] with high neutron source strength.

Performance as a function of design

Since it became public knowledge that construction of illicit nuclear weapons by non-state adversaries must be taken seriously[19], and that reactor-grade Pu is suitable for such bombs[17,18,24], the level of technology on which most discussions have centred can be described as 'crude amateur designs' in which the normal military design requirements for pure fissile material and for the symmetry, simultaneity, and speed of implosion are very considerably relaxed. The canonical description of such designs is that of Willrich and Taylor[19]:

> "Under conceivable circumstances, a few persons, possibly even one person working alone, who possessed ~10 kg of plutonium oxide and a substantial amount of chemical high explosive could, within several weeks [or perhaps less], design and build a crude fission bomb... [that] would have an excellent chance of exploding, ... probably ... with the power of at least 100 tons of chemical high explosives. This could be done using materials and equipment that could be purchased at a hardware store and from commercial suppliers of scientific equipment for student laboratories... [It] might yield as much as 20 kilotons of explosive power–the equal of the Nagasaki A-bomb [though the probability of such a high yield is quite small]."

"...very sophisticated thermal-hydraulic and neutronic calculations"[43] would not be needed. Several suitably comprehensive literature searches have in fact been conducted by amateurs. The bomb could fit in a car[41].

Making an effective, transportable fission bomb is not a trivial task. Safely realising a paper design in properly working apparatus would require alertness to subtleties and care and skill in technical arts (which many criminal enterprises have shown). The necessary human resources will be assumed here to have been obtained. The skills required for both design and fabrication naturally increase with increasing sophistication and have been taken into account in the policy conclusions drawn here.

Several studies[32,43,50,51] have dealt quantitatively with the heterogeneous class of flexible and imprecise designs grouped here as Level One technology. Calculations confirm that in the absence of gross incompetence or malfunction of major components, Level One technology is extremely likely to yield >0.01 kton, likely to yield in the range 0.1-1 kton, able on occasion to yield several kton, and unlikely to yield 10-20 kton.

A second level of technology might be characterised as 'imitation Trinity designs' or as 1945-vintage US technology. It uses special high-explosive components and detonators (all of which are commercially available) in a straightforward geometry to compress an accurately made metallic Pu core. Given the materials and information that have become widely available since the 1940s, such a technology might be typical of a low-level national effort to produce a bomb that can be depended on to work well

without previous testing (Trinity yielded 17 kton). It is not a clever technology (simpler means can produce better results) but is basic and reliable, and has been the subject of several amateur design exercises. Five distinguished nuclear weapons experts concluded that using weapons-grade Pu (or ^{233}U or highly enriched ^{235}U)

> "... it is possible to design low-technology devices that would reliably produce explosive yields up to the equivalent of 10 or 20 kilotons of TNT. With reactor-grade plutonium it is possible to design low-technology devices with probable yields 3–10 times lower than those mentioned above (depending on the design), but yields in the kiloton range could be accomplished. Militarily useful weapons with *reliable* nuclear yields in the kiloton range can therefore be constructed using low technology and reactor-grade plutonium"[24].

(This is consistent with De Volpi's Table L–6 results[37], given realistic choices of parameters.) As for the resources required, "a small group of people, none of whom have ever had access to the classified literature", could get by with "modest machine-shop facilities that could be contracted for without arousing suspicion" and with "a fraction" (perhaps a small fraction) of a million dollars for open-market equipment[24].

Recently declassified documents dealing with 1945 US technology give[1]

> "...quite precise quantitative information ... covering some aspects of how the probability distribution of nuclear yields changes with the isotopic composition of the plutonium used .... This information makes clear that with power reactor grade plutonium, an implosion weapon of even the simple kind first used by the US would reliably have yields between 1 and 20 kton"[52].

Preinitiation at the least favourable moment[50] in a Trinity-type bomb would still produce[1] reliable kiloton yields: the worst case, minimum, 'fizzle' yield is still a "militarily useful"[31] ~1 kton. This behaviour is chiefly a function of assembly rate, not neutron background, because the least favourable moment cannot get any less favourable. The same conclusion would therefore hold[42] even with arbitrarily high neutron source strength, as from 'a large fraction' of ^{242}Pu (ref. 46) and high ^{238}Pu (ref. 37). Contrary to Meyer *et a1.*[43], "slight mistakes in the knowledge of exact isotopic composition" could not "lead to neutralisation of the explosive design" and could indeed be readily accommodated by design.

Selden summarises[31]:

> "It is likely that a nuclear explosive designer would choose to minimise the ^{240}Pu concentration, given the choice. However, *an entirely credible national nuclear explosives capability could be constructed using only reactor grade plutonium.*"

Of course, the designer may choose to avoid the extra fiscal and political cost (if detected) of the *unambiguously military* dedicated facilities required[13] to make large amounts of the more conveniently useable weapons-grade Pu. Some governments may find advantages, notably civilian 'cover', in doing the best they can with their plentiful high-burn-up Pu instead. Recent classified analyses have therefore explored further levels of technological sophistication that can overcome the sub-optimal features of high-burn-up Pu and increase the ~1-kton *minimum* yield of Level Two technology.

Perhaps the most categorical statement of the results comes from a speech[14] by Commissioner Gilinsky (emphasis added):

> "...[S]o far as reactor-grade plutonium is concerned, the fact is that it is possible to use this material for nuclear warheads *at all levels of technical sophistication*. In other words, countries less advanced than the major industrial powers but nevertheless possessing nuclear power programs can make very respectable weapons. And, I might add, these are the very countries whose names turn up in every discussion of proliferation. Of course, when reactor grade plutonium is used there *may* be a penalty in performance that is considerable or *insignificant*, depending on the weapon design. But whatever we might once have thought, we now know that even simple [Level Two] designs, albeit with some uncertainties in yield, can serve as effective, highly powerful weapons—reliably in the kiloton range."

The italicised passages imply that further levels of technology exist with still higher yield and predictability than Level Two.

A third level of technology seeks to overcome preinitiation by extremely rapid assembly. The necessary rates of assembly can be calculated and seem to be readily attainable. One published configuration, for example, is stated to be able to compress a sizeable core at several times the 2 mm μs^{-1} radial rate mentioned earlier. Far higher rates are possible with this method, because in a convergent implosive system, shock pressures vary roughly as the inverse fourth power of radius and shock velocities as the inverse square of radius. Applying the same design to a small core can therefore achieve such high assembly velocities that the shock can traverse much of the core and insert very substantial reactivity before hydrodynamic disassembly forces can dominate. The probability of preinitiation then becomes small, the expected yield relatively large, and its dispersion small: in short, the performance penalty approaches the "insignificant"[14].

Calculations suggest that this Level Three technology is sufficient, using reactor-grade Pu, for almost any military objective, even with attempted 'denaturing'[37]. The method will readily occur to most governments and to many technically informed amateurs. The apparatus is not unduly difficult to achieve. It does not necessarily involve a higher technology than Level Two, and should be considered more a logical extension of Level One, a 'smart amateur design', than the exclusive province of governments. It does not necessarily require nuclear testing to ensure confidence in obtaining high yield, provided the maker is confident that the well-characterised non-nuclear components will function as designed. Non-nuclear test firings would, of course, increase this confidence.

Most military bombs are required to function normally in high neutron fluxes such as might arise from nearby nuclear explosions. Essentially the same design considerations apply as in the case of high internal neutron source strengths. It can be safely presumed that these problems are routinely overcome by various means, including thermonuclear techniques that could render the penalty from using reactor-grade Pu not only very small but nil, even at very high yields. This is a very high technology requiring elaborate theoretical, computational, and fabrication facilities, together with prior nuclear testing. But such sophistication is not required for governments or even for some subnational groups to extract from reactor-grade Pu, using Level Three technology, the kind of yield and predictability that the major nuclear powers would have found satisfactory for inclusion in their arsenals around the early 1960s.

Weapons effects and the implications of uncertain yield

Fissioning 1 kg of Pu yields (2.5 x 10^{24} fissions) x (~180 MeV of prompt energy per fission) 7.3 x 10^{13} J kg^{-1} or ~17 x 10^{12} gcal kg^{-1} 17kton kg^{-1}. This 17-kton yield (Hiroshima was 13 kton, Nagasaki 22 kton) corresponds to the conversion of a mass defect of only 0.8 g. But unlike chemical high explosives, some of the yield of nuclear explosives appears not as blast or heat but as prompt electromagnetic radiation at many frequencies, especially γ rays, and as prompt neutrons. The smaller the nuclear yield, the more the effects of the nuclear explosion are dominated by prompt radiation.

For example, a 'crude amateur design' yielding only 0.1 kton—which corresponds to fissioning only 6 g (a nominal efficiency of the order of 10^{-3}) and converting a mass defect of 5 mg—typically produces[19,53] 500 rem of prompt γ dose (roughly the LD_{50}, or dose likely to kill half those exposed to it) at unshielded ranges up to 300 m, plus 500 rem of prompt neutrons (~LD_{50}) to ~450 m, plus 500 rem of fallout exposure (~LD_{50}) to 300–1,000 m for people lingering for an hour. Yet

such a surface burst makes a crater only ~14 m in radius. Blast damage is also of shorter range than the prompt radiation—severe (overpressure to 101b in^{-2} = 0.68 bar) to 150m and moderate (3 lb in^{-2} = 0.20 bar) to 300m. The relatively limited blast damage, even at such low yield, however, could amplify the radiation effects by ~10^3 times if used to induce a 1% ground release from an operating I-GWe LWR (16-GCi inventory), ~10–100 times more from a reprocessing plant.

Effects of larger yields are readily, if roughly, calculable from standard scaling laws[19,53]. For example, a yield of 1 kton, a practical minimum with Level Two technology (but three orders of magnitude larger than a World War 11 blockbuster), would devastate several km^2, with 500 rem prompt radiation beyond 700 m and with 500 rem fallout around 1–3 km. If a yield Y expected to be 8 kton is in fact only 1kton, the blast area will diminish not by 7/8 but by 3/4 (as $Y^{2/3}$), and the lethally irradiated area only by half (as $Y^{1/3}$) (refs 1, 53). Such reductions would generally be smaller than the variability in effect expected from the varying circumstances of use; and except in special tactical-warfare conditions, the important thing is not whether the designer can predict the exact yield, but rather that the potential victim cannot.

Conclusions

The above discussion has sought to provide a discreet, selective, but adequate physical basis for understanding the scope for using reactor-grade Pu in fission bombs at some of the diverse levels of sophistication open to various potential users (the taxonomy given is not exhaustive). 'Denaturing' Pu by adding to it, singly or in combination, essentially inseparable[54] neutron-emitting diluents such as ^{238}Pu, ^{240}Pu, ^{242}Pu, or ^{252}Cf (ref. 55)—or indeed any other interfering material that cannot be readily removed, for example, by ion exchange—is "fallacious" and "not a valid concept"[31]. (Dilution with UO_2 or other materials requiring chemical or physical[56] separation is a valid concept–it means more material must be diverted and processed[19,25,34]—but does not solve the problem.) Taking all effects on weapons physics into account, a high $^{238,240,242}Pu$ content may reduce expected yield to a level that could devastate only a reduce expected yield to a level that could devastate only a modest portion of a city rather than all of it, and may make that yield much less predictable, if the bomb is crudely made. But these faults can be overcome by more clever design, without necessarily using high technology, and at Level Three this can be done by gifted amateurs. It is therefore incorrect to state categorically that bombs made from reactor-grade or deliberately 'denatured'[37] Pu are less effective, less powerful, or less reliable than those made from weapons-grade Pu. Whether these reservations hold, and whether by a meaningful margin, depend on the designer's intentions, skills, and resources, all of which may be unknowable. And the implication that the effects of even a crude, minimal 0.1–1 kton explosion would be tolerable for a free society is at best disingenuous[19-21,27].

The foregoing argument also implies that power reactors are not an implausible but are rather potentially a peculiarly convenient type of large-scale military Pu production reactor. This goes beyond the proposition that

> " . . . in situations of extreme tension states may turn to second or third best instruments to get their hands on weapons they regard as essential to their security. The point is that, with plutonium readily available, it may be turned to. And those groups within countries that want to go nuclear can pursue an ambiguous path of keeping their options open until the last minute under a commercial disguise"[57].

A government can either manipulate civil fuel cycles to produce substantial amounts of low-burn-up plutonium, or, especially using Level Three technology, use high-burn-up Pu in bombs with insignificant performance penalty. Regardless of possible technical measures[24,25,54,58,59], such Pu will become readily available in quantities of the order of 10^4–10^5 m_c yr^{-1}, and in extracted forms useable for weapons within hours or days, if plans proceed for commercial reprocessing, which is unsafe guardable both today[36] and in principle[14,59,60]. Making even high-burn-up Pu in domestic power reactors incurs no penalty in reactor efficiency or in equipment costs: a reactor-exporting country will gladly build the reactor, train the technicians, and pay for the whole package with generous export subsidies. If extracted, and using any of the numerous means of evading effective safeguards, the Pu discharged from a single large power reactor suffices for about 10^2 bombs per year, a large weapons programme, and there is the alternative of embezzling up to a few bombs' worth per reactor-year from the fuel cycle within its ~1%, statistical 'noise', a form of theft that can be made undetectable in principle. The marginal time and money required to use civil reactors for military production are orders of magnitude less[27] than those needed for dedicated military facilities[11,61] . The extra facilities and staff required could be hidden within the civil programme: the "ideal place to hide a tree is in a forest"[61]. And perhaps the greatest attraction of producing military Pu in a power reactor is that it has a civilian 'cover' and thus—at least until regional rivals follow suit—an apparently zero political cost.

In short, the somewhat greater technical difficulty of using power-reactor Pu for effective military bombs—assuming the reactor is actually operated at high fuel burn-up—may be more than counterbalanced by the greater political and economic ease of obtaining that Pu. It "should not be lightly disdained in favour of purer material from dedicated facilities"[61].

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